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Original Article

Development of an Accommodation-Dependent Eye Model and Studying the Effects of Accommodation on Electron and Proton Dose Conversion Coefficients

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Abstract

Introduction

International Commission on Radiological Protection (ICRP) has provided a comprehensive discussion on threshold dose for radiation-induced cataract in ICRP publication 116. Accordingly, various parts of the eye lens have different radio-sensitivities. Recently, some studies have been performed to develop a realistic eye model with the aim of providing accurate estimation of fluence-to-dose conversion coefficients for different parts of the eye. However, the effect of accommodation, which changes the lens shape and pupil size, on dose conversion coefficients has not been considered yet. In this study, we purport to develop an accommodation-dependent eye model and to study the effects of accommodation on the electron and proton fluence-to-dose conversion coefficients.

Materials and Methods

Herein, a modified eye model was developed by considering the effects of accommodation on the lens shape and pupil size. In addition, MCNPX 2.6 Monte Carlo transport code was used to calculate the effects of eye lens accommodation on electron and proton fluence-to-dose conversion coefficients.

Results

Calculation of dose conversion coefficients demonstrated that the accommodation causes up to 40% discrepancy for fluence-to-dose conversion coefficients of electrons in the range of 600 to 800 keV, which is due to the change of eye lens shape during the accommodation of the eye.

Conclusion

Since the accommodation of the eye change the lens shape and pupil size, it has considerable effect on fluence-to-dose conversion coefficients of electrons at some ranges of incident particle energies that should be considered in simulation. However, the fluctuation of dose conversion coefficients of protons is negligible.

Keywords: Eye lens, Accommodation, Monte Carlo Method, Mathematical Model

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1. Introduction

Everyone is exposed to ionizing and non-ionizing radiations from various sources including environmental, medical, and occupational radiation exposures. Although constraints for planned exposures are conventionally expressed as an annual effective dose, it is necessary to set some equivalent dose limits for radiosensitive and superficial organs such as the eye lens. Since the interaction of radiation with the lens tissue may cause deterministic effects, the lens tissue is not a constituent tissue in calculating the effective dose [1].

The most important effect of radiation on the eye lens is visual impairment, which is called radiation-induced cataract. This type of cataract may continue to progress for 2-3 years, causing considerable visual loss [2]. The International Commission on Radiological Protection (ICRP) in its 1990 recommendation report recommended the annual dose limit of 150 mSv for the eye lens [3]. The commission continues to recommend an annual equivalent dose limit for the eye lens of 150 mSv for occupationally exposed workers and 15 mSv for the public in subsequent publications [4,5]. Recently, for occupational exposures in planned exposure situations, the commission recommended an equivalent dose limit to the eye lens of 20 mSv per year, averaged over defined periods of five years, with no single year exceeding 50 mSv [6].

Since the received dose by the lens cannot be measured directly, it is generally determined by Monte Carlo calculation using computational eye models [7]. The survey of the radiobiological literature shows that the lens is the most radiosensitive structure in the eye. Moreover, it is recognized that the epithelial cells in the equatorial region of the lens are involved in radiation cataract induction [8-10]. Therefore, calculating the accurate dose received by different parts of the eye is highly essential.

Based on the recent epidemiological and anatomical studies, Behrens et al. designed a real eye model, in which many anatomical details were considered [7]. In their model, some substructures of the eye including aqueous humor, cornea, vitreous humor, and lens were simulated. The frontal layer of the lens positioned near the equator was determined as a significant volume in terms of radio-sensitivity and was known as sensitive volume. The main equations applied to construct Behrens' model are based on the mean ocular dimensions for the unaccommodated eye taken from Charles and Brown, thus, having simple spherical shapes [7,8].

Recently, different research groups calculated fluence-to-dose conversion coefficients of the eye lens for gamma, neutron, and charged particles using Behrens model and compared the results with those obtained by ICRP reference phantoms [7,11-13]. It is worth mentioning that all of the reported conversion coefficients are related to the relaxed state, while changes made to the eye lens during accommodation may affect these values. To study the effect of accommodation on dose conversion coefficients, it is necessary to apply changes in shape of the crystalline eye lens during accommodation.

Since the mid-nineteenth century, different models were reported for delineating the accommodation process [14-16]. These models were designed according to the experimental data and Scheimpflug images of a sample population. Accordingly, during accommodation, the lens becomes thicker and the depth of the anterior chamber decreases. In addition, the radius of the anterior and posterior lens surface changes such that the lens becomes more convex [17].

The changes in the radius and depth of the surfaces are very small (i.e., in order of some millimeters); however, these fluctuations should be taken into account when calculations for weakly penetrating radiation such as low-energy electrons or protons are performed. The aim of this study was to develop an accommodation-dependent eye model for dosimetry calculation and to study the effects of accommodation on the electron and proton fluence-to-dose conversion coefficients.

2. Materials and Methods

2.1.Developing Accommodation-Dependent Eye Model

Different models have been presented for describing the accommodation so far [14-16]. Developing the accommodation-dependent eye model, the eye lens of the Behrens model was reconstructed using four centered aspheric surfaces based on a simple and well-defined model of the accommodation introduced by Navarro et al. [14]. Accordingly, the anterior and posterior surfaces of the eye lens model were represented by the formula:

$$(1+Q)(x-x_0)^2+y^2+z^2-2R(x-x_0)=0 \qquad (1)$$

Where R is the radius of curvature, Q is the asphericity parameter, and x, y, z are the spatial coordinates, while x-axis is the optical axis. The values of Q, R, and x_0 were selected so that sufficient compatibility with Behrens model was provided.

Figure 1 exhibits the eye lens implemented by Behrens in comparison with the reconstructed eye lens based on Navarro model. Moreover, elemental compositions and densities of different substances used in the simulation are presented in Table 1.

According to a report by Navarro et al., the radius curvature and asphericity parameter of the anterior and posterior surfaces of the lens are varied during accommodation [14]. The functional variation of the lens parameters are shown in Table 2. In this table, parameters indexed by ‘0’ are initial values related to the unaccommodated state. Different values were reported for the initial values in different literature sources [14,17-19]. In this paper, initial values were chosen in such a way that the maximum range of radius changes is considered during accommodation.

The thicknesses of the lens and aqueous humor were adjusted by changing the x-coordinate of the curvature center (x_0). It is worth mentioning that the lens thickness in unaccommodated state was smaller than that of Behrens model. This fact caused the lens volume in accommodation-dependent eye model to be about 7% smaller than the lens volume in Behrens model. Since the lens volume is constant in different accommodation levels, the opening angle of the cone, which constructs the sensitive region, was changed in such a way that the volume of sensitive region remains constant. Figure 2 exhibits a schematic view of the accommodation-dependent eye lens in various accommodation states. Different parameters of the eye lens in diverse accommodation levels are shown in this figure.

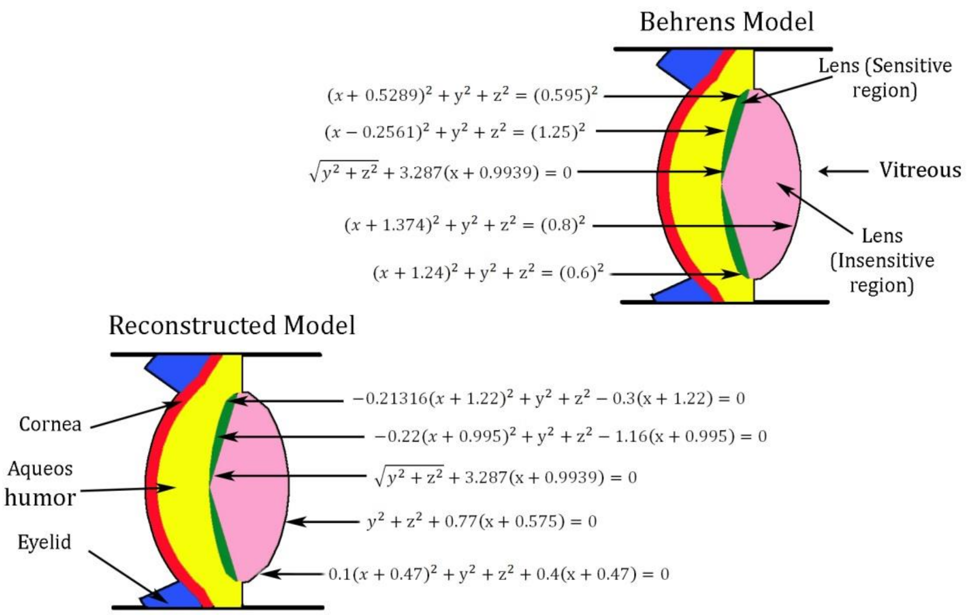

Figure 1.The eye lens implemented by Behrens in comparison with the reconstructed eye lens based on Navarro model

Table 1. Density and composition of substances used in the calculations

Element (%) \ Density	Lid	Lens (Sensitive/Insensitive)	Cornea	Aqueous Humor	Vitreous Humor
	1.09 (g/cm^3)	1.06 (g/cm^3)	1.076 (g/cm^3)	1.003 (g/cm^3)	1.0089 (g/cm^3)
H	10.0	9.6	10.16	11.2	11.2
C	20.4	19.5	12.62	-	-
N	4.2	5.7	3.69	-	-
O	64.5	64.6	73.14	88.8	88.8
Na	0.2	0.1	0.065	-	-
P	0.1	0.1	0.195	-	-
S	0.2	0.3	0.065	-	-
Cl	0.3	0.1	-	-	-
K	0.1	-	-	-	-

Table 2. Accommodation dependence of the lens parameter on accommodation A (in diopters)

Lens Parameter	Accommodation Dependence	
Anterior lens radius	$R^a = R_0^a - 1.75 \times \ln(A+1)$	$R_0^a = 1.16$ cm
Posterior lens radius	$R^p = R_0^p + 0.2294 \times \ln(A+1)$	$R_0^p = -0.77$ cm
Aqueous thickness	$D^a = D_0^a - 0.05 \times \ln(A+1)$	$D_0^a = 0.275$ cm
Lens thickness	$D^l = D_0^l + 0.1 \times \ln(A+1)$	$D_0^l = 0.4$ cm
Anterior lens asphericity	$Q^a = Q_0^a - 0.34 \times \ln(A+1)$	$Q_0^a = -3.2$
Posterior lens asphericity	$Q^p = Q_0^p - 0.125 \times \ln(A+1)$	$Q_0^p = -1$

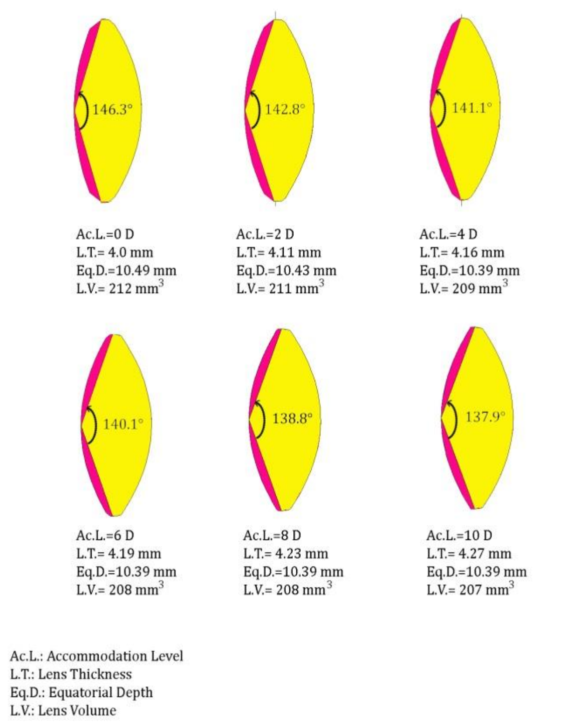

Figure 2. A schematic view of the accommodation-dependent eye lens in different accommodation states; different parameters of the eye lens in various accommodation levels

2.2. Monte Carlo Simulation

For calculation of the absorbed doses per electron and proton fluences in different parts of the eye, MCNPX Monte Carlo code, version 2.6.0, was employed [20].In order to estimate the dose conversion coefficient per fluence, the collision heating tally (+F6) with the unit of MeV/g was applied. The +F6 tally always applies to all particles in a problem and provides absorbed dose in a cell without considering Kerma approximation [20]. To compute dose conversion coefficient in unit of pGy.cm^2, each tally was multiplied by 160 and source surface using FM card. As known, the types of secondary particles produced in proton interaction are energy-dependent, while in electron interaction only photon could be produced [5].

Accordingly, for calculation of electron dose conversion coefficients, electron and photon were transported; however, for estimation of proton fluence-to-dose conversion coefficients, all the secondary particles such as neutron, photon, electron, as well as light and heavy ions were tracked. All the calculations were performed for 22 mono-energetic electron sources covering a range of 0.2 to 12 MeV and 9 mono-energetic proton sources including a range of 20 to 100 MeV. For all the calculations, relative errors were below 1% except for electrons with energy of 200keV, which had uncertainties around 2%.

2.3. Calculation Method

Calculations were carried out for six accommodation levels including 0, 2, 4, 6, 8, and 10 diopters. For each exposure, fluence-to-dose conversion coefficients were computed for various parts of the eye and lens substructures in different accommodation levels. Afterwards, the mean values of conversion coefficients were assessed by arithmetic averaging over six accommodation levels. Moreover, to investigate the dispersion of dose conversion coefficients due to the accommodation process, the coefficient of variation (CV) was determined using the following equation:

$$CV\ (\%) = \frac{\sigma}{(D/\varphi)_m} \qquad (2)$$

Where $(D/\varphi)_m$ the arithmetic mean value and σ is is the standard deviation of the conversion coefficients.

3. Results

Table 3 shows the mean values and CVs of electron fluence-to-dose conversion coefficients for sensitive region, insensitive region, and total lens. As can be observed, the fluctuations of dose conversion coefficients due to accommodation are very small; accordingly, CV values are below 1% for all electron energies. Exceptions are noted for electrons with kinetic energies between 600 and 800 keV, for which CV values rise to above 20%.In the worst situation, a dispersion of about 40% is observed for the sensitive region of the lens.

The fluctuations of dose conversion coefficients for the sensitive region during accommodation are depicted in Figure 3for 700 keV electrons.

Table 3. The mean values and CVs of electron fluence to dose conversion coefficients in unit $pGy.cm^2$ for six accommodated models

Energy (MeV)	Sensitive Region		Insensitive Region		Total Lens	
	Mean	CV(%)	Mean	CV(%)	Mean	CV(%)
0.2	0.005	0.51	0.003	0.14	0.004	0.19
0.3	0.008	0.45	0.006	0.11	0.007	0.20
0.4	0.013	0.93	0.010	0.15	0.010	0.34
0.5	0.020	0.28	0.014	0.40	0.015	0.37
0.6	0.166	41.90	0.021	5.02	0.047	28.30
0.7	8.851	20.11	0.330	32.73	1.851	21.90
0.8	54.558	7.20	3.907	14.75	12.947	9.08
1	269.039	0.72	52.084	1.33	90.800	1.03
1.25	402.265	0.36	187.870	0.54	226.129	0.48
1.5	439.474	0.17	318.808	0.25	340.340	0.23
1.75	432.241	0.27	391.001	0.07	398.361	0.10
2	412.201	0.12	410.838	0.18	411.082	0.13
2.5	368.918	0.23	383.770	0.16	381.120	0.11
3	339.627	0.22	349.272	0.13	347.551	0.08
3.5	325.412	0.29	325.324	0.12	325.340	0.10
4	316.941	0.17	310.497	0.18	311.646	0.13
5	307.288	0.07	297.564	0.15	299.299	0.13
6	304.586	0.13	294.687	0.08	296.275	0.06
7	301.687	0.13	293.953	0.02	295.334	0.01
8	300.271	0.23	288.907	0.07	290.935	0.09
10	299.304	0.22	289.704	0.07	291.417	0.07
12	296.798	0.85	291.667	0.39	293.581	0.41

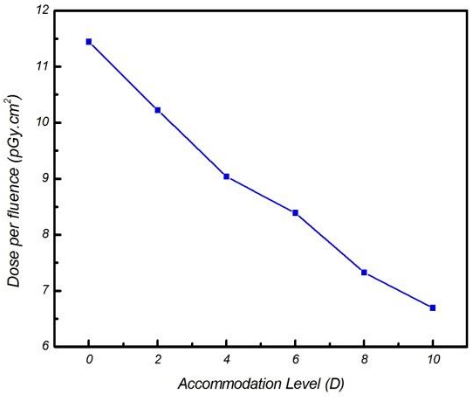

Figure 3. Fluctuations of dose conversion coefficients for the sensitive region in terms of accommodation level for 700keV electrons

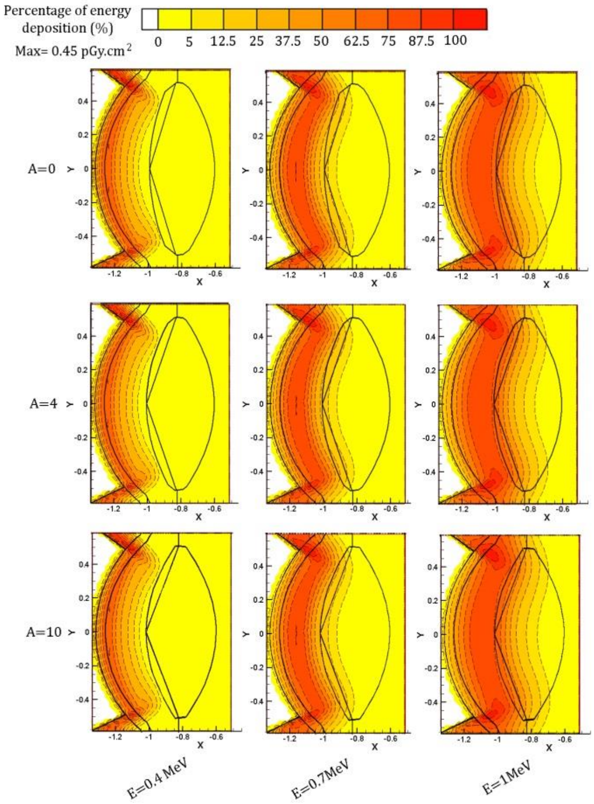

Figure 4. Cross-sectional plots of energy deposition distribution for three accommodation levels and three electron energies

It is obvious from the figure that increasing the accommodation level reduces the dose conversion coefficient for sensitive region. To investigate the reason for this behavior, cross-sectional plots of energy deposition distribution for three accommodation levels and three electron energies are provided in Figure 4. In this figure, iso-dose regions are classified in terms of percentage of the maximum value of deposited energy.

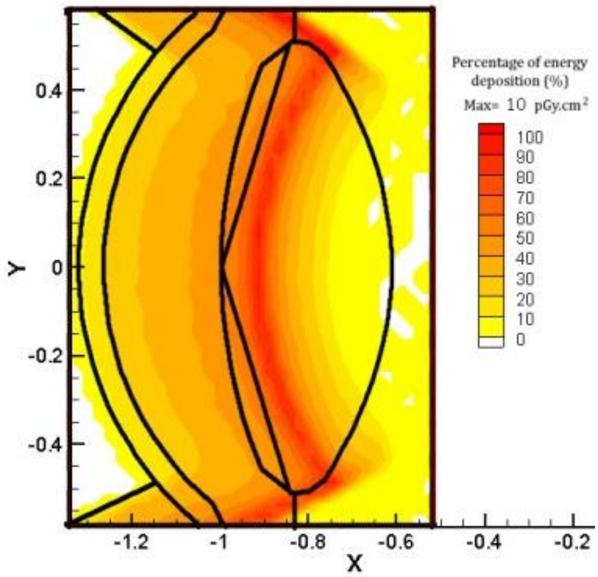

Figure 5.The energy deposition distribution for 20 MeV protons within an unaccommodated lens

The mean values and CVs of proton fluence-to-dose conversion coefficients for sensitive and insensitive regions and total lens are presented in Table 4. It can be observed that CV values are below 1%for all proton energies, and thus, accommodation process cannot affect dose conversion coefficients in different regions of the lens. Moreover, Figure 5 manifests the distribution of energy deposition in an unaccommodated eye for 20 MeV protons.

Table 4 The mean values and CVs of proton fluence to dose conversion coefficients in unit pGy.cm^2 for six accommodated models

Energy (MeV)	Sensitive Region		Insensitive Region		Total Lens	
	Mean	CV(%)	Mean	CV(%)	Mean	CV(%)
20	8281	0.43	4908	0.55	5510	0.31
30	3694	0.13	4366	0.12	4246	0.12
40	2694	0.02	2842	0.06	2816	0.05
50	2191	0.13	2235	0.04	2227	0.04
60	1786	0.07	1877	0.03	1861	0.03
70	1570	0.03	1635	0.02	1623	0.02
80	1465	0.04	1467	0.01	1467	0.02
90	1286	0.03	1303	0.02	1300	0.02
100	1203	0.08	1211	0.01	1210	0.02

4. Discussion

According to the data provided in Table 3, the variation of the fluence-to-dose conversion coefficient during accommodation for electrons in the range of 600 to 800 keV would be considerable, up to 40%, while for other energies the discrepancies are negligible. Accordingly, in the range of 600 to 800 keV, dose conversion coefficients of the eye lens, especially for the sensitive region, strongly depend on the accommodation level. It is clear from Figure 3 that at this range of energy, dose conversion coefficient decreases by increasing accommodation level. To explain the behavior of CV values for different energies, cross-sectional views of deposited energy distributions for three accommodation levels are demonstrated in Figure 4.

As mentioned before, by increasing accommodation level, the eye lens becomes more convex [16]. Consequently, when changing the lens shape causes some parts of the eye lens to move from an iso-dose region to another region, accommodation may affect dose conversion coefficients. At energies below 600 keV, the eye lens locates in a relatively uniform low-dose region. By making the lens convex, both sensitive and insensitive regions stay in a uniform low-dose region, and therefore, dose conversion coefficient does not vary significantly.

For electron energies between 600 and 800 keV, energy is liberated, such that some multiple iso-dose regions cover the lens volume. Changing the lens shape causes the central part of the lens to move to a higher iso-dose region, while the upper and lower parts are slightly pulled back. Since the upper and lower parts of the sensitive volume are thicker than the central part, by increasing the accommodation level, delivered dose to the sensitive region diminishes. There are similar trends for energies above 800 keV, but fluctuations of the received dose are minute in comparison with the delivered dose to the lens substructures.

The deposition of energy by protons as a function of travelled distance shows a characteristic maximum at the end of the range called the Bragg peak [21]; before the peak, the dose-depth graph is nearly flat. Figure 5 reveals the energy deposition distribution for 20 MeV protons within the unaccommodated lens. It is clear that for 20 MeV protons, the Bragg peak locates behind the lens, and thus, the lens lies within the flat dose plateau. By increasing proton energy, the Bragg peak moves forward, and the lens remains within plateau. This is why the CV values of proton dose conversion coefficients are lower than 1%.

Actually the data obtained by accommodation-dependent eye model might give a clue about the accuracy of dose conversion coefficients reported by ICRP for the eye lens. According to this study, changing the eye's focus from a far point to a near point during accommodation reflex may provide the uncertainty up to 40% for electron fluence-to-dose conversion coefficients in the range of 600 keV to 800 keV. However, proton fluence-to-dose conversion coefficients are approximately independent from accommodation reflex based on this investigation.

5. Conclusion

In this study, the effects of accommodation on the electron and proton fluence-to-dose conversion coefficients were studied. To this end, the eye lens of Behrens model was changed based on accommodation model introduced by Navarro et al. Afterwards, fluence-to-dose conversion coefficients for protons and electrons were computed for different accommodation levels. According to the obtained results, for electron energies between 600 and 800 keV, dose conversion coefficients are dependent on the accommodation levels, while they are independent from the lens shape for other energies. In addition, proton fluence-to-dose conversion coefficient is almost independent of the accommodation. It is worth mentioning that in addition to the accommodation, the depth of the lens may affect dose conversion coefficients. Therefore, in the next step, the effects of the lens depth on dose conversion coefficients should also be estimated.

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References

1. Bolch WE, Dietze G, Petoussi-Henss N, Zankl M. Dosimetric models of the eye and lens of the eye and their use in assessing dose coefficients for ocular exposures. Ann ICRP. 2015; 44(1 suppl): 91-111. doi:10.1177/0146645314562320.
2. Cantor LB, Rapuano CJ, Cioffi GA. Update on general medicine. Basic and clinical science course, section 1. American academy of ophthalmology;2014.
3. ICRP 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann ICRP. 1991; 21(1–3).
4. ICRP 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann ICRP. 2007; 37(2–4).
5. ICRP 2010. Conversion coefficients for radiological protection quantities for external radiation exposures. ICRP Publication 116. Ann ICRP. 2010; 40(2-5) : 1-257.
6. ICRP 2012. ICRP statement on tissue reactions/early and late effects of radiation in normal tissues and organs – threshold doses for tissue reactions in a radiation protection context. ICRP Publication 118.Ann ICRP. 2012; 41(1-2).
7. Behrens R, Dietze G, Zankl M. Dose conversion coefficients for electron exposure of the human eye lens. Phys Med Biol. 2009; 54: 4069-87. doi:10.1088/0031-9155/54/13/008.
8. Charles MW, Brown N. Dimensions of the human eye relevant to radiation protection (dosimetry). Phys Med Biol. 1975; 20: 202-18. doi:10.1088/0031-9155/20/2/002.
9. Worgul BV, Merriam Jr GR. The lens epithelium and radiation cataracts: II. Interphase death in the meridional rows?. Radiat Res. 1980; 84: 115-21.
10. Brown NP. The lens is more sensitive to radiation than we had believed. Br J Ophthalmol. 1997; 81: 257. doi:10.1136/bjo.81.4.257.
11. Behrens R, Dietze G. Dose conversion coefficients for photon exposure of the human eye lens. Phys Med Biol. 2011; 56: 415-37. doi:10.1088/0031-9155/56/2/009.
12. Manger RP, Bellamy MB, Eckerman, KF. Dose conversion coefficients for neutron exposure to the lens of the human eye. Radiat Prot Dosim. 2011; ncr202. doi:10.1093/rpd/ncr202.
13. Sakhaee M, Vejdani-Noghreiyan A, Ebrahimi-Khankook A. A comparison of simple and realistic eye models for calculation of fluence to dose conversion coefficients in a broad parallel beam incident of protons. Radiat Phys Chem. 2015; 106: 61-7. doi:10.1016/j.radphyschem.2014.07.004.
14. Navarro R, Santamaría J, Bescós J. Accommodation-dependent model of the human eye with aspherics. JOSA A. 1985; 2: 1273-80. doi:10.1364/JOSAA.2.001273.

15. Dubbelman M, Van der Heijde GL, Weeber HA, Vrensen GFJM. Changes in the internal structure of the human crystalline lens with age and accommodation. Vision Res. 2003; 43: 2363-75. doi:10.1016/S0042-6989(03)00428-0.
16. Wiemer NG, Dubbelman M, Hermans EA, Ringens PJ, Polak BC. (2008). Changes in the internal structure of the human crystalline lens with diabetes mellitus type 1 and type 2. Ophthalmology. 2008; 115: 2017-23. doi:10.1016/j.ophtha.2008.06.032.
17. Charman WN, Heron G. Fluctuations in accommodation: a review. Ophthal Physl Opt. 1988; 8: 153-64. doi:10.1111/j.1475-1313.1988.tb01031.x.
18. Brown N. The change in shape and internal form of the lens of the eye on accommodation. Exp Eye Res.1973; 15: 441-59. doi:10.1016/0014-4835(73)90136-X.
19. Dubbelman M, Van der Heijde GL, Weeber HA. Change in shape of the aging human crystalline lens with accommodation. Vision Res.2005; 45: 117-32. doi:10.1016/j.visres.2004.07.032.
20. Pelowitz, D. MCNPX User's Manual, Version 2.6.0. Los Alamos National Laboratory, Los Alamos, NM, USA. 2008.
21. DelaneyTF, Kooy HM. Proton and Charged Particle Radiotherapy. Lippincott Williams & Wilkins, Philadelphia, USA; 2008.