Evaluation of Lens Doses among Medical Staff Involved in Nuclear Medicine: Current Eye Radiation Exposure among Nuclear-Medicine Staff

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Abstract: The International Commission on Radiological Protection has lowered the annual equivalent eye-lens dose to 20 mSv. Although occupational exposure can be high in nuclear medicine (NM) departments, few studies have been conducted regarding eye-lens exposure among NM staff. This study aimed to estimate the annual lens doses of staff in an NM department and identify factors contributing to lens exposure. Four nurses and six radiographers performing positron emission tomography (PET) examinations and four radiographers performing radioisotope (RI) examinations (excluding PET) were recruited for this study. A lens dosimeter was attached near the left eye to measure the 3-mm-dose equivalent; a personal dosimeter was attached to the left side of the neck to measure the 1-cm- and 70-µm-dose equivalents. Measurements were acquired over six months, and the cumulative lens dose was doubled to derive the annual dose. Correlations between the lens and personal-dosimeter doses, between the lens dose and the numbers of procedures, and between the lens dose and the amounts of PET drugs (radiopharmaceuticals) injected were examined. Wilcoxon’s signed-rank test was used to compare lens and personal-dosimeter doses. The estimated annual doses were 0.93 ± 0.13 mSv for PET nurses, 0.71 ± 0.41 mSv for PET radiographers, and 1.10 ± 0.53 mSv for RI radiographers. For PET nurses, but not for PET or RI radiographers, there was a positive correlation between the numbers of procedures and lens doses and between amounts injected and lens doses. There was a significant difference between the lens and personal-dosimeter doses of PET nurses. The use of protective measures, such as shielding, should prevent NM staff from receiving lens doses > 20 mSv/year. However, depending on the height of the protective shield, PET nurses may be unable to assess the lens dose accurately using personal dosimeters.

Keywords: radiation protection and safety; nuclear medicine; positron emission tomography (PET); radioisotope (RI) examination; single-photon emission computed tomography (SPECT); eye-lens dose; nurse; occupational radiation exposure; radiographer; disaster medicine

1. Introduction

Radiation protection holds critical importance for individuals working in fields involving radiation, particularly due to potential occupational exposure of the eye lens. This importance is underscored by numerous reports of cataract development in radiation...
workers [1,2]. The International Commission on Radiological Protection (ICRP) issued a statement regarding tissue reactions in 2011, which led to a review of lens-dose limits in many countries. The ICRP established a mean annual lens-dose occupational exposure limit of 20 mSv over a five-year period, and the dose also should not exceed 50 mSv in any single year; the previous limit was 150 mSv/year [3]. Many studies have been conducted regarding lens exposure in medical personnel [4–12]. For instance, one study found that some physicians exceeded the annual lens dose of 20 mSv [13], while another demonstrated how protective equipment, such as eyewear, could effectively reduce lens exposure [14].

In International Atomic Energy Agency Tecdoc Series No. 1731 [14], a risk of significant lens exposure is acknowledged for staff involved in fluoroscopic interventional radiology (IVR), nuclear medicine (NM; particularly when using beta radiation sources), brachytherapy, computed tomography-guided puncture procedures, and cyclotrons. The likelihood that the lens-dose limit will be exceeded is particularly high for fluoroscopic IVR [15–25]. Lens exposure has also been reported in fluoroscopies, such as endoscopic retrograde cholangiopancreatography (ERCP) and respiratory endoscopy, as well as in CT-guided puncture procedures and brachytherapy [11,26,27]. However, few studies have evaluated lens exposure during NM examinations, although such examinations carry a high risk of occupational exposure. Moreover, among radiology technologists (RTs) who have performed at least one NM examination, there is an increased risk of cataracts [28]. Thus, there is a need for studies of lens exposure among medical personnel involved in NM examinations.

Unlike other radiological procedures, such as X-rays and CT scans, NM examinations involve the administration and imaging of radiopharmaceuticals using radiation emitted from radionuclides. As a result, pre- and post-examination operations, such as radiopharmaceutical preparation, drug administration, and patient contact, can also contribute to radiation exposure.

Personal dosimeters, used mainly for whole-body exposure assessments, are also suitable for lens dosimetry. In Japan, the higher of the two doses recorded at 1 cm and 70 μm from the skin surface [1-cm-dose equivalent, $H_{p}(10)$ and 70-μm-dose equivalent, $H_{p}(0.07)$, respectively], as estimated by personal dosimeters, is regarded as the lens dose. However, to assess the lens dose accurately, estimation of the dose within the vicinity of the lens at 3 mm from the skin surface [3-mm-dose equivalent, $H_{p}(3)$] has been recommended [15,29].

This study examined eye-lens exposure among nurses and RTs engaged in positron emission tomography (PET) examinations and among RTs engaged in radioisotope (RI) examinations other than PET (e.g., single-photon emission computed tomography [SPECT]). Long-term measurements of $H_{p}(3)$ values in the vicinity of the lens have not been widely reported for NM staff. Furthermore, there remains a lack of clarity concerning the relationships of $H_{p}(3)$ values in the vicinity of the lens with the numbers of procedures performed and the quantities of PET drugs administered to patients. In this study, we used a lens dosimeter to measure the $H_{p}(3)$ values of NM staff over a long period and then estimated the annual lens dose; we used this information to examine the relationship between the lens dose and the work performed.

2. Materials and Methods

2.1. Dosimeters

To measure the lens dose, a lens dosimeter (DOSIRIS; IRSN, Fontenay-aux-roses, France) and a personal dosimeter (Glass Badge; Chiyoda Technol, Tokyo, Japan) were used. The DOSIRIS dosimeter was placed near the left eye lens, and $H_{p}(3)$ values were measured. Commonly used in radionuclide (RI) examinations, $^{99m}$Tc emits 141 keV, and $^{18}$F, used in PET examinations, emits 511 keV of $\gamma$-rays. Given these energy ranges, the selection of an appropriately sensitive dosimeter was crucial for this study. DOSIRIS is a thermoluminescent dosimeter (element: $^{7}$LiF: Mg, Ti) that can measure X- and $\gamma$-ray energies from 24 keV to 1.25 MeV; it can measure average $\beta$-ray energies beginning at 0.8 MeV without an upper limit. The dose range that can be measured by DOSIRIS is 0.1 mSv to 1 Sv;
doses are estimated to two decimal places. DOSIRIS has excellent uniformity, dose linearity, energy dependence, and angle dependence in the diagnostic-X-ray energy range [30].

In this study, a glass badge dosimeter was worn on the left side of the neck, and $H_p(10)$ and $H_p(0.07)$ values were measured and compared; the higher value was regarded as the lens dose and was used for analysis. The glass badge uses silver-activated phosphate glass as the fluorescent element. The energy ranges are 10 keV to 10 MeV for X- and γ-rays and 130 keV to 3 MeV for β-rays. The measurement period was 1 month. Both the DOSIRIS and glass badge dosimeters were calibrated each month by Chiyoda Technology. The background was corrected via subtraction of the dose measured by a control dosimeter. All dose readings were also performed by Chiyoda Technol.

2.2. Subjects

The radiopharmaceuticals used for PET and RI (e.g., SPECT) examinations were $^{18}$F fluorodeoxyglucose ($^{18}$F-FDG) and technetium-99m ($^{99}$mTc), respectively. The numbers of examinations performed per month were also recorded.

This study was conducted from April to September 2018 at Sendai Kosei Hospital, a facility known for performing numerous NM examinations and with the ability to consistently measure occupational eye doses for these procedures. Over a 6-month period, measurements were obtained from four nurses involved in PET examinations. At this facility, four nurses are typically assigned to PET examinations, and measurements were performed on all of them.

A survey was also conducted of six RTs involved in PET examinations and four RTs involved in RI examinations, excluding PET examinations. Due to scheduling constraints, RTs were rotated monthly. One or two RTs were assigned to each of these examinations.

Measurements were taken 8 times for RTs involved in PET examinations and 10 times for RTs involved in RI examinations over a 6-month period. Specifically, for PET, 1-month measurements were performed for four RTs, and 2-month measurements were performed for two RTs. For RI, 1-month measurements were obtained for one RT, 2-month measurements were obtained for one RT, 3-month measurements were obtained for one RT, and 4-month measurements were obtained for one RT.

The duties of nurses involved in PET examinations included preparation of the automated injection device prior to drug administration, administration of $^{18}$F-FDG, and general patient care. To reduce exposure, protective shields were used during administration of $^{18}$F-FDG, but no special equipment (e.g., protective Pb glasses) was used to protect the eye lens. The layout of the examination room is shown in Figure 1. The duties of the RTs involved in the PET and RI examinations included assisting patients and operating the equipment. Similar to the nurses, the RTs did not wear protective glasses.

Figure 1. Layout of the examination room.
This study protocol was approved by the Ethics Committee of Sendai Kosei Hospital.

2.3. Data Analysis

We performed linear regression analysis to examine the correlations among the dose estimates of DOSIRIS and glass badge, the eye-lens doses measured by the two dosimeters, the numbers of procedures performed, and the lens and PET drug doses. Nurses’ exposure was analyzed using 6-month lens doses, while RTs were evaluated using 1-month lens doses. In the analysis of RTs, we did not consider the variability among workers, focusing solely on the relationship among lens dose, number of procedures, and PET drug dose. For the nurses, annual doses were estimated based on doses received over a 6-month period; we also recorded whether the 20 mSv/year threshold was exceeded. The annual lens dose was calculated using Equation (1) [5,21,31]:

\[
\text{Estimated annual lens dose} = 6\text{-month lens dose} \times 2
\]

In the case of RTs, the personnel changed monthly. Therefore, we used the 1-month lens dose to calculate the annual lens dose as follows:

\[
\text{Estimated annual lens dose} = 1\text{-month lens dose} \times 12
\]

The numbers of procedures performed annually by nurses and RTs vary among facilities, depending on the performance of the equipment and the number of staff. The number of procedures required for the annual eye-lens dose to exceed 20 mSv was calculated as follows:

\[
\text{Number of procedures required for eye-lens dose to exceed 20 mSv/year} = 20 / \text{estimated annual lens dose} \times \text{estimated annual number of procedures}
\]

Wilcoxon’s signed-rank test was used to compare the glass badge and DOSIRIS dose estimates. We chose this method based on a previous study that performed similar comparisons [21]. The test was performed on the 1-month lens dose data. \( p \)-values < 0.05 were considered statistically significant.

3. Results

3.1. Lens Doses for PET Nurses

Table 1 shows the \( H_{p}(10) \), \( H_{p}(0.07) \), and \( H_{p}(3) \) values for PET nurses, the numbers of procedures performed, and the amounts of drugs administered to patients during PET examinations. Over a 6-month period, the mean \( H_{p}(10) \) and \( H_{p}(0.07) \) (glass badge) values were \( 0.31 \pm 0.076 \) and \( 0.29 \pm 0.076 \) mSv, respectively; the mean monthly \( H_{p}(3) \) (DOSIRIS) value was \( 0.47 \pm 0.064 \) mSv. The respective annual doses were \( 0.62 \pm 0.15 \), \( 0.60 \pm 0.15 \), and \( 0.93 \pm 0.13 \) mSv (Table 2). The annual dose estimates were all considerably less than 20 mSv, although the doses measured by DOSIRIS were higher than those measured by the glass badge. The estimated number of procedures that would need to be performed by a PET nurse for an annual exposure dose > 20 mSv was 12,216.

Table 1. Radiation doses of nurses, numbers of procedures performed, and amounts of PET drugs administered to patients by nurses over a 6-month period.

<table>
<thead>
<tr>
<th>Number of Nurses</th>
<th>Neck Badge ( H_{p}(10) ) (mSv/6 Month)</th>
<th>Neck Badge ( H_{p}(0.07) ) (mSv/6 Month)</th>
<th>DOSIRIS ( H_{p}(3) ) (mSv/6 Month)</th>
<th>Number of Procedures (6 Months)</th>
<th>Injected Dose (GBq/6 Month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ns.1</td>
<td>0.34</td>
<td>0.32</td>
<td>0.57</td>
<td>321</td>
<td>104.07</td>
</tr>
<tr>
<td>Ns.2</td>
<td>0.4</td>
<td>0.39</td>
<td>0.43</td>
<td>304</td>
<td>98.29</td>
</tr>
<tr>
<td>Ns.3</td>
<td>0.19</td>
<td>0.18</td>
<td>0.4</td>
<td>240</td>
<td>77.34</td>
</tr>
<tr>
<td>Ns.4</td>
<td>0.31</td>
<td>0.3</td>
<td>0.46</td>
<td>271</td>
<td>87.11</td>
</tr>
<tr>
<td>mean ± SD</td>
<td>0.31 ± 0.076</td>
<td>0.29 ± 0.076</td>
<td>0.47 ± 0.064</td>
<td>284 ± 34.12</td>
<td>91.70 ± 10.29</td>
</tr>
<tr>
<td>median (IQR)</td>
<td>0.33 (0.28–0.36)</td>
<td>0.31 (0.27–0.34)</td>
<td>0.45 (0.42–0.49)</td>
<td>287.50 (263.25–308.25)</td>
<td>92.70 (84.67–99.74)</td>
</tr>
</tbody>
</table>
Table 2. Estimated annual eye-lens doses (mean ± standard deviation).

<table>
<thead>
<tr>
<th>Staff</th>
<th>Neck Badge $H_{p}(10)$ (mSv/Year)</th>
<th>Neck Badge $H_{p}(0.07)$ (mSv/Year)</th>
<th>DOSIRIS $H_{p}(3)$ (mSv/Year)</th>
<th>Number of Procedures (Year)</th>
<th>Injected Dose (GBq/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET nurses</td>
<td>0.62 ± 0.15</td>
<td>0.60 ± 0.15</td>
<td>0.93 ± 0.13</td>
<td>568.00 ± 68.24</td>
<td>183.40 ± 20.58</td>
</tr>
<tr>
<td>PET radiographer</td>
<td>0.53 ± 0.44</td>
<td>0.53 ± 0.44</td>
<td>0.71 ± 0.41</td>
<td>852.00 ± 188.40</td>
<td>270.44 ± 59.38</td>
</tr>
<tr>
<td>RI radiographer</td>
<td>0.92 ± 0.49</td>
<td>0.82 ± 0.53</td>
<td>1.10 ± 0.53</td>
<td>667.20 ± 372.90</td>
<td></td>
</tr>
</tbody>
</table>

3.2. Lens Doses for PET RTs

Table 3 shows the lens doses for PET and RI RTs, the numbers of procedures performed, and the amounts of drugs administered to patients during PET examinations. The mean monthly lens doses were 0.044 ± 0.036 mSv for the glass badge [$H_{p}(10)$ and $H_{p}(0.07)$] and 0.059 ± 0.034 mSv for DOSIRIS [$H_{p}(3)$]. The estimated annual lens doses were 0.53 ± 0.44 mSv for the glass badge [$H_{p}(10)$ and $H_{p}(0.07)$] and 0.71 ± 0.41 mSv for DOSIRIS [$H_{p}(3)$] (Table 2).

Table 3. Radiation doses of RTs, numbers of procedures performed, and amounts of PET drugs administered to patients each month by PET and RI RTs (Mean ± Standard Deviation, Median and IQR).

<table>
<thead>
<tr>
<th></th>
<th>Neck Badge $H_{p}(10)$ (mSv/Month)</th>
<th>Neck Badge $H_{p}(0.07)$ (mSv/Month)</th>
<th>DOSIRIS $H_{p}(3)$ (mSv/Month)</th>
<th>Number of Procedures (Month)</th>
<th>Injected Dose (GBq/Month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET radiographer</td>
<td>Mean ± SD 0.044 ± 0.036</td>
<td>0.044 ± 0.036</td>
<td>0.059 ± 0.034</td>
<td>71.0 ± 15.70</td>
<td>22.54 ± 4.95</td>
</tr>
<tr>
<td></td>
<td>Median (IQR) (0.05–0.068)</td>
<td>(0.05–0.068)</td>
<td>(0.035–0.09)</td>
<td>(71.0–80.25)</td>
<td>(24.75–84.25)</td>
</tr>
<tr>
<td>RI radiographer</td>
<td>Mean ± SD 0.077 ± 0.041</td>
<td>0.068 ± 0.044</td>
<td>0.088 ± 0.044</td>
<td>55.6 ± 31.07</td>
<td>24.31</td>
</tr>
<tr>
<td></td>
<td>Median (IQR) (0.05–0.096)</td>
<td>(0.05–0.096)</td>
<td>(0.063–0.11)</td>
<td>(21.42–25.12)</td>
<td></td>
</tr>
</tbody>
</table>

The annual lens-dose estimates were all considerably less than 20 mSv for PET RTs, although the doses measured by DOSIRIS were higher than those measured by the glass badge. The estimated number of procedures that would need to be performed by a PET RT for an exposure dose > 20 mSv/year was 24,000.

3.3. Lens Doses for RI RTs

For RI RTs, the mean monthly $H_{p}(10)$ and $H_{p}(0.07)$ values for the glass badge were 0.077 ± 0.041 and 0.068 ± 0.044 mSv, respectively; the mean monthly $H_{p}(0.07)$ value for DOSIRIS was 0.088 ± 0.044 mSv (Table 3). The estimated annual $H_{p}(10)$ and $H_{p}(0.07)$ values were 0.92 ± 0.49 and 0.82 ± 0.53 mSv for the glass badge, respectively, and 1.10 ± 0.53 mSv for DOSIRIS [$H_{p}(3)$]. The annual dose estimates were all considerably less than 20 mSv, although the doses measured by DOSIRIS were higher than those measured by the glass badge. The estimated number of procedures that would need to be performed by an RI RT for an exposure dose > 20 mSv/year was 12,128.

3.4. Comparison of Dosimeter Lens Doses

The eye-lens doses for PET nurses estimated by glass badge are plotted against the eye-lens doses estimated by DOSIRIS over a 6-month period in Figure 2. Linear regression analysis revealed weak correlations between $H_{p}(10)$ and $H_{p}(3)$ ($R^2 = 0.16$) and between $H_{p}(0.07)$ and $H_{p}(3)$ ($R^2 = 0.12$). The respective $R^2$ values for the PET and RI RTs were 0.74 and 0.88 (Figure 3).
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![Figure 2. Correlations between DOSIRIS- and glass badge-estimated lens doses for positron emission tomography (PET) nurses.](image1)

![Figure 3. Correlations between DOSIRIS- and glass badge-estimated lens doses for (a) PET radiology technologists (RTs) and (b) RI RTs.](image2)

A box plot of the glass badge- and DOSIRIS-estimated doses received over 1 month is shown in Figure 4. $H_{p}(10)$ and $H_{p}(0.07)$ values were similar, although $H_{p}(10)$ was slightly larger and was used in further analyses. The doses for PET nurses, PET RTs, and RI RTs are shown in Figure 4a–c, respectively. Wilcoxon’s signed-rank test revealed a significant difference between the estimated doses of the two dosimeters only for PET nurses [$p < 0.05$].

### 3.5. Relationships of Lens Doses with the Numbers of Procedures Performed and Amounts of PET Drugs Administered to Patients

Linear regression analysis revealed a significant, positive correlation between $H_{p}(3)$ values for PET nurses and the numbers of procedures performed over a 6-month period ($R^2 = 0.58$; Figure 5). No such significant correlation was observed for PET or RI RTs (Figure 6). Linear regression also revealed a significant, positive correlation between $H_{p}(3)$ values for PET nurses and the amounts of PET drugs administered to patients over a 6-month period ($R^2 = 0.59$; Figure 7). However, no such significant correlation was observed for PET or RI RTs (Figure 8).
Figure 4. Box plot of DOSIRIS- and glass badge-estimated lens doses to (a) PET nurses, (b) PET RTs, and (c) RI RTs measured over 1 month.

Figure 5. Correlation between DOSIRIS-estimated $H_p(3)$ values and numbers of procedures performed by PET nurses.
4. Discussion

Radiation protection is extremely important for medical workers, many of whom are exposed to radiation daily [32–34]. Therefore, our group (and many others) have conducted extensive studies of radiation protection for healthcare workers and patients [35–41]. The eye lens is composed of tissue with high radiosensitivity; therefore, lens protection is an important issue in medical radiology [42–45].

In the present study, the annual lens doses estimated by DOSIRIS for PET nurses, PET radiographers, and RI radiographers were considerably less than 20 mSv. The estimated numbers of procedures that would need to be performed for the annual lens exposure dose to exceed 20 mSv were 12,216 for PET nurses, 24,000 for PET radiographers, and 40,800 for RI radiographers.

Figure 5. Correlation between DOSIRIS-estimated $H_p(3)$ values and numbers of procedures performed by (a) PET nurses.

Figure 6. Correlation between DOSIRIS-estimated $H_p(3)$ values and numbers of procedures performed by (a) PET radiographers and (b) RI radiographers.

Figure 7. Correlation between DOSIRIS-estimated $H_p(3)$ values and amounts of PET drugs administered to patients by PET nurses.

Figure 8. Correlation between DOSIRIS-estimated $H_p(3)$ values and amounts of PET drugs administered to patients by PET radiographers.
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Table 4 shows the annual lens doses estimated in previous studies. In the study by Guiu-Souto et al. [46], the annual $H_p(3)$ value of PET nurses was estimated using a Monte Carlo simulation based on measured $H_p(10)$ values. In the study by Lindholm et al. [47], the $H_p(3)$ values of RTs involved in NM examinations, including PET scans, were measured directly to estimate the annual dose. Sarti et al. [48] estimated the $H_p(3)$ values of staff involved in the preparation and administration of radiopharmaceuticals. Wrzesien et al. [49] estimated the annual lens doses of PET and RI nurses based on daily doses. Similarly, Dehghan et al. [50] estimated the annual lens doses of medical staff involved in NM examinations. The lens-dose estimates in this study are comparable with—or lower than—the estimates in the previous investigations. In particular, the annual doses of PET nurses according to Wrzesien et al. were much higher than the annual doses in the present study. These differences may be explained by our use of automatic injectors; Wrzesien et al. [49] administered PET drugs manually, which increases the radionuclide exposure time.

Table 4. Annual lens doses in previous studies.

<table>
<thead>
<tr>
<th>Author</th>
<th>Staff</th>
<th>Annual Lens Dose (mSv/Year)</th>
<th>Dosimeter (Detector Element)</th>
<th>Dosimeter Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guiu-Souto et al. [43]</td>
<td>PET nurses</td>
<td>0.93 ± 0.13</td>
<td>EPD® Mk2.3 #1 (electronic personal dosimeter)</td>
<td>neck</td>
</tr>
<tr>
<td>C. Lindholm et al. [44]</td>
<td>PET and RI radiological technicians</td>
<td>1.1 ± 0.1</td>
<td>EYE-D™ #2 (TLD)</td>
<td>near the eyes</td>
</tr>
<tr>
<td>D. Sarti et al. [45]</td>
<td>$^{18}$F and $^{99m}$Tc preparation workers</td>
<td>0.16–0.88</td>
<td>EYE-D™ #2 (TLD)</td>
<td>near the eyes</td>
</tr>
<tr>
<td></td>
<td>$^{18}$F and $^{99m}$Tc administration workers</td>
<td>0.33–2.18</td>
<td>EYE-D™ #2 (TLD)</td>
<td>near the eyes</td>
</tr>
<tr>
<td>M. Wrzesien et al. [46]</td>
<td>PET nurses (preparation-administration)</td>
<td>5–9</td>
<td>TLD</td>
<td>near the eyes</td>
</tr>
<tr>
<td></td>
<td>RI nurses</td>
<td>1.3</td>
<td>TLD</td>
<td>near the eyes</td>
</tr>
<tr>
<td>Dehghan N et al. [47]</td>
<td>Nuclear medicine staff</td>
<td>2.24</td>
<td>TLD</td>
<td>near the eyes</td>
</tr>
<tr>
<td>this study</td>
<td>PET nurses</td>
<td>0.93 ± 0.13</td>
<td>DOSIRIS™</td>
<td>near the eyes</td>
</tr>
<tr>
<td></td>
<td>PET radiological technicians</td>
<td>0.71 ± 0.41</td>
<td>DOSIRIS™</td>
<td>near the eyes</td>
</tr>
<tr>
<td></td>
<td>RI radiological technicians</td>
<td>1.10 ± 0.53</td>
<td>DOSIRIS™</td>
<td>near the eyes</td>
</tr>
</tbody>
</table>

#1 EPD® Mk2.3 (Thermo Electron Corporation Waltham, MA, USA). #2 EYE-D™ (Radcard, Poland).

Multiple studies have estimated the eye-lens doses of nurses and RTs. According to Haga et al. [21], the annual lens dose of nurses involved in cardiovascular IVR examinations was 3.26 ± 1.95 mSv, whereas Medici et al. [51] reported a mean annual lens dose of nurses involved in urologic IVR examinations of 7.3 ± 3.4 mSv. Zagorska et al. [52] estimated that the mean annual lens dose of nurses involved in endoscopic retrograde
cholangiopancreatography (ERCP) procedures was 10.7 mSv. Furthermore, Suzuki et al. [53] estimated that the mean annual lens dose of RTs assisting patients during computed tomography examinations was 8.47 mSv. As stated above, the annual lens doses estimated in this study were lower than the doses in previous investigations. In other words, while numerous studies have been conducted on these types of examinations or treatments, our results presented lower doses relative to previous research [54–57]. Thus, NM examinations may be less likely than IVR, ERCP, and computed tomography examinations to result in excessive lens doses to healthcare workers.

Overall, the eye-lens doses estimated by the glass badge dosimeter in this study were lower than those estimated by DOSIRIS, particularly those of PET nurses. Lindholm et al. [47] reported a strong correlation between personal dosimeter [H\(_p\)(10)]- and lens-dosimeter [H\(_p\)(3); EYE-D; Gammadata Instrument AB, Uppsala, Sweden]-estimated lens doses of RTs performing NM examinations (R\(^2\) = 0.81). Similarly, Dabin et al. [58] reported a positive correlation between the personal dosimeter [H\(_p\)(10)]- and lens dosimeter [H\(_p\)(3); EYE-D]-estimated lens doses of medical staff in an NM department (Pearson’s r = 0.62). Our estimations of the doses received by PET and RI radiographers were similar to the findings in previous studies, although the results for PET nurses were not consistent with previous reports. This discrepancy could be explained by differences in the radiation shielding used during PET drug administration. In our study, the glass badge dosimeter was protected by a lead shield, whereas DOSIRIS was not (Figure 9). The angle dependence of the dosimeters may also have affected the results. Similarly, the weak correlation between H\(_p\)(3) and H\(_p\)(0.07) can be explained by the variation in protection conditions during drug administration.

Figure 9. Protective measures used during PET drug administration.

In this study, H\(_p\)(10) and H\(_p\)(0.07) values, as measured by the glass badge dosimeter, were similar, although H\(_p\)(10) values were slightly higher in all cases. This difference potentially occurred because H\(_p\)(10) is measured in a deeper skin layer. In facilities where β-ray sources are used for examinations or treatments, it may be better to estimate H\(_p\)(0.07) values
rather than $H_p(10)$ values because $H_p(10)$ values are not suitable for evaluating lens doses attributable to $\beta$-rays \[59\].

Regarding the relationship between lens dose and the number of procedures performed, a positive correlation was identified in this study for PET nurses (Figure 5) but not for PET or RI RTs (Figure 6). The number of PET examinations involving $^{18}$F-FDG is increasing in Japan; the demand for such examinations is expected to continue increasing. Accordingly, concerns have been expressed regarding eye-lens doses among nurses who supervise PET scans. The number of PET procedures per nurse can be reduced by rotating their shifts. In contrast, we observed no clear relationship between lens doses and the numbers of procedures performed by PET and RI RTs; this difference potentially occurred because, unlike nurses, these staff members do not directly assist patients \[60\]. Many of the patients in this study had cancer with severe symptoms; thus, they required more assistance. Therefore, the time spent in close proximity with patients may have been more extensive than is usual for nurses.

Similar to the case with the number of procedures, although we observed a positive correlation between the eye-lens doses of nurses and the amounts of PET drugs administered to patients, this relationship was not observed in PET RTs. Among RTs, excessive lens exposure is unlikely if they are not in close proximity to patients, even if a high radiation dose is used.

Future studies could perform Monte Carlo simulations using GEometry ANd Tracking 4, GATE, and Monte Carlo N-Particle Transport Code to facilitate this examination \[61–64\]. These techniques would facilitate an in-depth analysis of $\gamma$-ray behavior during drug administration and examination work, leading to enhanced radiation protection strategies for nurses and RTs in NM examinations.

In summary, radiation-dose control and lens protection are important in reducing occupational exposure \[65\]. The International Atomic Energy Agency classifies NM examinations as being high risk with respect to lens exposure \[15\]. When working with radiopharmaceuticals, a protective shield should be used. We found that lens-dose limits are unlikely to be exceeded for staff involved in NM examinations when protective equipment is used appropriately. Moreover, in PET nurses, the estimated lens doses differed between those measured with personal dosimeters attached to the neck and with lens dosimeters attached near the lens. Depending on the height/shape of the protective shield used during NM examinations, standard/conventional lens dose-management measures may not be adequate when using the glass badge dosimeter; DOSIRIS is needed.

The small number of participants was a limitation of this study. In addition, we did not consider the clinical experience or body size of the nurses or RTs; both factors may have affected the eye-lens doses. Furthermore, the use of real-time dosimeters may help to elucidate the factors that contribute to lens exposure among NM department staff \[66,67\].

5. Conclusions

We estimated the lens doses of nurses and RTs involved in PET examinations and of RTs involved in RI examinations. The results indicated that, if protective equipment is used appropriately, there is an extremely low likelihood that these medical staff will receive an annual eye-lens dose $> 20 \text{ mSv}$. For PET nurses, the lens dose increased with the numbers of procedures performed and the amounts of PET drugs administered to patients. For RTs, the time spent assisting patients was a greater determinant of lens dose than the numbers of procedures performed. The results also imply that, particularly for PET nurses, lens doses may be underestimated by personal dosimeters, depending on the height of the protective shield.

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K.C.; data curation, M.F., Y.H., M.S. (Masahiro Sota), Y.L., and M.S. (Masatoshi Suzuki); writing—original draft preparation, M.F. and Y.H.; writing—review and editing, T.M., Y.H. (Yoshio Hosoi), Y.L., M.S. (Masahiro Sota), and K.C.; visualization, M.F., M.S. (Masahiro Sota), Y.L., and M.S. (Masatoshi Suzuki); supervision, T.M., Y.H. (Yoshio Hosoi), and K.C.; project administration, Y.K., M.A., and K.C.; funding acquisition, K.C. All authors have read and agreed to the published version of the manuscript.

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