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Radiation Protection Dosimetry

AIR KERMA TO *H*p(3) CONVERSION COEFFICIENTS FOR IEC 61267 RQR X-RAY RADIATION QUALITIES: APPLICATION TO DOSE MONITORING OF THE LENS OF THE EYE IN MEDICAL DIAGNOSTICS

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Abstract

Recent studies highlight the fact that the new eye lens dose limit can be exceeded in interventional radiology procedures and that eye lens monitoring could be required for these workers. The recommended operational quantity for monitoring of eye lens exposure is the personal dose equivalent at 3 mm depth *H*p(3) (ICRU 51). However, there are no available conversion coefficients in international standards, while in the literature coefficients have only been calculated for monoenergetic beams and for ISO 4037-1 X-ray qualities. The aim of this article is to provide air kerma to *H*p(3) conversion coefficients for a cylindrical phantom made of ICRU-4 elements tissue-equivalent material for RQR radiation qualities (IEC-61267) from 40 to 120 kV and for angles of incidence from 0 to 180°, which are characteristic of medical workplace. Analytic calculations using interpolation techniques and Monte Carlo modelling have been compared.

Issue Section: Paper

INTRODUCTION

The recommended operational quantity to monitor exposure to the eye lens is the personal dose equivalent at 3 mm depth *H*p(3)(1, 2). However, in practice, this quantity has rarely been used up to now. International standard IEC 62387:2012(3) provides informative data of conversion coefficients at 3 mm depth for the slab phantom for the

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head in which the eyes are embedded. Several works have recently supplied complementary data. Within the framework of the European project ORAMED(6), Gualdrini *et al.*(7) recommended the use of a 4-elements ICRU tissue cylindrical phantom of 20 cm diameter and 20 cm height. A recent study(8) demonstrates that, for photon radiation, on both a slab and a cylinder phantom, the results are equivalent for angles up to 60°. For angles >60°, an appropriate phantom for dosemeters to be worn on the head has to be used, and consequently conversion coefficients for this purpose are needed. Gualdrini *et al.*(9) provided conversion coefficients from air kerma to *H*p(3) for monoenergetic photon fields and for some X-ray beams of interest. Behrens published a complete series of $hpK(3,\mathrm{R},\alpha)$ for ISO 4037-1 qualities using a slab phantom(10), and later on for the cylindrical phantom(11). The recent interest and need to perform eye lens monitoring are due to the new recommendations of ICRP 118(12) of a dose limit of 20 mSv y^{-1} for occupational exposure to the eye. The new requirement is a serious challenge especially for the medical fields of interventional radiology and cardiology. The aim of this article is to provide air kerma to *H*p(3) conversion coefficients for the cylindrical phantom for RQR IEC-61267(13) X-ray beams for angles of incidence from 0 to 180°. The RQR2 to RQR9 IEC-61267 qualities were chosen because they provide a better approximation of the radiation spectra found in practice in interventional cardiology and radiology workplace than ISO 4037-1 qualities and are often used in intercomparisons in this field. The study also discusses the influence of different approaches used in the literature for the calculation of conversion coefficients. As opposed to ISO 4037-1 qualities, IEC-61267 does not specify the filtration needed to produce RQR beams. RQR qualities are defined by the tube voltage and the nominal first half-value layer. In order to be reproduced, one has to adjust them in order to obtain a ratio between air kerma (or air kerma rate) with and without a filter of thickness equal to the nominal first half-value layer between 0.485 and 0.515. The study estimates the influence of the filtration used in different laboratories for $hpK(3)$ conversion coefficients.

MATERIALS AND METHODS

The kerma-to-personal dose equivalent *H*p(3) conversion coefficient for the cylinder is defined as the ratio of the quantities *H*p(3) and the air kerma *K*a:

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The conversion coefficient depends on the energy, the directional distribution of the incident radiation and also the phantom used in the calibration. $hpK(3,\mathrm{RQR},\alpha)\mathrm{cyl}$ values for different RQR radiation qualities and angles α from 0 to 180° were assessed by means of two methods: analytic calculations through interpolation techniques and Monte Carlo modelling. Both methods are detailed below. As mentioned above, RQR qualities can be generated by using different added filtration, and, therefore, the energy spectrum of the beams can be slightly different depending on the laboratory. In this article, calculations are performed for the RQR spectra generated at the secondary standard laboratory at Universitat Politècnica de Catalunya (UPC) (Column 3 in Table 1). To evaluate the influence of the filtration used by different laboratories, calculations are repeated for the RQR spectra used by the Metrology Institute of Germany Physikalisch-Technische Bundesanstalt (PTB), using the information provided in PTB calibration certificates(14) (Column 4 in Table 1). The inherent filtration for UPC and PTB beams is equal to 7 mmBe. In addition, results have also been compared with $hpK(3)$ coefficients calculated by the French National Metrology Laboratory CEA LIST/LNE LNHB(5) for RQR7 and RQR9 nominal HVL values (Column 5, Table 1).

Table 1.

Characteristics of RQR qualities used in this article for the $hpK(3,\mathrm{RQR},\alpha)\mathrm{cyl}$ calculation.

	Tube voltage (kV)	HVL (mmAl)			Added filtration (mmAl)		
		UPC	PTB[a]	CEA[b]	UPC	PTB	CEA
RQR2	40	1.41	1.42		2.5	2.49	
RQR3	50	1.78	1.77		2.5	2.46	
RQR4	60	2.11	2.19		2.5	2.68	
RQR5	70	2.39	2.57		2.5	2.83	
RQR6	80	3.01	3.01		3.0	2.99	
RQR7	90	3.48	3.48	3.48	3.0	3.18	3.0

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		UPC	PTB	CEA	UPC	PTB	CEA
RQR8	100	3.86	3.96		3.0	3.36	
RQR9	120	4.98	5.00	5.00	3.5	3.73	3.39

[a] Data obtained from PTB calibration certificates(14) .

[b] CEA LIST/LNE LNHB Table 2.6 reference(5) .

Monte Carlo simulation

The simulation study to obtain the conversion coefficients was performed using two Monte Carlo codes: PENELOPE(15) and MCNPX(16).

The air kerma and Hp(3) in the ICRU tissue cylindrical phantom were calculated employing both Monte Carlo codes to obtain the hpK(3,RQR,0) conversion factors for normal incidence. In the set-up geometry, the cylindrical phantom surrounded by air is irradiated by a 20 cm × 20 cm collimated square beam, placed at 1 m from the phantom front face.

The photon fluence spectra for the radiation qualities of interest were determined from the XCOMP5 program(17). Photon fluence values per unit energy ($\mathrm{d}\varphi/\mathrm{d}E$) are given for integer values of energy from 1 keV to the tube voltage (Vmax), in steps of 1 keV. The input data introduced for each quality and laboratory were tube voltage, inherent filtration (7 mmBe), additional filtration and anode angle of the tube (18°).

To assess Hp(3) values, a 0.5-mm-thick sensitive volume was placed at 3 mm depth within the cylinder. Parallelepipeds of 1 mm width, 0.5 mm thickness and 5 cm height were used as scoring volumes for both Monte Carlo codes. Conversion coefficients for angles from 0 to 180° were evaluated only with MCNPX. PENELOPE was used to compare the results only for normal incidence. The statistical uncertainty of the Monte Carlo simulations was within 0.1–1 % at one standard deviation. It is worth mentioning that PENELOPE and MCNPX manage the simulation output process in different ways.

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The requested PENELOPE output for the calculation of Hp(3) was the energy deposited in the detection material. This quantity was then divided by the mass of the scoring kerma, transport of secondary electrons and positrons was disregarded.

For the MCNPX calculations, energy deposition tally F6 was used. *hpK*(3,RQR,0) coefficients obtained by PENELOPE were calculated considering the secondary electron transport, while those obtained by MCNPX disregarded the secondary particles (kerma approximation mode). The maximum range of electrons is 3 mm generated by 1 MeV photons in ICRU tissue; thus, this comparison is aimed on one hand to verify the validity of the air kerma approximation and on the other to evaluate the differences when using two well-known Monte Carlo programs.

Analytical method

hpK(3,RQR,0) conversion coefficients were calculated for RQR qualities and for a varying angle of incidence from 0 to 180° by implementing the interpolation technique suggested by Behrens(10). Conversion coefficients for monoenergetic photon beams were taken from Gualdrini *et al.*(9) The following steps were considered.

(a) As for the Monte Carlo simulation, the photon fluence spectra (dφ/d*E*) for the radiation qualities of interest were determined from the XCOMP5 program(17). (b) Subsequently, the average conversion coefficients *hpK*(3, RQR, α) were calculated by applying the following equation:

$$h_{\mathrm{p}K}(3,\mathrm{RQR},\alpha) = \frac{\sum_{i=1\ \mathrm{keV}}^{V_{\max}} \frac{\mathrm{d}\phi}{\mathrm{d}E}\cdot h_{\mathrm{p}K}(3,E_i,\alpha)\cdot E_i\cdot\frac{\mu_{\mathrm{en}}(E_i)}{\rho}}{\sum_{i=1\ \mathrm{keV}}^{V_{\max}} \frac{\mathrm{d}\phi}{\mathrm{d}E}\cdot E_i\cdot\frac{\mu_{\mathrm{en}}(E_i)}{\rho}}$$

hpK(3, *Ei*, α) correspond to monoenergetic photons for the ICRU cylindrical phantom calculated by Gualdrini *et al.*(9)

The formula represents the ratio between dose equivalent at 3 mm depth and air kerma, calculated for the radiation quality of interest RQR. In the equation, dφ/d*E* is the fluence per unit energy, and *V*max is the voltage applied to the X-ray tube to generate the radiation beam. *hpK*(3, RQR, α) are the conversion coefficients obtained by using a cubic spline interpolation at low energies (for energies between 10 and 40 keV and for angles >90°) and a linear logarithmic interpolation (linear in values and logarithmic in energy). The mass energy absorption coefficients μen(*Ei*)/ρ for photons

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RESULTS

Monte Carlo simulation

The difference between PENELOPE and MCNPX $hpK(3, \mathrm{RQR}, 0)$ was <1 %. The statistical uncertainty for both Monte Carlo codes was within 1 %, for one standard deviation. This result confirms the validity of the kerma approximation used in the following calculations.

Analytical method

The MCNPX output was compared with the values obtained by interpolation. For all the considered incident angles, $hpK(3, \mathrm{RQR}, \alpha)$ differences were <0.8 %. This result highlights the fact that the analytical method is both a good and quick estimation tool for the calculation of conversion coefficients within the analysed energy range, provided that you have the conversion coefficients for monoenergetic photon beams. As suggested by Behrens, for angles >90°, an approximation with a cubic polynomial can better estimate conversion coefficients at low energies from 10 up to 40 keV, and thus avoid unrealistic results. Indeed, in this angle and energy range, the difference between analytical and simulated outputs is reduced from a maximum of 7 % (linear interpolation on a log–lin) to values within 0.8 % (cubic spline interpolation). Therefore, Monte Carlo modelling has been considered the golden standard method even if interpolation results lead to very good approximations when this technique has been chosen carefully.

Influence of RQR reproduced in different laboratories

Table 2 data were compared with conversion coefficients calculated for PTB RQR qualities. Results showed good agreement. Differences were <1.5 % for angles <90° and between 1 and 7 % for larger angles. The larger disagreement was found for RQR5 and RQR8 qualities, where differences in added filtration are higher.

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Table 2.

Angles (°)	***hpK*(3,R,*α*)—MCNPX**							
	RQR2	**RQR3**	**RQR4**	**RQR5**	**RQR6**	**RQR7**	**RQR8**	**RQR9**
0	1.106	1.178	1.232	1.27	1.336	1.368	1.394	1.456
10	1.099	1.172	1.226	1.268	1.337	1.369	1.396	1.455
15	1.099	1.172	1.226	1.269	1.336	1.369	1.397	1.456
20	1.094	1.167	1.221	1.262	1.329	1.363	1.39	1.449
30	1.081	1.154	1.208	1.247	1.314	1.347	1.373	1.437
40	1.060	1.140	1.186	1.228	1.295	1.33	1.358	1.418
45	1.043	1.117	1.171	1.215	1.283	1.317	1.346	1.408
50	1.019	1.093	1.149	1.195	1.263	1.296	1.324	1.388
60	0.965	1.041	1.097	1.141	1.211	1.247	1.276	1.341
70	0.883	0.945	1.016	1.055	1.128	1.166	1.197	1.265
75	0.800	0.882	0.941	0.989	1.064	1.102	1.134	1.207
80	0.705	0.787	0.859	0.902	0.981	1.02	1.052	1.128
90	0.450	0.533	0.595	0.643	0.723	0.766	0.802	0.884
105	0.131	0.186	0.232	0.269	0.33	0.365	0.396	0.467
120	0.039	0.067	0.093	0.117	0.153	0.177	0.198	0.246
135	0.015	0.030	0.046	0.062	0.086	0.102	0.117	0.151
150	0.008	0.018	0.029	0.04	0.057	0.07	0.081	0.107
165	0.005	0.013	0.022	0.031	0.046	0.056	0.066	0.088
180	0.004	0.011	0.020	0.029	0.042	0.052	0.062	0.082

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90°. In this case, results agreed to within 0.6 %.

CONCLUSIONS

Conversion coefficients from air kerma to equivalent dose at 3 mm depth for radiation qualities RQR 2–9 and for angles of incidence from 0 to 180° are provided for the cylindrical phantom. The given data were calculated by using the MCNPX Monte Carlo code in the kerma approximation and were validated for normal incidence by using the PENELOPE Monte Carlo code with secondary particle transport. Although Monte Carlo calculations were considered the golden standard method, the study demonstrates the utility of the interpolation method to calculate specific conversion coefficients when this technique is chosen carefully. The conversion coefficients given in Table 2 are calculated for RQR qualities as defined in the lab of the present study. However, it has been verified that up to an angle of incidence of 90°, they can be used by other laboratories to within an uncertainty of 2 % (one standard deviation). This is the same uncertainty stated in ISO 4037-3 for ISO 4037-1 qualities conversion coefficients.

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REFERENCES

1 International Commission on Radiation Units and Measurements (ICRU). Measurement of Dose Equivalents from External Photon and Electron Radiations. ICRU Report 47, ICRU Publications (1992).

2 International Commission on Radiation Units and Measurements. Quantities and Units in Radiation Protection Dosimetry. ICRU Report 51. ICRU (1993).

3 IEC 62387. Radiation Protection Instrumentation—Passive Integrating Dosimetry Systems for Personal and Environmental Monitoring of Photon and Beta Radiation (2012).

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Function of Photon Energy—Part 1: Radiation Characteristics and Production Method. ISO 4037-1. ISO (1996).

5 International Organization for Standardization. X and Gamma Reference Radiation for Calibrating Dosemeters and Dose Rate Meters and for Determining Their Response as a Function of Photon Energy—Part 3: Calibration of Area and Personal Dosemeters and the Measurement of Their Response as a Function of Energy and Angle of Incidence. ISO 4037-3. ISO (1999).

6 Vanhavere F. et al. ORAMED: Optimization of Radiation Protection of Medical Staff. EURADOS Report 2012-02, ISSN 2226-8057, ISBN 978-3-943701-01-2, p. 88. (2012).

7 Gualdrini G. et al. A new cylindrical phantom for eye lens dosimetry development. *Radiat. Meas.* 46 (11), 1231–1234 (2011).
Google Scholar CrossRef

8 Behrens R., Hupe O. Influence of the phantom shape (slab, cylinder or Alderson) on the performance of an *H*p(3) eye dosemeter. *Radiat. Prot. Dosim.* 1–9 (2015). https://doi.org/10.1093/rpd/ncv366.

9 Gualdrini G., Bordy J. M., Daures J., Fantuzzi E., Ferrari P., Mariotti F., Vanhavere F. Air kerma to *H*p(3) conversion coefficients for photons from 10 keV to 10 MeV, calculated in a cylindrical phantom. *Radiat. Prot. Dosim.* 154 (4), 517–521 (2013).
Google Scholar CrossRef

10 Behrens R. Air kerma to dose equivalent conversion coefficients not included in ISO 4037-3. *Radiat. Prot. Dosim.* 147 (3), 373–379 (2011).
Google Scholar CrossRef

11 Behrens R. Air kerma to dose equivalent conversion coefficients for a new cylinder phantom for photon reference radiation qualities. *Radiat. Prot. Dosim.* 151 (3), 450–455 (2012).
Google Scholar CrossRef

12 International Commission on Radiological Protection. 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 41(1/2) (2012).

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13 International Electro Technical Commission (IEC) Medical Diagnostic X-Ray Equipment—

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14 PTB calibration certificate dated 2012-06-20. Calibration mark PTB60188-12.

15 Salvat F., Fernández-Varea J. M., Sempau J. PENELOPE 2006: A Code System for Monte Carlo Simulation of Electron and Photon Transport. Workshop Proceedings Barcelona, Spain, 4–7 July 2006, OECD 2006 NEA No. 6222, Nuclear Energy Agency Organisation for Economic Co-operation and Development (2006).

16 Pelowitz D. B. (ed). MCNPX User's Manual, Version 2.6.0. Los Alamos National Laboratory Report LA-CP-05-0369 (2005).

17 Nowotny R., Hofer A. XCOMP5, program for calculating diagnostic x-ray spectra. *RoeFo, Fortschr. Geb. Roentgenstr. Nuklearmed.* 142, 685–689 (1985).

Google Scholar CrossRef

18 Hubbell J. H., Seltzer S. M. Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients 1 keV to 20 MeV for Elements Z=1 to 92 and 48 Additional Substances of Dosimetric Interest. Report NISTIR 5632 (1995). The data are available on http://www.nist.gov/pml/data/xraycoef/index.cfm .

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