Development of Detailed Eye Models for Pediatric Phantoms

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1. Introduction

The annual dose limit for the eye lens was 150 mSv for occupational exposure, which was recommended by the International Commission on Radiological Protection (ICRP) in the 2007 Recommendation [1], but this dose limit has been reduced to 20 mSv with the publication of ICRP Publication 118 [2]; with this reduction, the accurate assessment of lens dose has become more important.

ICRP Publication 116 [3] provides the lens dose coefficients for external exposures, which were produced by using either the adult voxel-type reference computational phantoms described in ICRP Publication 110 [4] or by using the detailed eye model developed by Behrens et al [5]. The detailed eye model was used to calculate the dose coefficients for weakly penetrating radiations for which ICRP-110 reference phantoms do not provide reliable values due to their finite voxel resolutions. Recently, the detailed eye model has been incorporated into the new mesh-type ICRP reference computational phantoms developed within ICRP Task Group 103 [6].

Although the detailed eye model of Behrens et al [5] has been successfully used for lens dose assessment of adults, it is unacceptable for the lens dose assessment of children considering that the anatomical dimensions of pediatric eyes are significantly different from those of adult eyes [7-8]. It should be also noted that children generally have greater sensitivity to radiation [9-10]. The International Atomic Energy Agency suggested that children under five are about two to five times more sensitive to cataract induction by radiation exposures than adults [11].

In the present study, we propose a set of detailed eye models for children at different ages (i.e., newborn and 1-, 5-, 10-, and 15-year olds), considered in ICRP Publication 89 [12], which have been developed from the anatomical information of pediatric eyes in scientific literatures. The developed eye models were then implemented into a Monte Carlo particle transport code, Geant4, to calculate lens doses for electron exposures, and the calculated values were compared with those calculated with the adult eye model of Behrens et al [5].

2. Material and Methods

2.1 Construction of Eye Models

Fig. 1 shows the adult eye model of Behrens et al [5], which was developed based on the nine main anatomical parameters of an adult eye given in Charles and Brown [13]. The nine anatomical parameters are as follows: (1) the lens thickness along the optical axis (LT), (2) the equatorial diameter of the lens (ED), (3) the radius of curvature of the anterior surface of the lens (RAL), (4) the radius of curvature of the posterior surface of the lens (RPL), (5) the corneal thickness along the optical axis (CT), (6) the corneal diameter (CD), (7) the radius of curvature of the anterior surface of the cornea (RAC), (8) the anterior chamber depth along the optical axis (ACD), and (9) the radius of curvature of the anterior surface of the sclera (RAS). In the present study, these parameters for the children were determined from various scientific literatures and used to construct pediatric eye models.

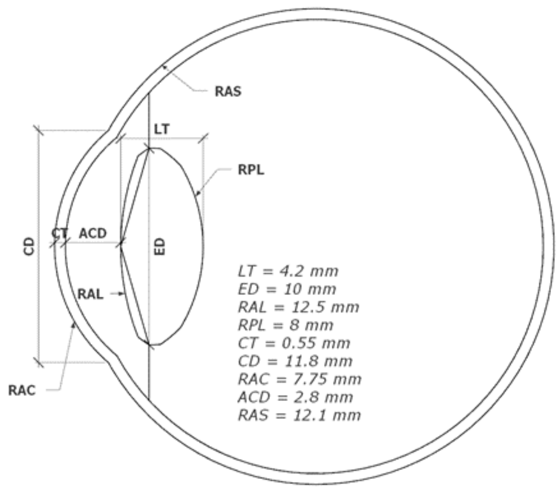


Fig. 1. Adult eye model of Behrens et al [5] along with nine anatomical parameters: LT, the lens thickness along the optical axis; ED, the equatorial diameter of the lens; RAL, the radius of curvature of the anterior surface of the lens; RPL, the radius of curvature of the posterior surface of the lens; CT, the corneal thickness along the optical axis; CD, the corneal diameter; RAC, the radius of curvature of the anterior surface of the cornea; ACD, the anterior chamber depth along the optical axis; RAS, the radius of curvature of the anterior surface of the sclera.

Table I: The determined values of the nine anatomical parameters for pediatric detailed eye models.

	LT (mm)	ED (mm)	RAL (mm)	RPL (mm)	CT (mm)	CD (mm)	RAC (mm)	ACD (mm)	RAS (mm)
Newborn	4.00	6.44	4.99	3.83	0.58	9.66	6.96	2.60	8.92
1year	3.96	7.10	5.85	4.52	0.54	11.15	7.93	3.05	9.39
5 years	3.82	7.53	6.40	4.97	0.55	11.80	7.75	3.45	10.92
10 years	3.63	7.94	7.42	5.47	0.55	11.80	7.75	3.75	11.24
15 years	3.45	8.35	8.43	5.98	0.55	11.80	7.75	3.78	11.54

Augusteyn [7] found that the LT gradually decreases from 4 mm (at birth) to a minimum of ~3.3 mm in the mid to late teens. Therefore, in the present study, the 4 mm was taken as the LT of the newborn. The LTs of the other ages (i.e., 1-, 5-, 10-, and 15-year olds) were determined by linear interpolation between the 4 mm (at birth) and the 3.3 mm (19-year old, which was assumed in the present study).

The ED, RAL, and RPL of the newborn and 1- and 5-year olds were determined by using the regression equations given in the study of Ishii et al [14]. It should be noted that these equations were derived from the data from one month to 6 years; thus, the values calculated from the equations at one month were considered for those of the newborn in the present study. The ED, RAL, and RPL for the 10- and 15-year olds were determined by linear interpolation between the values of the 5-year old and the adult (i.e., 35-year old).

Many studies [15, 16] indicated that the cornea rapidly grows until around 3 years, attaining the adult size. Therefore, the CT, CD, and RAC of the 5-, 10-, and 15-year olds were assumed to have the same values of the adult. The CTs of the newborn and 1-year old were obtained from Uva et al [17] and Hussein et al [18], respectively. The CDs of the newborn and 1-year old were obtained from Muller and Doughty [16]. The RAC of the newborn was taken from Isenberg et al [19]. The RAC of the 1-year old was calculated by linear interpolation between the 6-month value in Isenberg et al [19] and the 9-month value in Mutti et al [20].

The ACD of the newborn was obtained from ICRP Publication 23 [21]. The ACD of the 10-year old was obtained from Zadnik et al [22] which provides age-specific average values of the ACDs from 6 to 14 years. The ACD of the 15-year old was determined by uising the linear regression equation derived from the average values from 10 to 14 years, as ACD changes little in this period (~1.6%). The ACDs of the 1- and 5-year olds were calculated by linear extrapolation between the 6-year average value in Zadnik et al [22] and the 9-month average value in Mutti et al [20].

Lastly, the RASs of all the children were determined so that the entire mass of the eye exactly matches to the reference value in ICRP Publication 89 [12] for each age.

2.2 Dose Calculation with Geant4

The eye models developed in the present study were implemented into the Geant4 code (ver. 10.03) to calculate lens dose values for electron exposures. The eye models were implemented by using the G4Sphere, G4Corn, and three Boolean solids (i.e., G4UnionSolid, G4IntersectionSolid, and G4SubtractionSolid) in Geant4. Monoenergetic electron beams from 0.03 to 100 MeV were irradiated to the bare eye models in the antero-posterior (AP) direction. The physics library of the *G4EmLivermorePhysics* was used to transport electrons and secondary photons. The secondary production cut value of 1 μm was applied for all particles. The statistical errors of the calculated values were all less than 5%.

3. Results and Discussions

Table I lists the values of the nine anatomical parameters of the pediatric eyes determined in the present study. Based on the determined values, a set of detailed eye models were constructed, as shown in Fig. 3. Specific dimensions for the constructed eye models are listed in Table II.

Fig. 2 shows the ratio of pediatric lens dose to adult lens dose for electron exposure calculated with pediatric and adult eye models. It can be seen that for the energies higher than 2 MeV, the dose ratio is close to unity, meaning that the pediatric lens doses are close to the adult lens doses. On the other hands, for the lower energies (≤ 2 MeV), which is the typical energy range of beta radiations, the ratio is much less than unity, meaning

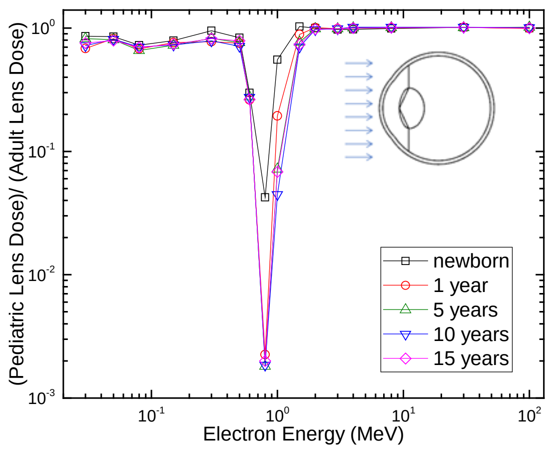


Fig. 2. The ratio of pediatric lens dose to adult lens dose when exposed to electron parallel beam in AP direction.

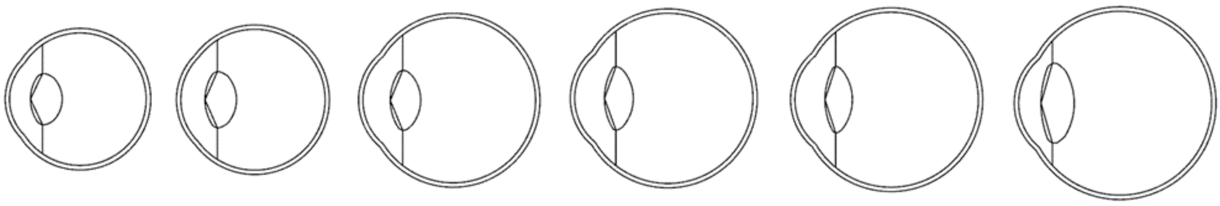
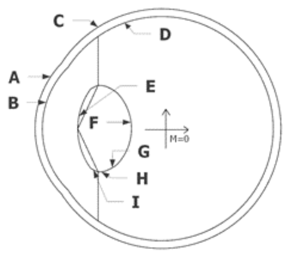


Fig. 3. Pediatric detailed eye models developed in the present study, along with adult detailed eye model developed by Behrens et al [5].

Table II: Specific dimensions of constructed pediatric detailed eye models. All dimensions are given in mm. M denotes the x-position of the centers of the spheres (M=0 denotes the center of the eyeball) and r denotes the corresponding radii.



	newborn		**1 year**		**5 years**		**10 years**		**15 years**	
	M	r	M	r	M	r	M	r	M	r
A	-2.42	6.96	-1.84	7.93	-4.07	7.75	-4.46	7.75	-4.81	7.75
B	-2.42	6.38	-1.84	7.39	-4.07	7.20	-4.46	7.20	-4.81	7.20
C	0	8.86	0	9.33	0	10.84	0	11.17	0	11.47
D	0	8.28	0	8.79	0	10.29	0	10.62	0	10.92
E	-1.21	4.99	-0.33	5.85	-1.42	6.40	-0.49	7.42	0.20	8.43
F	-6.03	3.83	-6.74	4.52	-8.97	4.97	-9.75	5.47	-10.76	5.98
G	-5.32	3.36	-5.71	3.74	-8.23	4.42	-8.28	4.47	-9.20	4.88
H	-4.83	3.22	-5.16	3.58	-6.69	3.80	-6.72	3.98	-7.44	4.22
I	-3.40	3.46	-3.41	3.78	-4.78	4.07	-5.57	4.07	-4.87	4.64

that the pediatric lens doses are much smaller than adult lens doses. For the energies lower than 0.6 MeV, the differences from the adult lens doses are ~30% on the average. For the energies between 0.6 MeV and 2 MeV, the differences were more significant by up to 552 times at 0.8 MeV for 5-year-old eye model. These differences are due mainly to the fact that the lens of the pediatric eye models is located deeper than that of the adult eye model. It is also notably seen that the newborn lens doses are relatively larger than the other pediatric lens doses. This is because the newborn ACD is much smaller than the other pediatric ACDs (see Table III).

4. Conclusions

In the present study, the detailed eye models were developed for children at different ages (newborn and 1-, 5-, 10-, and 15-year olds) which are considered in ICRP Publication 89 [12]. The developed eye models were then used to calculate the lens doses for electron exposures, and the calculated values were compared with those of the adult eye model. From the comparison, it was found that the pediatric lens doses were indeed significantly different from those of the adult, up to by ~500 (for the 5-year old). We expect that the developed pediatric eye models can be used in various studies requiring lens dose assessment for children. In addition, the pediatric eye models will be incorporated into the new mesh-type reference computational phantoms (MRCPs) for children, which are currently under development in ICRP Task Group 103.

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