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TECHNICAL MATERIAL

Proposal of framework for decision making of additional monitoring of eye lens dose for radiation workers

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This work presents a framework of decision-making for additional monitoring of eye lens dose for radiation workers in reflect to the reduction of the annual dose limit of the eye lens dose. For a quantitative scheme to systematically estimate (non-) homogeneity of exposure, the proposed “homogeneity index (HI)” is introduced. The HIs were estimated by Monte Carlo calculations and found not to exceed up to 10 for γ-ray exposure situations. Applying the HI as a criterion of condition branching to decision-making process of additional monitoring of eye lens dose, proposed decision-making process was shown to cover entirely radiation workers required additional monitoring in the benchmark.

Keywords: bremsstrahlung; eye lens dose; occupational exposure; radiation protection; equivalent dose; Monte Carlo calculation

1. Introduction

This work aims to propose a reasonable framework for decision making process for additional monitoring of eye lens dose of radiation workers. The reduced occupational dose limit for the lens of the eye has been adopted by the International Atomic Energy Agency [1], the European Union [2] and the United States [3]. Annual equivalent dose limit for the lens of the eye for occupational exposure in planned situations was reduced from 150 mSv to 20 mSv averaged over five consecutive years and 50 mSv in any single year. Comprehensive survey in medical sector has been made [4] and the technical document for eye lens dose monitoring has been released from the IAEA [5]. In Japan, eye lens dose has been estimated from dose received on the trunk of radiation workers by selecting appropriate personal dose equivalent, i.e. $H_p(10)$ or $H_p(0.07)$. Additional monitoring has been implemented in each radiation workplace, according to experts’ judgement. However, there is no systematic framework for decision making whether additional monitoring should be performed or not. It heavily depends on a rule of thumb or a work habit/experience in each radiation workplace.

Table 1 shows the scheme for individual monitoring scheme for radiation workers from the IAEA-TECDOC-1731[5]. They proposed key parameters as an Impact factor (IF) which may affects doses radiation worker may be received. However, applying the scheme to radiation monitoring in workplace would be somewhat difficult. This scheme

Table 1. Brief monitoring scheme for photon exposure, proposed by IAEA-TECDOC-1731 [5]

<table>
<tr><th colspan="3">Comment</th><th>Impact Factor</th></tr>
<tr><td colspan="3">Is the mean photon energy below about 40 keV?</td><td rowspan="3">A(Energy and Angle)</td></tr>
<tr><td rowspan="2">If yes
↓
$H_p(0.07)$ may be used but not $H_p(10)$</td><td colspan="2">If no
↓
Is the radiation coming mainly from the front or is the person moving in the radiation field?</td></tr>
<tr><td>If yes
↓
$H_p(0.07)$ or $H_p(10)$ may be used</td><td>If no
↓
$H_p(0.07)$ may be used but not $H_p(10)$</td></tr>
<tr><td colspan="3">Are homogenous radiation field present?</td><td rowspan="2">B(geometry)</td></tr>
<tr><td>If yes
↓
Monitoring on the trunk may be used.</td><td colspan="2">If no
↓
Monitoring near the eyes is necessary.</td></tr>
<tr><td colspan="3">Is protective equipment such as lead glasses, ceiling, table shields, and lateral suspended shields in use?</td><td rowspan="2">C(Protective Equipment)</td></tr>
<tr><td>If used for the eye
↓
Monitoring near the eyes and below the protective equipment or below an equivalent layer of material is necessary. Otherwise, appropriate correction factors to take the shielding into account should be applied.</td><td colspan="2">If used for the trunk (e.g. a lead apron)
↓
Monitoring below the shielding underestimates the doses to the lens of the eyes as the eye is not covered by the trunk shielding.
↓
Separate monitoring near the eyes is necessary.</td></tr>
</table>

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*Corresponding author. Email: kowatari.munehiko@jaea.go.jp doesn't care about which personal dose equivalent unit is to be used for eye lens monitoring and quantitative criterion on the homogeneity of exposure to workers.

The study presents a framework of decision-making process for additional monitoring of eye lens dose for radiation workers by means of a quantitative assessment of inhomogeneity of exposure. Referred to the IAEA's proposal, the proposed framework for decision making was compared and benchmarked using the published dose record data in Japan. In order to make this brief scheme shown in **Table 1** applicable to implementation of additional monitoring, authors proposed to introduce quantitative index, i.e. homogeneity index (HI) as criterion, expressing inhomogeneity of exposure. In this work, we defined homogeneous exposure as an exposure situation where radiation worker would receive almost the same eye lens dose as dose measured on the trunk, considering that estimation of eye lens dose from dose that workers received on the trunk has been implemented in Japan. The HI was estimated using the Monte Carlo (MC) calculations by modeling actual radiation situations and compared those obtained by benchmark experiments using physical phantom. Quantitative estimation of HIs by MC calculation has advantages to apply to possible radiation exposure situations and to estimate possible exposure itself prior to actual radiation works. Prior to develop the decision-making scheme, investigation on how IFs recommended by the IAEA affect the dose was also made by our method. In addition to evaluation of IFs, other key parameters were also assessed in the investigation.

2. Material and methods

2.1. Investigation on impact factor recommended by the IAEA

The IAEA-TECDOC-1731[5] provides the criterion of IF (A) as the photon energy of 40 keV. After the unit in personal dose equivalent to be monitored is selected, radiation field would be judged if radiation field is homogenous, using the IF (B). Through these condition branches, there is no specific criterion regarding "homogeneity of the radiation field". There is also required to be monitored for eye lens dose even under nonhomogeneous irradiation conditions in the case that dose to be received were to be estimated quite small such as less than 10 μSv y^{-1} and found to be wasteful. In addition, both energy of incident particle and exposure geometry definitely lead to nonhomogeneous exposure to workers. This also implies that both IFs have to be taken into account simultaneously. From this viewpoint, the developed HI might provide a quantitative criterion how much non-homogeneously workers are exposed with radiation protection officers, including effects of incident particle and exposure geometry in nonhomogeneous exposure situations.

2.2. A quantitative index for inhomogeneity of exposure, homogeneity index (HI)

This work introduces a quantitative index, HI which expresses how much radiation workers are exposed non-homogeneously for their radiation work. HIs were defined as the ratio of the personal dose equivalent for the eye lens monitoring to that for the whole-body monitoring and shown in the following equations;

$$\mathrm{HI}^{\mathrm{eye}}_{\gamma\text{-ray}} = \frac{H_{\mathrm{p}}(3)_{\mathrm{head}}}{H_{\mathrm{p}}(10)_{\mathrm{trunk}}} \tag{1}$$

$$\mathrm{HI}^{\mathrm{eye}}_{\beta\text{-ray}} = \frac{H_{\mathrm{p}}(3)_{\mathrm{head}}}{H_{\mathrm{p}}(3)_{\mathrm{trunk}}} \tag{2}$$

In our project, a set of HIs obtained by MC calculation using the PHITS [6] code introduced with a mathematical phantom has been calculated for some typical exposure situations. Personal dose equivalents, $H_p(d)$, were directly calculated in terms of scoring the absorbed dose inside the defined region using the mathematical phantom shown in the Figure 1, according to the definition provided by ICRP 74 [7]. The scoring volumes for the evaluation of $H_p(3)_{head}$ and $H_p(d)_{trunk}$ were located at 3 mm depth below the surface at the forehead (1.0 cm(L)×3.69 cm(W)×0.01 cm(D)) close to the eyes and at d mm depth below the left side of the chest (1.0 cm(L)×6.18 cm(W)×0.01 cm(D) for d =3 and 10 mm, 1.0 cm(L)×6.18 cm(W)×5 μm(D) for d =0.07 mm), respectively. HIs were then evaluated by dividing absorbed dose $H_p(3)_{head}$ by $H_p(d)_{trunk}$. In the article, $H_p(10)$ and $H_p(3)$ were chosen for estimating trunk dose and $H_p(3)$ was selected for eye lens dose estimation.

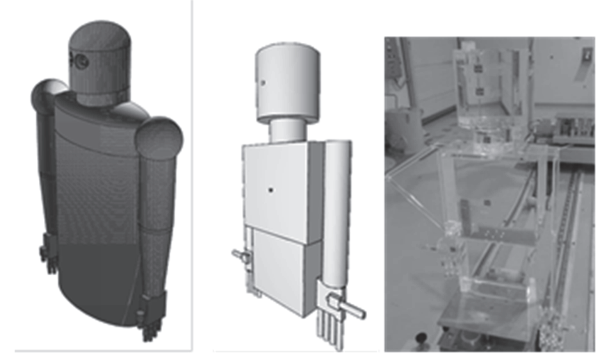

Figure 1. Schematic view of the mathematical phantom (left) used for the calculations of the HIs and the physical phantom (center: the modelling for MC calculations, right: the picture of the phantom) for the benchmark.

Verification of calculated HIs was conducted by the benchmark measurements using a simplified physical phantom shown in **Figure 1**. Measurements of dose equivalent received at the head and trunk of the simplified physical phantom were carried out at the Facility of Radiation Standards (FRS) in Japan Atomic Energy Agency (JAEA) [8]. The simplified physical phantom consists of four PMMA-made water tanks and PMMA made hands. The hands can be positioned freely the head angle is adjustable. Optically-stimulated luminescence dosimeters (OSLD) (nanoDot™ manufactured by Landauer. Inc.) were employed to measure the dose at specified positions on the phantom. Measured HIs in the AP irradiation condition in ^{60}Co γ-ray and ^{90}Sr-^{90}Y β-ray were in good agreement with those calculated within 3%. Detail on verification was already reported in the reference [9] and found to be applicable to actual radiation workplaces [10].

3. Results and discussion

3.1. Assessment of the inhomogeneity of exposure to workers

The quantitative assessment of inhomogeneity of exposure to workers was made by the MC calculations. This was focused on whether or not the HI would properly express the homogeneity of exposure to radiation workers. The IF (A) and (B) provided in IAEA-TECDOC-1731 [5] were also assessed by calculating the HI in some typical exposure situations, i.e. (a) ISO irradiation condition that reproduces homogeneous exposure situation and (b) inhomogeneous exposure situation due to point source.

The MC calculations indicated that HIs ranged between 0.8 and 1.4 with energies from 0.06 to 6.0 MeV of γ-ray under ISO irradiation condition. For β-ray irradiation, HIs were estimated to be between 1.04 and 1.07 under the same ISO irradiation condition as γ-ray, if the whole-body dose to β-ray was evaluated in terms of $H_p(3)$. This revealed that radiation workers might be non-homogeneously exposed even in the homogeneous exposure situation due to γ-ray. Results imply that dose which workers receive might excess annual dose limit unintentionally if radiation works were to be practiced under the condition that planned dose is close to the annual dose limit.

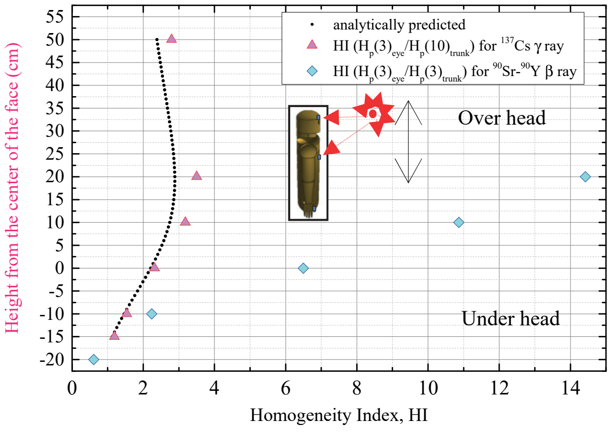

Figure 2. Comparison of HIs for γ- and β-rays when the height of the point source from the center of the face of worker varies.

Figure 2 shows the comparison of HIs for γ- and β-rays when a height of point source varies from a fixed distance of 40 cm. Increasing the height means that point source is going up from the center of the face to overhead position. In the figure, analytically expected value was also superimposed. As for the γ-ray from ^{137}Cs (662 keV), HIs varied between 1.19 and 3.50 as height changes from -15 cm to 50 cm. The results clearly showed that the HIs would be predicted by analytical calculations using the inverse square law. However, HIs increased drastically up to 14 for the case of ^{90}Sr-^{90}Y β-rays.

Figure 3 shows the comparison of HIs for γ- and β-rays as a function of the distance from worker to the point source. In this case, a distance of point source varies, fixing the same height of the eye of worker. HIs decreased as the distance between worker and the point source increased. Obtained HIs for γ-ray from ^{137}Cs could vary almost according to the inverse square law. On the other hand, HIs was evaluated to be more than 16 at the distance of 30 cm for ^{90}Sr-^{90}Y β-ray irradiation.

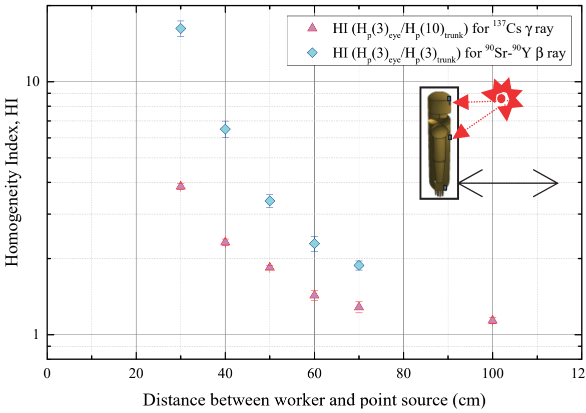

Figure 3. Comparison of HIs for γ- and β-rays as a function of the distance from worker to the point source.

A series of MC calculations and benchmark experiments also showed our method could reproduce HI^{eye}s within around 15% even in actual radiation workplaces where radiation worker often might encounter in nuclear sector [10]. Measured and calculated results of HI^{eye}s didn't exceed 4.0 even in radiation workplaces where radiation workers are exposed due to ^{15}O (emitting β^+ and annihilation photons) uniformly existing inside the accelerator room [10]. HI was also found to give reasonable and quantitative assessment of inhomogeneity of exposure to the lens of the eyes to radiation workers without any prejudice.

3.2. Discussion on proposed decision making process

A framework of decision-making for additional monitoring of eye lens dose for radiation workers was proposed in the **Figure 4**. It should be noted that the proposed decision making scheme is focused on conservativeness and is updatable, especially for values of planed dose and HI^{eye} used for criteria. As shown in the previous subsection, HI^{eye} could express inhomogeneous exposure situation quantitatively, considering both incident particle and its energy and geometry of exposure situations. Calculated results also imply that HIs would be applicable to a parameter for decision making process. In the proposed methodology, decision making for additional monitoring of the lens of the eye starts from whether or not planned exposure exceeds 0.1 mSv for a month or once per unit radiation work. The 0.1 mSv comes from one-fifth of 0.5 mSv, which corresponds to about three-tens of 1.66 mSv per single month. After checked the planned exposure, the methodology enables reasonable decision making for the eye lens dose by introduced the HI as condition branches. In the proposed case, a safety factor was set as more than 5, so as not to exceed dose limit unintentionally. The benchmark was attempted by using the published data of annual effective dose of radiation workers in Japan [11]. In the benchmark, workers whose effective dose exceeds 5 mSv per single year (=5 mSv /12 months = 0.416… mSv month^{-1} ~0.5 mSv month^{-1}) were categorized as a subject for additional monitoring of eye lens dose. Around 0.7% of radiation workers must wear additional dosimeter for eye lens dose monitoring at the most, even if all workers were to exceed the criteria using the HIs. The benchmark also implies that fewer personnel would be subject to be monitored additionally for eye lens dose taken into consideration of proper use of protection equipment in workplace.

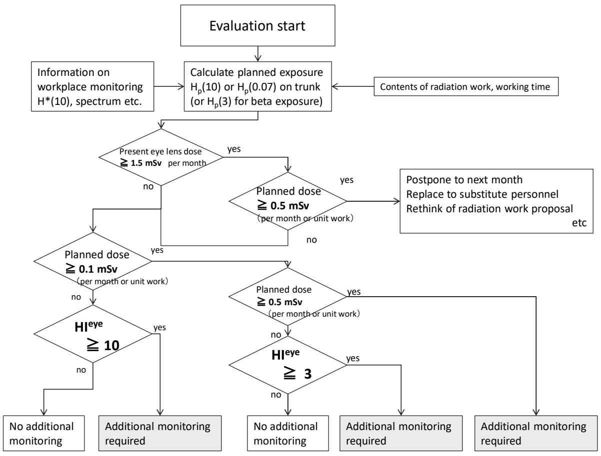

Figure 4. Proposed decision making scheme of additional monitoring of eye lens dose of radiation workers.

4. Conclusion

The article presented consistent decision-making process for additional monitoring for eye lens dose of radiation workers to make ready in advance for the introduction of the revised annual equivalent dose limit of the lens of the eye. The parameter so-called homogeneity index (HI) which expresses how radiation worker will be exposed unevenly was introduced for the condition branch in the proposed decision-making process. The HI was estimated for homogenous and inhomogeneous exposure situations due to γ- and β-rays, by MC calculations. MC calculations showed HI^{eye}s could be reproduced within around 15% in actual radiation workplaces and HI^{eye}s would not exceed 10 under exposure conditions due to γ-ray, such as exposure with energy ranging between 0.06 and 1.0 MeV from surface and/or volume sources.

The proposal of decision making process and its benchmark using published data of annual effective dose of radiation workers in Japan clarified the followings;

1) Developed method to calculate the HI was proved to be powerful tool to express inhomogeneity of exposure and to integrate the effect from affecting factors for exposure to the lens of the eye of workers.

2) Planned exposure in certain period was revealed to be the key parameter rather than other parameters such as type of radiation and its energy and angle and geometry.

3) The benchmark using the published data of annual exposure of radiation workers in Japan showed that only 0.7% of radiation workers must wear additional dosimeter for eye lens dose monitoring at the most.

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