DOI: 10.15669/pnst.4.788

Progress in Nuclear Science and Technology
Volume 4 (2014) pp. 788-792

ARTICLE

Calculation of equivalent dose for the lens of the eye in a positron field using EGS5

Sumi Yokoyama[a*] and Katsunori Aoki[ab]

[a]*Fujita Health University of Health Science, 1-98 Dengakugakubo Kutsukake-cho Toyoake-shi, Aichi-ken 470-1192, Japan,*
[b]*Japan Atomic Energy Agency, 4-33 Muramatsu, Tokai-mura, Naka-gun, Ibaraki-ken 319-1194, Japan*

The equivalent dose rate per positron fluence for the human eye lens is calculated using a Monte Carlo simulation code, EGS5, with two mathematical models (a computational head voxel phantom and a simple eye model). The eye lens doses for medical staff and carers as received from a radiopharmaceutical such as ^{18}F-FDG, which is used in PET examinations, when spilled on the floor, and from positrons passing through a thin injection tube are calculated using a simple eye model. At energies less than 1 MeV, the equivalent dose for the eye lens per electron and positron fluence as calculated using the simple eye model was a maximum of three orders of magnitude lower than that for the head voxel phantom. These values for the simple eye model were equal to the calculation results obtained using the eye lens model in ICRP Publication 116 and those reported in past studies. The eye lens dose rates from the point and tube sources of ^{18}F-FDG as calculated using our simple eye model are about 0.57 and 0.37 μSv min^{-1} MBq^{-1} at 5 cm, respectively. The doses at 10 cm were one-third to half of those at 5 cm.

Keywords: ***eye lens; dose evaluation; positron; head voxel phantom; mathematical eye model; medical staff***

1. Introduction

On the basis of recent epidemiological studies on cataracts of the eye lens, the International Commission on Radiological Protection (ICRP) has recommended an equivalent dose limit of 20 mSv in a year for the lens of the eye, averaged over defined periods of 5 years, with no single year exceeding 50 mSv for occupational exposure in a planned exposure situation [1].

The ICRP also issued Publication 110 and Publication 116 related to conversion coefficients, which is presented by a dose quantity to fluence or air kerma and calculated using a realistic human body computational phantom in 2010 and 2012, respectively [2,3]. However, the voxel phantom is not appropriate for a detailed calculation of doses for small organs, such as the eye lens. The voxel size is too large for the calculation, as mentioned in ICRP Publication 116.

Geometrical eye models represented by some spheres have been developed by Behrens et al. [4,5] to calculate the dose for the eye lens. In ICRP Publication 116, dose conversion coefficients for electrons calculated using the voxel phantom and the eye lens model developed by Behrens et. al, are compared [3].

In Japan, the workers handling radionuclides are not required to measure a 3-mm dose equivalent, Hp(3), which is equal to the dose for the eye lens for external exposure in a electron and positron field, although the dose limit for the eye lens is based on ICRP Publication 60[6]. This is because Hp(3) is complemented by $H_p(10)$ and $H_p(0.07)$. However, the present dose limit for the eye lens and the method of dose assessment may be changed in the future according to the recommendation of the ICRP.

In positron emission tomography (PET) facilities, the medical staff work with ^{18}F-FDG and are in proximity to injection tubes administering ^{18}F-FDG and other radiopharmaceuticals to patients. In an earlier study by Minami et al., the dose for medical staff working in a PET facility was measured [7]. Furthermore, by measuring and calculating the dose conversion coefficient for positron emitters using EGS5, which is a Monte Carlo simulation code to calculate transport of electron and photon particles with energy above a few keV to hundred GeV in arbitrary geometry[8], Kato et al. found that the personal skin doses of the staff working with ^{18}F are derived from positrons emitted from the injection tube [9]. These results suggest that the eye dose for the medical staff in these facilities may also increase by careless handling of the source of positron emitters in the injection tube.

This study aims to evaluate the radiation dose from a positron emitter such as ^{18}F for the eye lens of medical staff in PET facilities. The equivalent dose rate per

*Corresponding author. Email: sumi0704@fujita-hu.ac.jp

electron and positron fluence for the eye lens is calculated using EGS5, with two mathematical models (a computational head voxel phantom and a simple eye model). The calculated dose rate per positron fluence for the head voxel phantom and simple eye model is compared with the values given in ICRP Publications 74 and 116[3,10].

2. Calculation methods and conditions

2.1. Development of code for computational head voxel phantom

In the calculation of the eye lens dose for a head voxel phantom, the EGS5 user code developed to estimate the patient dose received during a CT examination by Morishita et al.[11] and a head part of the adult male voxel phantom provided by ICRP Publication 110 (head voxel phantom) as shown in **Figure 1**, were used. The head voxel phantom has a slice thickness (voxel height) of 8.0 mm and in-plane resolution of 2.137 mm. The weight and composition materials of the organs and tissues in the ICRP Publication 110 are used as the input data for our calculation. The volume and weight of the organs and tissues of our head voxel phantom are given in **Table 1**. Figure 1 shows the size of the head voxel phantom, irradiation source area, and irradiation direction. The electron and positron beam is irradiated toward the front of the face of the head voxel phantom in an aligned and expanded radiation field.

2.2. Development of simple eye model

A simple eye model was developed to calculate the reasonable eye lens dose from electrons and positrons. The calculated eye lens dose for head voxel phantom will be higher than real one because the position of the eye lens of the voxel phantom is different from a real eye lens position. The voxel size is too large and a voxel of the eye lens exist at a surface of eye bulb as shown in Figure 1.

Figure 2 shows our simple eye model. The calculations were performed with the EGS5 user code, UCEYEDOSE. This eye model, which is similar to the model developed by Behrens et al., is expressed by a combination of some spheres. The size and geometry of the eye bulb and lens are as large as those of the model of Behrens et al. However, the high-sensitivity region of the lens is 0.047-cm-thick uniform layer for simplicity in our model. Furthermore only an eye bulb and lens are included, although they are surrounded by the skull and soft tissues such as brain and skin to simplify the model.

The irradiation direction of the broad parallel electron or positron beam emitted from the source area is shown in **Figure 3**. The source area of 18.4 cm^2 (inside of a circle of 2.42cm in diameter) is identical in size to the cross section of the eye lens. The dose is calculated for antero-posterior (AP) irradiation.

The developed UCEYEDOSE code is checked by comparing the results with the absorbed dose per fluence for a single energy electron from 0.7 to 10 MeV at a depth of 3 cm as given in ICRP Publication 74, and with positrons calculated using the ICRU slab phantom by Kato et al.[9,10,12]. In a validation of calculation, the simple eye model in the UCEYEDOSE code was replaced with the ICRU slab phantom. These calculation results were in good agreement with the data for the electron given in ICRP Publication 74 and the data for the positron as obtained by Kato et al.

Table 1. Volume and weight of organs and tissues of the head voxel phantom.

Organ	Male		
	Volume [cm^3]	Mass [g]	Reference mass [g]
Blood	973.7	1032.1	5600
Brain	1381.0	1450.0	1450
Eyes	14.3	15.0	15
Eye lenses	0.4	0.4	0.4
Lymphatic tissue	134.0	138.0	730
Muscle tissue	27619.0	29000.0	29000
Esophagus	38.8	40.0	40
Residual tissue	21535.2	20458.4	18200
Salivary glands	82.5	85.0	85
Skin	3420.2	3728.0	3300
Cortical bone	2291.7	4400.0	4400
Cartilage	1000.0	1100.0	1100
Teeth	18.2	50.0	50
Thyroid	19.2	20.0	20
Tongue	69.5	73.0	73
Tonsils	2.9	3.0	3

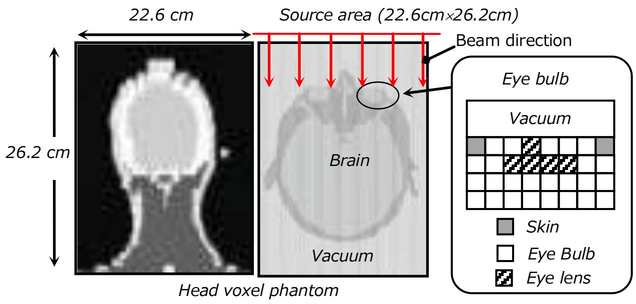

Figure 1. Height and width of head voxel phantom, electron source area, and irradiation direction (AP irradiation in an aligned and expanded radiation field) in our calculation.

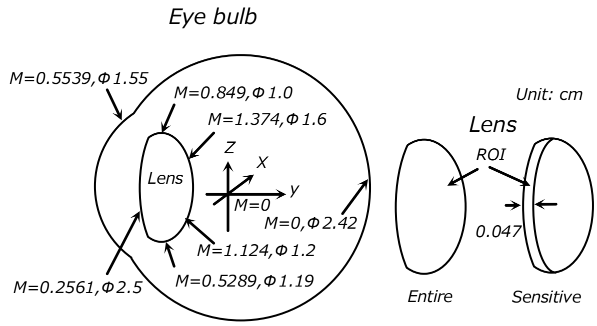

Figure 2. Size of the simple eye model and entire and sensitive regions of interest (ROI) of the lens. M is the value along the y axis at the center of the coordinate. Φ is the diameter.

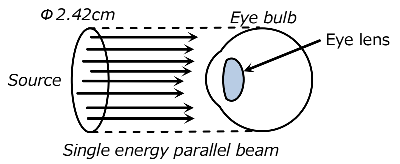

Figure 3. Geometric condition of broad parallel electron, positron or proton beam irradiation direction, source area to calculate the eye lens dose.

2.3. Calculation method for eye lens dose from ^{18}F point and tube sources using the simple eye model

In PET facilities, medical staff may be exposed to a ^{18}F point source such as ^{18}F-FDG that has been spilled on the floor or to a ^{18}F area source such as an injection tube while administering ^{18}F-FDG to patients.

To estimate the eye lens dose from these sources, the calculation system is constructed as shown in **Figure 4**. The radioactivity of ^{18}F point and tube sources is 1 MBq. The distances from the eye model to the sources are 5, 10, 20, and 30 cm. The tube, which is composed of polybutadiene, has an outer diameter of 0.21 cm and an inner diameter of 0.11 cm, and is 30 cm long. The center of the sources is set at the center of the eye lens.

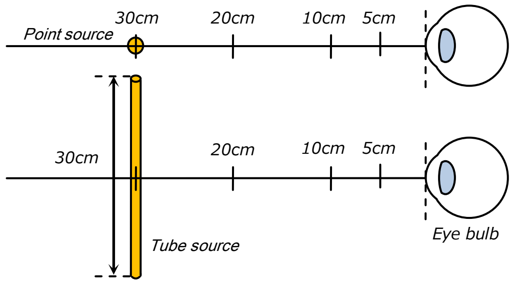

Figure 4. Side view of dose calculation geometry for the ^{18}F point and tube sources.

3. Results and discussion

3.1. Eye lens dose for the electron calculated using the head voxel phantom

Figure 5 shows the equivalent dose of electrons per fluence for the eye lens of the head voxel phantom as calculated by EGS5, that given in ICRP Publication 74, and the dose calculated using the stylized eye lens model given in ICRP Publication 116. Our calculated dose by the head voxel phantom is larger than the dose values reported in ICRP Publications 74 and 116. This tendency is similar to the dose calculated by the voxel phantom as reported in ICRP Publication 116.

3.2. Eye lens dose for an electron calculated using the simple eye model

The eye lens doses for electrons per fluence calculated using our simple eye model (high-sensitivity and entire regions), Behrens et al.'s model (high-sensitivity and entire regions), and the model of ICRP Publication 116 (entire region) are shown in **Figure 6**. In the energy range of 0.07–1 MeV, the difference in the dose data of our study, Behrens et al.'s studies, and ICRP Publication 116 is within 5%. In the energy range of 1–10 MeV, our dose values are lower than those in Behrens et al.'s studies and ICRP Publication 116. However, the maximum difference between our dose data for the entire eye lens and that of ICRP Publication 116 is about 20%.

3.3. Estimation of eye lens dose per positron fluence

Figure 7 shows the eye lens dose per positron fluence calculated using our head voxel phantom, our simple eye model (high-sensitivity and entire regions), ICRU slab phantom, and ICRP Publication 116. Our calculation results for the entire eye lens and high-sensitivity region of the eye lens at 0.1–1 MeV are lower than those calculations using the ICRU slab phantom, our head voxel phantom, and the ICRP voxel phantom.

Our calculated dose results using the simple eye model are the same as the data obtained using the voxel phantom in ICRP Publication 116 at 1–2 MeV, and are lower than the other dose data at energies greater than 2 MeV.

3.4. Estimation of eye lens dose from ^{18}F sources

The calculated eye lens doses per minute at distances of 5, 10, 20, and 30 cm from 1 MBq of ^{18}F point and tube sources are shown in **Figure 8**. The calculation is performed using our simple eye model. The eye lens doses from the point source without a cover and the tube source is twice that of the tube source at 5 cm. The positron from the source would contribute to the eye lens dose directly. The dose for the point source is equal to that from the tube source at 10 cm. The doses at 10 cm from the point and tube sources are one-third and half of those at 5cm, respectively. This is because most positrons are annihilated before reaching the eye lens and only annihilated photons contribute to the dose for the eye, as is clear from the earlier study by Katoh et al. [9].

During a PET examination, 185 MBq of ^{18}F-FDG is usually administered to an adult man weighing 70 kg. If this amount of ^{18}F-FDG is trapped in the injection tube, the equivalent dose for the eye of the medical staff would be about 70 μSv/min 5 cm away from the tube.

4. Conclusion

A lower dose limit for the eye lens was recommended by ICRP. Thus, it is important to estimate the dose for the eye lens because the measurement of the 3-mm dose equivalent, which equals the eye lens dose, is not mandatory in Japan. The eye lens dose per electron or positron fluence was calculated using a head voxel phantom and a simple eye model by the EGS5 user code.

Furthermore, the eye lens dose for positrons and annihilation photons emitted from ^{18}F point and tube sources was calculated using the simple eye model to estimate the dose resulting from actual exposure of medical staff in PET facilities.

The eye lens dose per monoenergetic electron and positron fluencies were compared with the data reported in ICRP Publications 74 and 116 for AP irradiation. The eye lens dose per electron fluence calculated by our model is in close agreement with the data of the stylized model in ICRP Publication 116. The eye lens dose per positron fluence calculated by our simple eye model is substantially lower than the data obtained from the ICRP voxel phantom below 1 MeV. Thus, the eye lens dose from a positron should also be estimated using a mathematical eye model.

The eye lens dose from 1 MBq of ^{18}F-FDG point and that in the injection tube sources was calculated by our simple eye model. As this result, The eye lens doses from the point source without a cover and the tube source are 0.57 and 0.37μ Sv/min at 5 cm, respectively. The dose of the eye lens for the radiological technologist and nurse in close proximity to the ^{18}F-FDG tube may be high when they prepare, check, or set it for the patients as routine work. Even though the exposure dose is low, the eye lens dose can be reduced by avoiding being unnecessarily close to the tube.

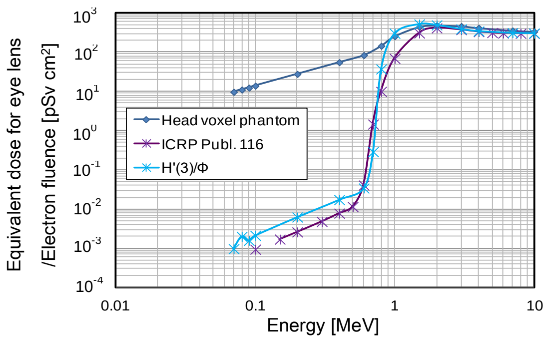

Figure 5. Equivalent dose per electron fluence for the eye lens considered in our study and corresponding doses given in ICRP Publications 74 and 116.

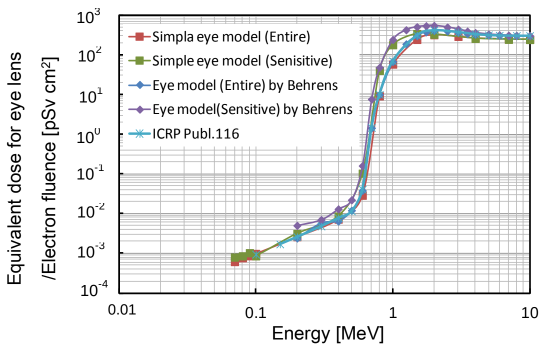

Figure 6. Equivalent dose per electron fluence for the eye lens considered in our study, Behrens et al.'s studies, and ICRP Publication 116.

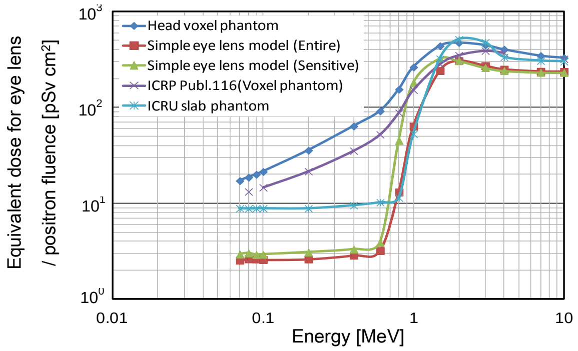

Figure 7. Equivalent dose per positron fluence for the eye lens in the present study.

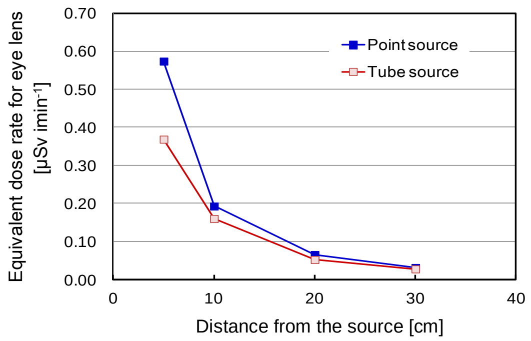

Figure 8. Equivalent dose for the eye lens from ^{18}F point and tube sources.

References

[1] ICRP, *Statement on Tissue Reactions*, ICRP ref 4825-3093-1464 (2011).

[2] ICRP, *Adult Reference Computational Phantoms, ICRP Publication 110*, Ann. ICRP, 39 (2009).

[3] ICRP, *Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposure, ICRP Publication 116*, Ann. ICRP, 40 (2012).

[4] R. Behrens, G. Dietze and M. Zankl, Dose conversion coefficients for electron exposure of the human eye lens, *Phys. Med. Biol.* 54 (2009), pp. 4069-4087.

[5] R. Behrens, G. Dietze and M. Zankl, Corrigendum, Dose conversion coefficients for electron exposure of the human eye lens, *Phys. Med. Bio.l* 55 (2010), pp. 3937-3945.

[6] ICRP, *1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60*, Ann. ICRP, 21 (1-3), (1991).

[7] K. Minami, K. Ejiri, H. Toyama, Y. Saito, K. Nishikawa, S. Sato, K. Kawabata, A. Turuta and K. Katada, Occupational radiation exposure from ^{18}F-FDG in a PET clinic, *Japanese Association for Cancer Detection and Diagnosis* 14 (2007), pp.177-181.

[8] H. Hirayama, Y. Namito, A. Bielajew, S.

Wilderman and W. Nelson, *The EGS 5 code system*, SLAC-R-730 and KEK Report 2005-8 (2005).

[9] T. Katoh, K. Aoki, S. Yokoyama, K. Ejiri, K. Minami, H. Yashima, T. Nakamura and H. Hirayama, *Calculation of personal dose equivalent for positron-emitting radionuclides using Monte Carlo code EGS 5*, *Radiat. Prot. Dosim.* 146 (1-3) (2011), pp. 202-205.

[10] ICRP, *Conversion Coefficients for Use in Radiological Protection against External Radiation, ICRP Publication 74*, Ann. ICRP, 26, (1996).

[11] Y. Morishita and S. Koyama, Simulation of X-ray CT using Monte Carlo method, *Proceedings of the Joint International Conference on Supercomputing in Nuclear Applications and Monte Carlo 2010*, (2010). E6 10304. [USB]

[12] H. Hirayama, Calculation of absorbed dose at 0.07, 3.0 and 10.0 mm depths in a slab phantom for monoenergetic electrons, *Radiat. Prot. Dosim.* 51 (1994), pp. 107-124.