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NOTE

AIR KERMA TO $H_P(3)$ CONVERSION COEFFICIENTS FOR PHOTONS FROM 10 keV TO 10 MeV, CALCULATED IN A CYLINDRICAL PHANTOM

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In the framework of the ORAMED project (Optimization of RAdiation protection for MEDical staff), funded by the European Union Seventh Framework Programme, different studies were aimed at improving the quality of radiation protection in interventional radiology and nuclear medicine. The main results of the project were presented during a final workshop held in Barcelona in January 2011, the proceedings of which are available in the open literature. One of the ORAMED tasks was focused on the problem of eye-lens photon exposure of the medical staff, a topic that gained more importance especially after the ICRP decision to lower the limiting equivalent dose to 20 mSv per year. The present technical note has the scope, besides briefly summarising the physical reasons of the proposal and the practical implications, to provide, in tabular form, a set of air kerma to $H_p(3)$ conversion coefficients based on the adoption of a theoretical cylindrical model that is well suited for reproduction of the mass and the shape of a human head.

INTRODUCTION

In the framework of the ORAMED project (Optimization of RAdiation protection for MEDical staff), funded by European Union[(1)], different studies aimed at improving the quality of radiation protection practices for the exposed operators were carried out.

Among the topics treated by ORAMED, one was concerned with eye-lens dosimetry, to which special attention was devoted[(2)] recently, after the statement issued by ICRP, proposing to reduce the corresponding limit for occupational exposure from 150 to 20 mSv per year. This decision, taken after the final ORAMED workshop was held, was substantially highlighting one of the main topics treated during the ORAMED project: implementing the $H_p(3)$ operational quantity in the operative practice to better assess doses to the eye lens.

A central part of the ORAMED work on the topic, preceded by other investigations[(3, 4)], was the introduction of a new right cylindrical phantom (20 cm in diameter and 20 cm in height) in its theoretical version (ICRU-4 elements tissue-equivalent material) for the evaluation of $H_p(3)$ conversion coefficients and its corresponding poly-methyl-methacrylate (PMMA) water-filled experimental version for type test and calibration purposes[(5, 6)].

Some general comparisons between the new photon $H_p(3)$ coefficients and the radiation protection quantities $H_{eye\ lens}$ were already presented during the ORAMED final Workshop[(7)], the proceedings of which recently appeared in a special issue of radiation measurements[(8)].

The scope of this paper is to provide a complete tabulation of $H_p(3)/K_a$ and their angular dependence factors, for use in the radiation protection practice.

THEORETICAL DISCUSSION OF $H_P(3)$ OPERATIONAL QUANTITY IN ORAMED

A dosemeter designed in terms of the $H_p(3)$ quantity and consequently calibrated on the most appropriate phantom should be able to estimate as better as possible the eye-lens equivalent dose. It means that it should provide a conservative estimate of the eye-lens dose without excessive overestimation.

The choice of a suitable theoretical phantom should be based on physical considerations on the scattering properties of this phantom compared with the head. It seems, therefore, intuitive that the phantom proposed until now, i.e. the trunk phantom made of 4-element ICRU theoretical material of $30\times30\times15$ cm^3, is not a good solution to achieving an optimised procedure for eye-lens dosimetry. In fact, the dimensions of such a phantom (13 500 cm^3) are far larger than a real head volume ($\sim$6300 cm^3) with an associated larger quantity of tissue available as a scatterer of the incident radiation.

Secondly, a thickness of 15 cm is too small to represent the head and this leads to unphysical lack of shield in a PA irradiation (notwithstanding the fact that eye-lens exposure could be of concern only for front irradiation, the PA component contributes to the rotational exposure also for the eye lens, in case this has to be taken into account).

Thirdly, the presence of the edges leads again to unphysical effect at large incident angles, already criticised also for $H_p(10)$ that exhibits a sharp drop at a 90° impinging radiation incidence. Of course, according to the choice made by the MIRD Committee, the best simple structure could be an elliptical cylinder, but this choice seems to be rather unpractical especially from the point of view of the possible corresponding calibration phantom.

A reasonable compromise, in compliance with the mass under study and the shape, was a right cylinder of a 20-cm diameter and a 20-cm height. A smaller diameter could have been proposed, but the decision was taken on the basis of two considerations:

- Establishing a head simple model, taking into account the presence of the bone structures besides the only soft tissue. As the theoretical model is composed only of soft tissue, a slightly larger diameter might compensate for the higher interaction properties of the bone, contributing both to absorption and to scattering.
- Easy and cheap fabrication—a concern was based on the fact that a suitable PMMA cylindrical shell could be easily commercially found with no need to look for unusual dimensions and shapes that could increase the cost very significantly.

$H_P(3)$ OPERATIONAL QUANTITY STUDY

The problem was investigated through Monte Carlo modelling. The codes MCNP5[9], PENELOPE idem[10] and MCNPX idem[11] were used to obtain the conversion coefficients. The phantom was simulated as a 20 cm height 20 cm diameter cylinder of 4-element ICRU tissue (10.1 % H, 11.1 % C, 2.6 % N and 76.2 % O) with a mass density of 1.0 g·cm^{-3}.

The calculation of personal dose equivalent at a 3 mm depth was performed *in vacuo* with an expanded and aligned field both in kerma approximation and with full electron transport. Because 3 mm is nearly the maximum range of electrons generated by 1MeV incident photons in ICRU tissue, the difference between the two approaches becomes evident beyond this energy[6, 12].

AIR KERMA TO $H_P(3)$ CONVERSION COEFFICIENTS

$H_p(3)$ was calculated at a depth of 3 mm below the phantom surface in a set of 40 scoring volumes. The values were evaluated with MCNP5 and PENELOPE.

Table 1. Energies of photon beams and directions with respect to the normal to the incident surface of the phantom.

Energy	Angles
10, 20, 30, 40, 50, 60 keV	0°, 10°, 15°, 20°, 30°
70, 80, 90, 100, 110, 150, 200 keV	45°, 60°, 75°
300, 400, 500, 600, 700, 800 , 900 keV	90°, 105°, 120°
1, 1.1, 1.5, 2, 3, 4, 5, 6, 7, 8, 10 MeV	135°, 150°,
	165°, 180°

Monoenergetic photons were transported with source energies from 10 keV to 10 MeV, in an aligned and expanded field: a series of 31 monochromatic photon beams and 15 different incident angles were analysed (Table 1).

Owing to the cylindrical geometry, all the angle-dependent coefficients were calculated in the same run. The scoring volumes were cylindrical segments azimuthally placed at every 15° increment across the cylinder midplane, with a 0.5 mm thickness, 5 cm height and a 0.4° aperture.

Particular attention was devoted to the evaluation of photon–electron non-equilibrium at a 3 mm depth occurring for source photons of energies above 1 MeV.

Depending on the primary energy and incident angle, the statistical precision of the Monte Carlo results spanned within 0.2–0.5 % at one confidence level.

A complete tabulation of the conversion coefficients $H_P(3)/K_a$ is provided in Tables 2 and 3. The values reported are the averages between the PENELOPE (with its own database)[10] and the MCNP5 (with photon library mcplib04[13]) values.

The fluence to air kerma conversion coefficients were calculated employing the same sets of cross sections used for the transport calculation in the cylindrical model.

IMPLICATIONS FOR THE DOSEMETER TYPE TEST AND CALIBRATION

As stated by ISO 4037-3[14], a calibration phantom should reproduce as better as possible the absorption and scattering features of the part of the body on which the dosemeter is worn. In order to perform an accurate eye-lens dose assessment, the dosemeter should be placed near the eyes. That implies the need for the adoption of a calibration phantom reproducing as better as possible the shape and the mass of the head. This consideration motivated the present proposal of a simple cylindrical phantom.

The adoption of a corresponding PMMA water-filled cylindrical phantom will be a consequence of the present proposal with its implications for the type testing and calibration criteria for eye-lens dosemeters[15].

Table 2. $H_p(3,0°)/K_a$ **and ratio** $H_p(3,\alpha)/H_p(3,0°)$ **values averaged from PENELOPE and MCNP5—kerma approximation.**

Photon energy, MeV	$H_p(3,0°)/K_a$, Sv Gy^{-1}	Ratio $H_p(3,\alpha)/H_p(3,0°)$, kerma approximation														
		0°	10°	15°	20°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
0.010	0.244	1.000	0.978	0.951	0.917	0.809	0.571	0.274	0.044	0.001	0.000	0.000	0.000	0.000	0.000	0.000
0.020	0.919	1.000	0.996	0.992	0.986	0.969	0.919	0.821	0.612	0.220	0.018	0.001	0.000	0.000	0.000	0.000
0.030	1.219	1.000	0.998	0.995	0.991	0.982	0.956	0.899	0.775	0.482	0.161	0.047	0.017	0.008	0.005	0.004
0.040	1.448	1.000	0.998	0.996	0.992	0.984	0.959	0.912	0.815	0.584	0.279	0.126	0.065	0.040	0.030	0.028
0.050	1.597	1.000	0.997	0.995	0.993	0.984	0.963	0.919	0.834	0.632	0.348	0.185	0.110	0.077	0.062	0.057
0.060	1.667	1.000	0.997	0.995	0.993	0.986	0.964	0.926	0.848	0.663	0.391	0.224	0.143	0.103	0.086	0.080
0.070	1.674	1.000	0.998	0.996	0.994	0.987	0.970	0.935	0.863	0.689	0.421	0.250	0.164	0.123	0.103	0.097
0.080	1.649	1.000	0.999	0.999	0.995	0.990	0.974	0.944	0.878	0.710	0.444	0.270	0.180	0.136	0.115	0.109
0.090	1.614	1.000	1.000	0.999	0.997	0.992	0.979	0.952	0.891	0.728	0.462	0.285	0.192	0.146	0.124	0.117
0.100	1.581	1.000	1.000	0.999	0.997	0.994	0.983	0.958	0.901	0.742	0.477	0.298	0.203	0.154	0.131	0.124
0.110	1.550	1.000	1.000	0.999	0.997	0.995	0.985	0.963	0.910	0.755	0.492	0.310	0.212	0.161	0.138	0.131
0.150	1.449	1.000	0.999	0.999	0.998	0.997	0.994	0.979	0.938	0.794	0.535	0.348	0.244	0.188	0.161	0.153
0.200	1.372	1.000	1.000	1.000	0.999	1.000	1.000	0.993	0.959	0.830	0.578	0.388	0.278	0.218	0.188	0.179
0.300	1.286	1.000	1.000	1.002	1.001	1.002	1.005	1.006	0.986	0.875	0.642	0.453	0.338	0.270	0.236	0.227
0.400	1.240	1.000	1.001	1.001	1.000	1.002	1.008	1.011	0.997	0.902	0.684	0.502	0.384	0.316	0.279	0.268
0.500	1.210	1.000	1.001	1.002	1.002	1.002	1.010	1.014	1.003	0.919	0.716	0.539	0.422	0.351	0.315	0.303
0.600	1.191	1.000	1.000	1.001	1.001	1.005	1.010	1.014	1.007	0.929	0.740	0.569	0.454	0.383	0.345	0.334
0.700	1.176	1.000	1.000	1.001	1.000	1.002	1.008	1.014	1.010	0.940	0.760	0.595	0.483	0.411	0.373	0.360
0.800	1.167	1.000	0.998	0.999	1.000	1.002	1.007	1.012	1.009	0.945	0.773	0.614	0.504	0.435	0.396	0.384
0.900	1.156	1.000	1.001	1.002	1.001	1.004	1.009	1.015	1.012	0.951	0.789	0.636	0.526	0.458	0.420	0.407
1.000	1.152	1.000	0.997	0.999	1.001	0.999	1.005	1.010	1.009	0.955	0.795	0.651	0.545	0.476	0.437	0.424
1.100	1.144	1.000	1.000	0.999	1.002	1.002	1.009	1.013	1.013	0.960	0.810	0.667	0.560	0.494	0.456	0.444
1.500	1.129	1.000	1.003	1.001	1.002	1.003	1.009	1.014	1.011	0.968	0.837	0.712	0.616	0.552	0.516	0.504
2.000	1.120	1.000	0.999	1.002	1.001	1.002	1.007	1.009	1.007	0.973	0.860	0.747	0.659	0.600	0.565	0.554
3.000	1.110	1.000	1.000	0.999	0.999	1.000	1.003	1.006	1.002	0.973	0.876	0.781	0.704	0.651	0.619	0.610
4.000	1.103	1.000	0.999	0.997	0.998	0.999	1.001	1.000	1.000	0.976	0.895	0.810	0.742	0.695	0.665	0.656
5.000	1.098	1.000	0.997	0.997	0.997	0.998	0.999	0.997	0.995	0.974	0.901	0.824	0.762	0.716	0.691	0.682
6.000	1.090	1.000	0.998	0.998	0.996	0.999	0.997	1.000	0.994	0.973	0.905	0.836	0.776	0.733	0.707	0.699
7.000	1.085	1.000	0.998	0.998	0.998	0.998	1.000	0.999	0.995	0.976	0.906	0.836	0.778	0.737	0.711	0.703
8.000	1.079	1.000	1.000	1.000	0.997	0.999	0.998	0.995	0.993	0.972	0.911	0.846	0.793	0.752	0.729	0.725
10.000	1.070	1.000	0.995	0.999	0.999	0.997	0.998	0.997	0.992	0.975	0.912	0.852	0.800	0.765	0.741	0.734

Table 3. $H_p(3,0°)/K_a$ and ratio $H_p(3,\alpha)/H_p(3,0°)$ values averaged from PENELOPE and MCNP5—electron transport.

Photon energy, MeV	$H_p(3,0°)/K_a$, Sv Gy^{-1}	Ratio $H_p(3,\alpha)/H_p(3,0°)$, dose														
		0°	10°	15°	20°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
0.010	0.244	1.000	0.977	0.954	0.918	0.808	0.572	0.276	0.044	0.001	0.000	0.000	0.000	0.000	0.000	0.000
0.020	0.914	1.000	1.000	0.997	0.992	0.976	0.923	0.821	0.611	0.221	0.019	0.001	0.000	0.000	0.000	0.000
0.030	1.217	1.000	0.999	0.992	0.997	0.988	0.959	0.896	0.775	0.487	0.161	0.047	0.017	0.008	0.005	0.004
0.040	1.442	1.000	1.005	0.989	0.995	0.991	0.966	0.915	0.819	0.592	0.284	0.126	0.064	0.042	0.031	0.027
0.050	1.593	1.000	0.997	0.993	0.991	0.989	0.965	0.922	0.836	0.638	0.350	0.187	0.112	0.075	0.062	0.054
0.060	1.670	1.000	0.997	0.989	0.992	0.984	0.962	0.918	0.843	0.665	0.391	0.223	0.142	0.103	0.085	0.082
0.070	1.671	1.000	0.999	0.997	0.996	0.990	0.966	0.934	0.863	0.688	0.423	0.251	0.163	0.121	0.101	0.097
0.080	1.644	1.000	1.002	1.000	0.998	0.994	0.976	0.947	0.876	0.715	0.448	0.269	0.184	0.134	0.113	0.111
0.090	1.607	1.000	1.004	1.002	1.004	0.996	0.976	0.955	0.889	0.732	0.465	0.288	0.194	0.146	0.125	0.118
0.100	1.573	1.000	1.006	1.006	1.008	0.998	0.980	0.960	0.904	0.751	0.482	0.300	0.205	0.155	0.132	0.121
0.110	1.541	1.000	1.003	1.003	1.007	1.001	0.985	0.964	0.916	0.766	0.495	0.313	0.215	0.164	0.139	0.129
0.150	1.452	1.000	0.997	0.996	0.998	0.998	0.985	0.975	0.930	0.801	0.537	0.348	0.243	0.187	0.159	0.153
0.200	1.369	1.000	1.003	0.997	1.003	1.003	1.002	0.993	0.958	0.835	0.579	0.392	0.279	0.217	0.188	0.181
0.300	1.281	1.000	1.009	1.005	1.006	1.010	1.012	1.009	0.984	0.888	0.644	0.456	0.338	0.272	0.236	0.228
0.400	1.242	1.000	1.003	0.999	1.007	1.003	1.006	1.006	0.991	0.909	0.689	0.503	0.382	0.315	0.280	0.270
0.500	1.209	1.000	1.006	1.002	1.006	1.006	1.007	1.005	1.002	0.927	0.719	0.542	0.423	0.351	0.314	0.304
0.600	1.184	1.000	1.008	1.000	1.014	1.010	1.010	1.014	1.006	0.943	0.748	0.573	0.464	0.385	0.350	0.337
0.700	1.169	1.000	1.003	1.009	1.012	1.006	1.013	1.013	1.008	0.948	0.770	0.598	0.486	0.417	0.380	0.365
0.800	1.155	1.000	1.010	1.010	1.015	1.009	1.016	1.019	1.015	0.960	0.786	0.618	0.512	0.438	0.403	0.397
0.900	1.154	1.000	1.006	0.999	1.008	1.008	1.014	1.013	1.007	0.956	0.790	0.635	0.530	0.457	0.420	0.414
1.000	1.147	1.000	1.007	1.006	1.004	1.008	1.014	1.012	1.014	0.967	0.800	0.656	0.546	0.475	0.444	0.431
1.100	1.131	1.000	1.004	1.008	1.008	1.013	1.019	1.025	1.024	0.974	0.821	0.674	0.569	0.502	0.464	0.448
1.500	0.975	1.000	1.008	1.007	1.023	1.045	1.083	1.132	1.153	1.124	0.977	0.822	0.712	0.640	0.596	0.584
2.000	0.740	1.000	1.021	1.020	1.052	1.093	1.209	1.336	1.428	1.431	1.292	1.118	0.995	0.909	0.853	0.841
3.000	0.461	1.000	1.028	1.038	1.080	1.164	1.399	1.688	1.987	2.139	2.041	1.873	1.703	1.596	1.514	1.504
4.000	0.328	1.000	1.017	1.031	1.074	1.174	1.476	1.933	2.491	2.835	2.828	2.656	2.482	2.330	2.244	2.213
5.000	0.250	1.000	1.018	1.046	1.089	1.204	1.523	2.108	2.908	3.527	3.654	3.477	3.328	3.146	3.026	2.995
6.000	0.201	1.000	1.026	1.041	1.089	1.196	1.555	2.202	3.262	4.189	4.446	4.335	4.156	3.939	3.841	3.770
7.000	0.168	1.000	1.034	1.051	1.091	1.194	1.560	2.252	3.510	4.746	5.264	5.193	4.959	4.750	4.635	4.590
8.000	0.145	1.000	1.036	1.054	1.083	1.191	1.550	2.279	3.723	5.286	6.004	5.997	5.791	5.530	5.404	5.360
10.000	0.115	1.000	1.022	1.045	1.069	1.175	1.513	2.259	3.901	6.162	7.358	7.457	7.287	7.051	6.886	6.803

CONCLUSION

The aim of the paper was to provide a set of conversion coefficients that could contribute to improving the overall quality of eye-lens dose assessment procedures.

In this framework, a cylindrical numerical model was proposed. Photon $H_p(3)/K_a$ conversion coefficients were calculated and presented in a tabular form.

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