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A new cylindrical phantom for eye lens dosimetry development

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ABSTRACT

Due to the recent new interest of the dosimetric community generated by evidence of larger number of induced cataracts for the same absorbed dose, in the frame work of the ORAMED project (Oramed, 2008) a task was devoted to the critical revision of the eye lens dose assessment procedures. The present paper summarizes the Monte Carlo analyses carried out to optimize the $H_p(3,\Omega)$ calculations in order to produce a set of conversion coefficients $H_p(3,\Omega)/K_a$ as close as possible to those of the limiting quantity H_T(eye lens)/Ka. Comparison were carried out with already published values calculated for a previous theoretical phantom, mainly suited for the calculations of $H_p(10,\Omega)/K_a$.

1. Introduction

Cataract is an eye disease characterized by the eye lens opacity. Most of the eye tissues present a radio-sensitivity on average comparable to that of the skin. The internal eye chamber, in particular the lens is more radio-sensitive also to low radiation doses (Biagini, 1999). Various epidemiological studies highlighted a higher incidence of cataracts than previously foreseen. Anyway, the relationship between the dose received and the incidence of cataracts in man is not yet clear. Previous estimates by ICRP, mainly based on the investigation on the survivors of the Hiroshima and Nagasaki bombings (August 1945) indicated a minimum threshold dose of 2 Gy for single irradiation and 5 Gy for fractionated and protracted exposure to induce cataract (ICRP, 1991; NCRP, 1993). Anyway, more recent studies put in evidence an excess of cataracts at doses lower than 0.5 Gy, whilst other studies did not provide any significant proof of the existence of a threshold dose (Nakashima et al. 2006; Worgul et al. 2007; Chodick et al. 2008). It was recognized that serious uncertainties exist about the mechanisms of insurgence of the disease itself, if only deterministic or stochastic or both. The previously explained reasons put in evidence the need of a detailed re-evaluation of the eye lens radio-sensitivity. To enter into the specific aspect of the dosimetry assessment it can be useful to mention ICRP 103 (ICRP, 2008) in its paragraph 103 "……A depth $d = 3$ mm has been proposed for the rare case of monitoring the dose to the lens of the eye. In practice, however, $H_p(3)$ has rarely been monitored and $H_p(0.07)$ can be used for the same monitoring purpose". The scarce interest devoted until now on the $H_p(3)$ quantity is also demonstrated by the lack of official data in ICRP-74 and ICRU-57 (ICRP, 1995; ICRU, 1998). In these documents only conversion coefficients for electrons are reported (for normal incidence $H'(3,0)$ values are reported whilst for the angular dependence the values are based on a parallelepiped theoretical phantom of $30 \times 30 \times 15$ cm^3). Some years ago a set of $H_p(3,\Omega)/K_a$ conversion coefficients were calculated for the same slab at the former GSF in Munchen (actually Helmholtz Zentrum) by Till et al., (1995).

Following the evidence of a larger number of cataracts, it was felt within the ORAMED project that the overall procedure for a correct eye lens dose assessment should be proposed, starting from a better suited study on the limiting quantity, through a more realistic evaluation of the operational quantity, the definition of an adequate protocol for type test and calibration of eye lens devoted dosemeters, (Bilski et al., 2011) and finally the construction of a dosemeter optimized to respond in terms of $H_p(3)$ (Bordy et al.,

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2011). In parallel with the ORAMED activities on the operational quantity, detailed computational studies on the H_T(eye lens) both for electrons and photons were carried out by Behrens and Dietze (2011) and Behrens et al. (2009), with an improved model of the eye, in which the radio-sensitive and non radio-sensitive volumes are clearly distinguished, much better than the crude eye model as used in the MIRD based model (Snyder et al. 1969) in which all the eye volume was considered as radio-sensitive. The studies herewith presented, carried out within the ORAMED project, had the main scope to guarantee an optimized approach to the eye lens dosimetric evaluations, in all the aspects, from the theoretical quantities to the operative practice.

2. Materials and methods

The study on a new model for the $H_p(3)$ operation quantity assessment for photons was based on some simple physical considerations, mainly related to the real backscatter properties of the head and on the angular behavior of the quantity that is, especially for photons, much linked to the shape and mass of the target and to the usual phantom used for CTDI (Computed Tomography Dose Index) measurement in diagnostic procedures. The main point of concern was that a $30 \times 30 \times 15$ cm^3, well representing the trunk especially for nearly normal exposures, was not well suited to emulate the head in which the eyes are embedded. Apart from the mass difference that is evident, also the presence of the edges of the slab imply a strongly divergent behavior in such a geometry compared with what happens within a head. Therefore, an intermediate solution based on the adoption of an ICRU 4-element tissue equivalent material $15 \times 20 \times 20$ cm^3 phantom investigated in a previous study (Ferrari et al., 2005) was superseded by a cylinder of 20 cm diameter and 20 cm height. The choice was lead by anatomical considerations (a bit larger diameter to account for the important presence of the skull bone) and practical to ease the construction of a suited calibration phantom (PMMA pipes of 20 cm diameter are commercially available and cheap).

Two Monte Carlo codes were used to compute the conversion coefficients (Mariotti and Gualdrini, 2009; Daures et al., 2009): MCNPX (Pelowitz, 2005) and PENELOPE (Salvat et al., 2001). The adopted model is reported in Fig. 1.

An aligned and expanded field of photons collides with the entire phantom. The source is modeled as a square of 20×20 cm^2 corresponding to the vertical section of the cylinder, that is considered in vacuum (Fig. 1). Scoring cylindrical shells at 3 mm depth were modeled at the following stated angles:

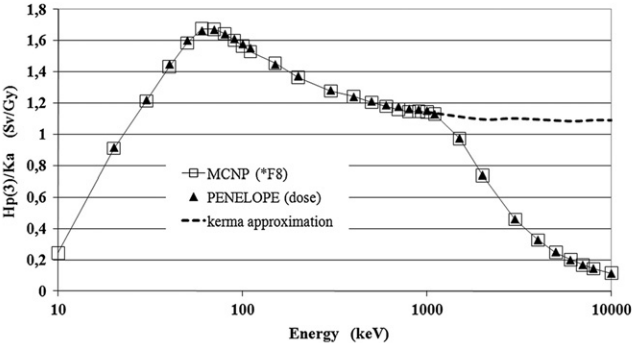

Fig. 2. Fully coupled photon electron transport calculations results versus kerma approximation for evaluating $H_p(3,0°)/K_a$.

$\Omega = 0°, 10°, 30°, 40°, 50°, 60°, 70°, 75°, 80°, 90°, 100°, 110°, 120°, 130°, 140°, 145°, 150°, 160°, 170°, 180°$

The investigated energies are:

10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 800 KeV and 1. 2, 3, 6, 8, 10 MeV

The calculations were normally run in the so-called kerma approximation with MCNPX, assuming that 3 mm tissue thickness was sufficient to establish the conditions of photon–electron equilibrium. Thus, we employed the energy deposition scoring option of the code that automatically folds the photon spectral fluence with the corresponding mass energy absorption coefficients. In addition calculations were done with and without kerma approximation with the PENELOPE code (for P-E transport the secondary electron energy deposition was scored).

Of course the equilibrium condition is not fulfilled for photon energies above 1 MeV, due to the associated secondary electrons, which range overcomes 3 mm. Fig. 2 shows the energy dependent plot of $H_p(3,0°)/K_a$. It should be pointed out that, notwithstanding that the energy domain above 1 MeV is outside the interest of the studies carried out for medical exposures in interventional radiology (energies below 150 keV), other higher energy fields of application could become of concern in the future. At present the official conversion coefficients sets for the photons operational quantities are given in kerma approximation corresponding to a situation of complete equilibrium. It is worth to remind that the definition of the operational quantities relies on the concept of expanded and aligned field, thus the calculations should be done in vacuum. It would result rather complicated to take into account the possible partial equilibrium, time and position dependent,

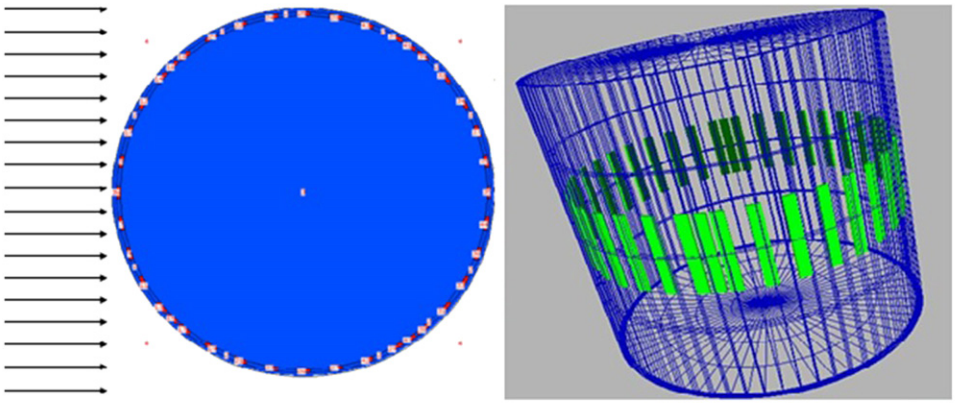

Fig. 1. Monte Carlo model of the cylindrical geometry adopted in the calculations. In the figure all the scoring regions are visible; thanks to the phantom symmetry for each angle (except 0° and 180°) the results can be scored in two symmetric volumes, with respect the beam axis (e.g. −15° and 15°, −30° and 30° etc.), and averaged. The scoring cells are cylindrical sectors of 0.68 cm^3 (5 cm high, 2 mm thick, 4° wide) centered at 3 mm depth from the external surface.

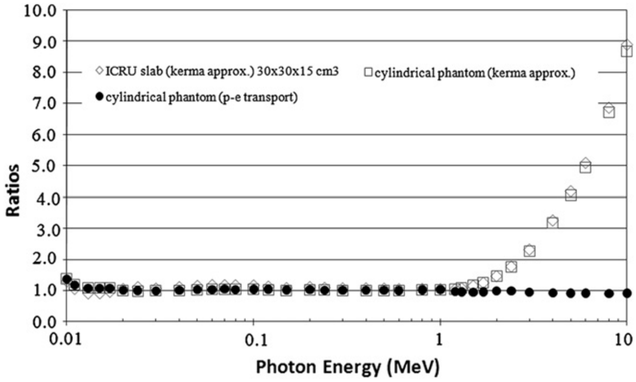

Fig. 3. Normally incident photons: Comparison between the H_T(eye lens) (Behrens and Dietze, 2011) and $H_p(3)$ as obtained using the cylindrical phantom (this work) and the traditional 30 × 30 × 15 cm^3 slab (Till, E., Zankl, M., Drexler, G., 1995).

condition related to the presence of air between the source and the "target". This simplified approach, that leads to conservative estimates at higher energies, is acceptable in the majority of the situations. However could be that some scenarios require a more accurate evaluation of the doses and the usage of conversion coefficients based on p-e transport, at least inside the phantom, should be suggested.

3. Compliance of the operational quantity $H_p(3)$ with the limiting quantity H_T(eye lens)

In order to evaluate the suitability of the newly calculated conversion coefficients, comparing them with previous compilations based on different shape theoretical phantoms, various irradiation scenarios were reproduced and for each of them it was investigated how the dose equivalent calculated on the basis of a given phantom complied with the corresponding limiting quantity (AP, LAT, PA and ROT irradiations). It should be pointed out that the comparison is made on a series of theoretical irradiation conditions that are partially beyond the scope of the Interventional Radiology/Ineterventional Cardiology procedures, limited to a practical range of exposure angles from normal to maximum 90° and a full correspondence with the type test and calibration condition cannot be found in the comparison herewith presented, covering a larger number of irradiation scenarios and only limited to judging the overall compliance of the newly proposed $H_p(3,\Omega)/K_a$ conversion coefficients with H_T(eye lens)/K_a.

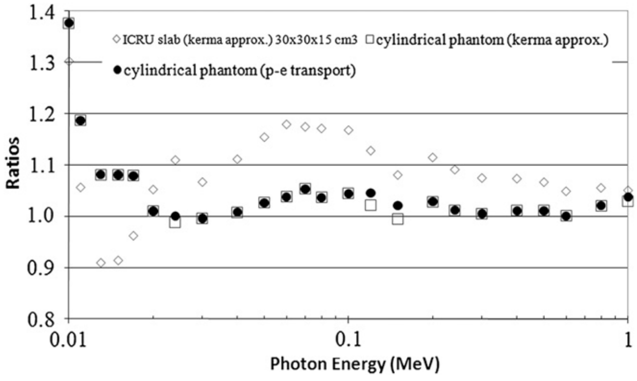

Fig. 4. A detail of Fig. 3 showing the comparison between the H_T(eye lens) by Behrens and Dietze, (2011) and $H_p(3)$ as obtained using the cylindrical phantom (this work) and the traditional 30 × 30 × 15 cm^3 slab (Till et al., 1995) below 1 MeV.

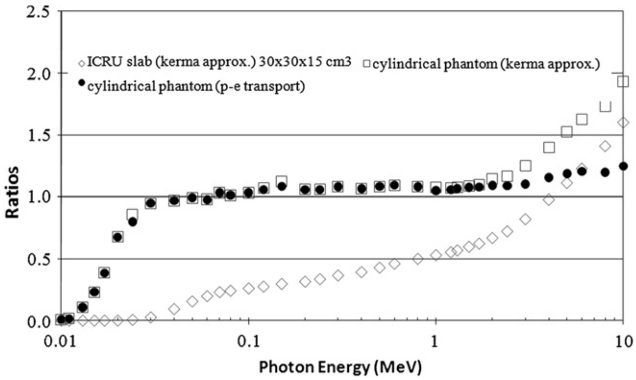

Fig. 5. Laterally incident photons: Comparison between the H_T(eye lens) by Behrens and Dietze, (2011) and $H_p(3)$ as obtained using the cylindrical phantom (this work) and the traditional 30 × 30 × 15 cm^3 slab (Till et al., 1995).

In figures from 3 to 6 a selection of plots is presented summarizing the cases in which the most significant divergences between operational and protection quantities were detected. The kerma approximation data results were obtained utilizing MCNPX whilst the coupled photon electron transport results were calculated with Penelope. As the operational quantity should be a reasonable estimate of limiting quantity the ratios are expected to be larger than unity. For AP exposure (Figs. 3 and 4) the larger size and mass of the 30 × 30 × 15 cm^3 phantom implies a larger backscatter compared with the real head, with a consequent overestimation of the energy deposition of about 20%. A very satisfactory agreement of the operational quantity and the radiation protection quantity is obtained relying on the proposed cylindrical theoretical phantom for $H_p(3)$ assessments. For LAT irradiation (90°) (Fig. 5) the largest deviation occurs due to the width of the slab phantom (the scoring volume is 15 cm far from the edge), that implies a larger attenuation. Also here the agreement with the cylinder based results is very satisfactory except for energies lower than 30 keV for which all phantoms fail because of the dominance of the geometrical shape and internal radiation sensitive structure of the eye in case of lateral irradiation For PA irradiation (not reported), the lower thickness (15 cm) of the slab compared with the cylinder diameter (20 cm) implies a lower attenuation toward the scoring volume at 180°, and a consequent overestimation of the radiation protection quantity. For ROT irradiation (Fig. 6), assuming an equiprobable posture of the operator at all the angles of incidence (from AP to PA through LAT), the slab based conversion coefficients underestimate H_T(lens) of about 25%.

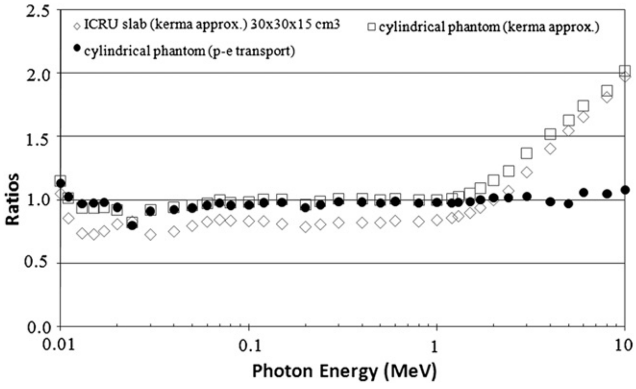

Fig. 6. Rotational photon exposure: Comparison between the H_T(eye lens) by Behrens and Dietze, (2011) and $H_p(3)$ as obtained using the cylindrical phantom (this work) and the traditional 30 × 30 × 15 cm^3 slab (Till et al., 1995).

4. Discussion and conclusion

The previous investigation contributed to learn that for eye lens dosimetry a better suited theoretical approach and the proposal of a corresponding calibration phantom is practicable. Similarly to what happened for the wrist and finger, for which problem dependent conversion coefficients and appropriate calibration phantoms could be provided, also for the eye lens it is easy to create a Monte Carlo model producing conversion coefficients for the operational quantity better approaching H_T(eye lens) and a corresponding PMMA water filled cylindrical phantom, easy to be built using commercially available materials. Calculations of electron and neutron conversion coefficients are planned for the near future. The simple proposed procedure could contribute to the quality of the dosimetry measurements for the eye lens exposure.

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