Monitoring the eye lens

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Abstract
In this work, it was investigated which type of dosemeter (i.e. measuring which personal dose equivalent quantity) is suitable to monitor the eye lens dose depending on the type of application. The main results are: In pure photon radiation fields, dosemeters measuring $H_p(0.07)$ may be used; in case beta radiation significantly contributes to the dose, dosemeters measuring $H_p(3)$ are advisable. In addition, it was found that the question of which type of calibration phantom is to be used for the quantity $H_p(3)$ –slab or cylinder phantom– is of less significance compared to the question: which part of the eye lens should serve as basis for the determination of conversion coefficients for the eye lens dose?

Keywords
Eye lens dose; operational dose quantities

1. Introduction

To prevent the induction of cataracts by ionizing radiation (especially photons or betas), the International Commission on Radiological Protection (ICRP) has lowered the annual dose limit for the eye lens from 150 mSv down to 20 mSv for occupational exposures[1]. Thus, protecting the eye and monitoring the lens dose to prevent exceeding the dose limit are more necessary than formerly assumed. Of course, the first choice is always to avoid exposures to ionizing radiation as far as possible, i.e. to use protective measures such as lead glass shields or goggles, when possible. However, not all exposures are avoidable; in these cases a suitable method to monitor the eye lens dose must be available. The first question is: which type of dosemeter (i.e. measuring which personal dose equivalent quantity) should be used to monitor the eye lens dose? Secondly, the type of phantom the quantity is defined in for calibration purposes is discussed (especially for the quantity $H_p(3)$). Finally, the question as to how the eye lens dose should be defined is discussed.

2. Method

The different personal dose equivalent quantities, $H_p(d)_{slab}$, $H_p(d)_{cyl}$, and $H_p(d)_{rod}$ used for calibrations, the indices denoting the definition in a slab, a cylinder, and a rod phantom, respectively, were compared to the eye lens dose, H_{lens}, i.e. their conversion coefficients from air kerma and fluence for photons and electrons, respectively, were divided by the conversion coefficients of the eye lens dose. In other words, the response of ideal dosemeters for the different calibration quantities is compared to the eye lens dose. This comparison was performed for the eye lens dose as currently defined by the ICRP[2], namely by averaging the deposited energy over the entire lens: H_{lens}. In addition, the comparison was performed for the lens dose based only on the significant volume of the lens: the volume in which the cell nuclei are located[2,3]: $H_{lens,s}$. This latter comparison was only performed for electron radiation, as the differences of H_{lens} and $H_{lens,s}$ are not significant for photons[5].
The definition phantoms referred to in this work are the following: the 30 cm x 30 cm x 15 cm slab and the 30 cm long x 1.9 cm diameter rod both defined long ago by the International Commission on Radiation Units (ICRU), and the new 20 cm high x 20 cm diameter cylinder recently suggested by the ORAMED project (Optimization of RAdiation protection for MEDical) for eye lens dosimetry[6]. Table 1 shows the data sources from which the different conversion coefficients were taken.

Table 1. Reference from which the conversion coefficients were taken.

Conversion coefficient for monoenergetic particles	Data source
Data for photons	
$h_{\mathrm{p}K}(0.07)_{\mathrm{slab}}$ and $h_{\mathrm{p}K}(10)_{\mathrm{slab}}$ for $\alpha = 0°$, 60° and 75°	ICRP 74[7]
$h_{\mathrm{p}K}(0.07)_{\mathrm{slab}}$ and $h_{\mathrm{p}K}(10)_{\mathrm{slab}}$ for $\alpha = 90°$	Till et al.[8]
$h_{\mathrm{p}K}(3)_{\mathrm{slab}}$	Till et al.[8]
$h_{\mathrm{p}K}(3)_{\mathrm{cyl}}$	Vanhavere et al.[9]
$h_{\mathrm{p}K}(0.07)_{\mathrm{rod}}$	Grosswendt[10]
$h_{\mathrm{lens}K}$ for $\alpha = 0°$ and 90° based on the entire lens	ICRP 116[2]
$h_{\mathrm{lens}K}$ for $\alpha = 75°$ based on the entire lens	Behrens and Dietze[5]
$h_{\mathrm{lens}K,\mathrm{s}}$ for all α based on the significant volume	Behrens and Dietze[5]
Data for electrons	
$h_{\mathrm{p}\Phi}(0.07)_{\mathrm{slab}}$, $h_{\mathrm{p}\Phi}(3)_{\mathrm{slab}}$, and $h_{\mathrm{p}\Phi}(10)_{\mathrm{slab}}$	ICRP 74[7]
$h_{\mathrm{p}\Phi}(3)_{\mathrm{cyl}}$	Ferrari and Gualdrini[11]
$h_{\mathrm{lens}\Phi}$ for $\alpha = 0°$ based on the entire lens	ICRP 116[2]
$h_{\mathrm{lens}\Phi}$ for $\alpha = 45°$, 60°, and 75° based on the entire lens	Behrens[12]
$h_{\mathrm{lens}\Phi}$ for all α based on the significant volume	Behrens[12]

3. Results

3.1 Detailed results

Figure 1 shows the ratio of different dose equivalent quantities within different calibration phantoms and the eye lens dose (based on the entire lens) depending on the photon energy for angles of incidence of $\alpha = 0°$, 60°, 75°, and 90°. This ratio is nearly equal for all values of $\alpha < 60°$, therefore, data are only shown for $\alpha = 0°$ and $\alpha \geq 60°$.

From the solid black curves it can be seen that the quantity $H_{\mathrm{p}}(0.07)$ strongly overestimates the eye lens dose, H_{lens}, at photon energies below 30 keV. The reason is that low-energy photons are significantly attenuated within the tissue in front of the eye lens of almost 3 mm, which is quite thick compared to 0.07 mm. For photon energies around 100 keV, $H_{\mathrm{p}}(0.07)$ underestimates H_{lens} by up to 25 % when the rod phantom is chosen as a definition basis. However, when $H_{\mathrm{p}}(0.07)$ dosemeters are worn near the eye they will rather respond according to the curve "$H_{\mathrm{p}}(0.07)_{\mathrm{slab}}$ / H_{lens}" as they often also detect radiation scattered back from the head. Therefore, a lot of extremity dosemeters measuring $H_{\mathrm{p}}(0.07)$, e.g. ring dosemeters, show nearly the same calibration factor irrespective of the calibration phantom. This was shown for the slab and the rod phantom by Behrens et al.[13]. Consequently, extremity dosemeters for $H_{\mathrm{p}}(0.07)$ may be used to monitor the eye lens dose in pure photon radiation fields.

At $\alpha = 90°$, the eye lens dose, H_{lens}, is extremely underestimated by all quantities defined in the slab phantom, $H_{\mathrm{p}}(d)_{\mathrm{slab}}$, as the radiation has to penetrate the phantom from the side in order to reach the reference point, namely 15 cm of ICRU tissue. This is, of course, much more material compared to the material in front of the eye lens, resulting in the extreme underestimation. However, no real dosemeter has so much material at its side and, consequently, its indication is much higher, possibly quite close to the eye lens dose, H_{lens}, as at $\alpha = 75°$.

From the dashed blue curve it can be seen that the quantity $H_{\mathrm{p}}(10)$ underestimates H_{lens}, especially for low photon energies and at large angles of incidence. This was expected, as the eye lens lies about 3 mm below the surface, being much less tissue compared to 10 mm.

Finally, the dotted orange curves show that the quantity $H_{\mathrm{p}}(3)$ almost adequately estimates H_{lens} irrespective of the phantom used for its definition (slab or cylinder). Only at $\alpha = 90°$ is the definition in the cylinder phantom more adequate compared to the slab phantom. However, usually neither calibrations nor type tests of dosemeters are performed at 90° angle of incidence, therefore, also the slab phantom can be used for the calibration of $H_p(3)$ dosemeters, see above. This is discussed in more detail in another paper[14].

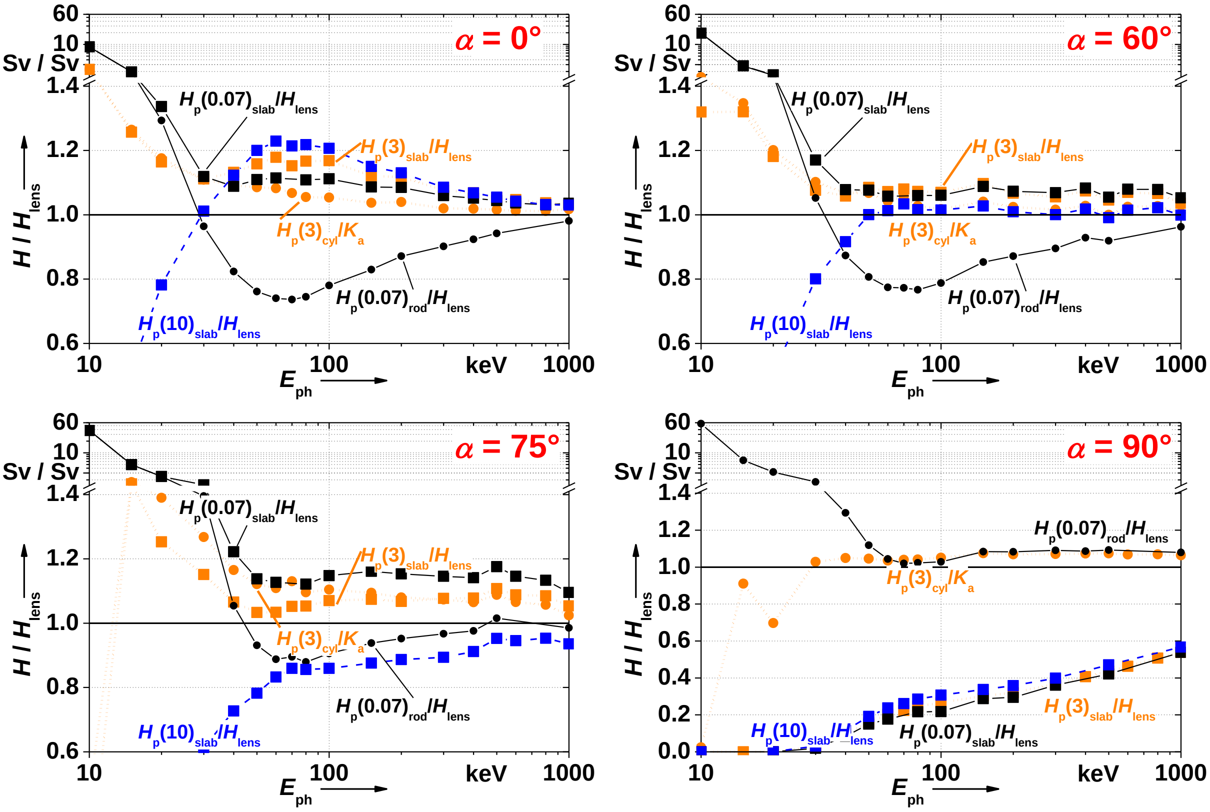

Figure 1. Ratio of dose equivalent quantities $H_p(d)$ and the eye lens dose, H_{lens}, depending on the photon energy for different angles of radiation incidence, see graphs. The ordinate has a linear scale below and a logarithmic scale above 1.4 Sv/Sv.

Figure 2 shows the ratio of different dose equivalent quantities within different calibration phantoms and the eye lens dose (based on the entire lens) depending on the electron energy for angles of incidence of $\alpha = 0°$, 45°, 60°, and 75°. For $\alpha = 90°$, data are only available for the operational quantity $H_p(3)_{cyl}$, therefore, no figure is given for that angle of incidence.

From the solid black curves it can be seen that $H_p(0.07)$ extremely overestimates H_{lens} at electron energies below about 2 MeV (up to several orders of magnitude below 1 MeV electron energy), again due to the absorption within the tissue in front of the eye lens.

Similar to photon radiation, the dashed blue curve shows that $H_p(10)$ underestimates H_{lens}, especially for low electron energies and at large angles of incidence.

Finally, the dotted orange curves show that the quantity $H_p(3)$ almost adequately estimates H_{lens} irrespective of the phantom used for its definition (slab or cylinder).

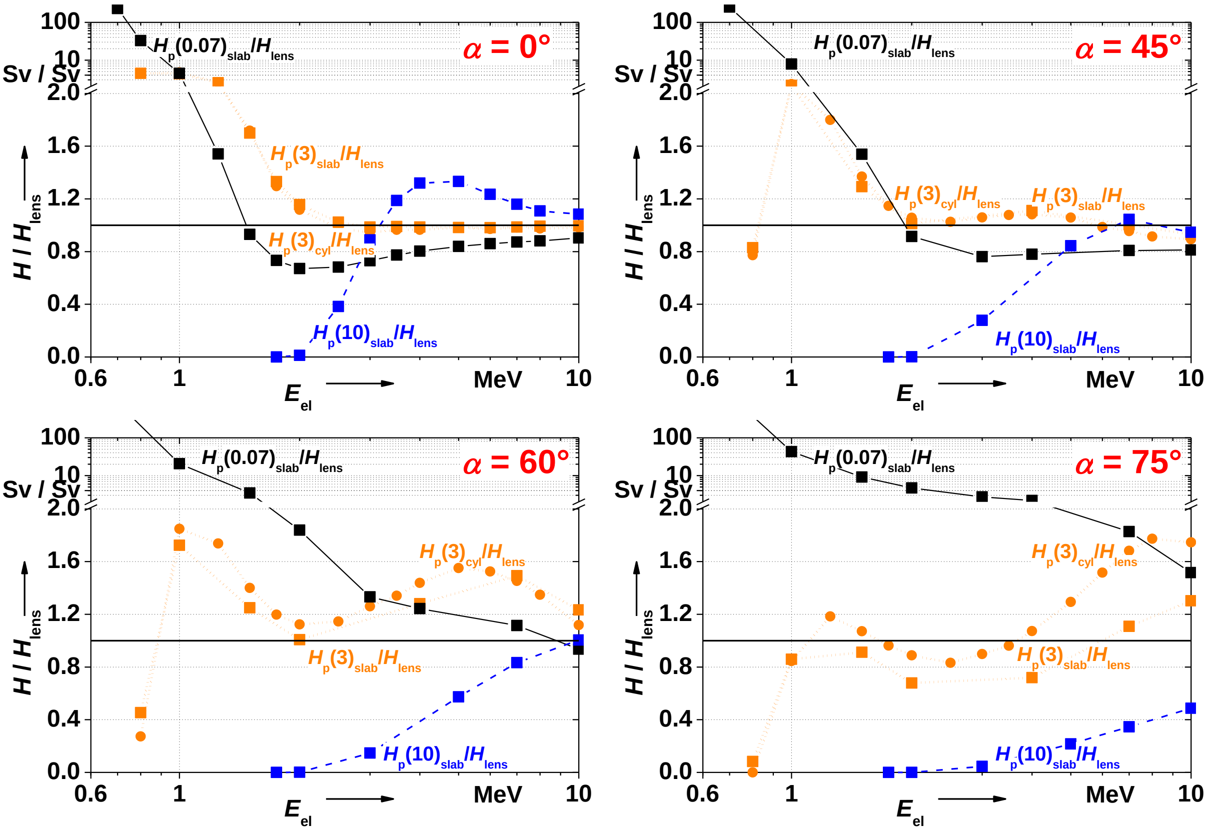

Figure 2. Ratio of dose equivalent quantities $H_p(d)$ and the eye lens dose, H_{lens}, based on the entire volume of the eye lens, depending on the electron energy for different angles of radiation incidence, see graphs. The ordinate has a linear scale below and a logarithmic scale above 2 Sv/Sv.

Figure 3 shows the ratio of different dose equivalent quantities within different calibration phantoms and the eye lens dose (based on the significant volume of the lens) depending on the electron energy for angles of incidence of $\alpha = 0°$, 45°, 60°, and 75°. In comparison to Figure 2 it is obvious that the main features for the quantities $H_p(0.07)$ and $H_p(10)$ are the same for both the eye lens dose based on the entire lens, H_{lens}, and the eye lens dose based on the significant volume of the lens, $H_{lens,s}$. However, the quantity $H_p(3)$ significantly underestimates the eye lens dose based on the significant volume of the lens, $H_{lens,s}$, for small electron energies with a stronger underestimation, the higher the angle of incidence α is. The reason is that the cell nuclei (the significant volume of the lens) are located on the front side of the lens (at a minimum of about 2.8 mm tissue equivalent material below the surface[3,4]) and, therefore, electrons with energies below about 2 MeV reach this part of the lens, but not its rear part. This energy region is of special importance as most beta-emitting radionuclides have their mean electron energy in this energy region. This demonstrates that the question of how to define the eye lens dose is much more important than the question which type of phantom should be used for the calibration in terms of $H_p(3)$ (slab or cylinder). Consequently, a quantity more conservative for eye lens dosimetry than $H_p(3)$ could be defined, e.g. $H_p(2.8)$ according to the minimum depth of the significant volume of the eye lens or even a smaller depth d could be chosen in order to assure conservativeness also at large angles of radiation incidence. However, this discussion is beyond the scope of this paper but is more appropriate within the International Commission on Radiation Units (ICRU).

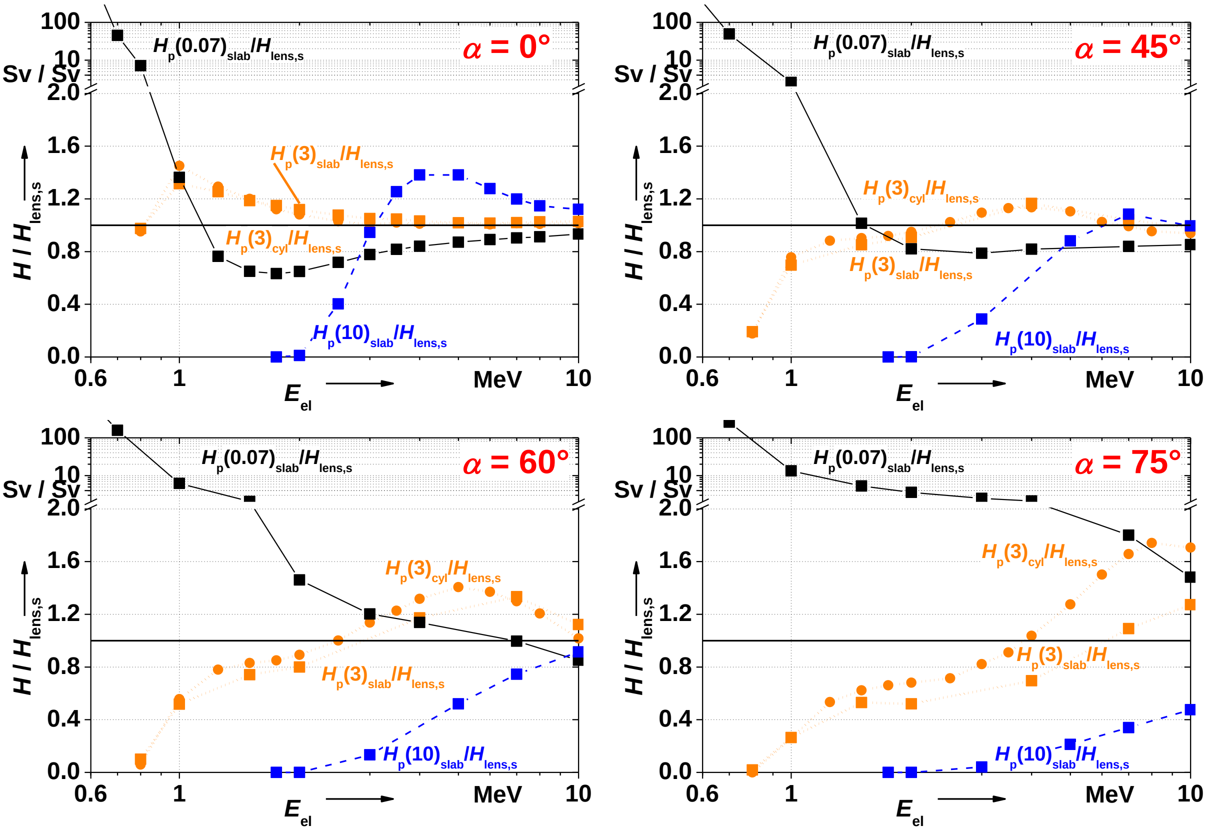

Figure 3. Ratio of dose equivalent quantities $H_p(d)$ and the eye lens dose, H_{lens}, based on the significant volume of the eye lens, depending on the electron energy for different angles of radiation incidence, see graphs. The ordinate has a linear scale below and a logarithmic scale above 2 Sv/Sv.

3.2 Summary of results

In pure photon radiation fields, e.g. in interventional radiology, $H_p(0.07)$ dosemeters are appropriate to monitor the lens dose when worn near the eye and if they detect radiation scattered back from the head (which is usually the case when their back consists of thin plastic). In beta radiation fields, e.g. in nuclear medicine, $H_p(0.07)$ dosemeters may overestimate the lens dose by a factor of 100 or more. Thus, they are unsuitable here.

$H_p(3)$ dosemeters are designed to monitor the lens dose, as the radiation-sensitive part of the lens (the significant volume) lies about 3 mm within the eye. Up to now, only very few $H_p(3)$ dosemeters exist, but, by construction, they should correctly monitor the lens dose also in beta fields. However, this has not yet been demonstrated. Appropriate recommendations for type tests of passive eye lens dosemeters measuring the quantity $H_p(3)$ are contained in a standard of the International Electrotechnical Commission (IEC): IEC 62387[15].

$H_p(10)$ dosemeters are designed to monitor the whole body dose as the inner organs are assumed to lie at least 10 mm within the trunk. $H_p(10)$ dosemeters usually underestimate the lens dose and are, therefore, unsuitable.

All these findings are also valid for realistic radiation fields as demonstrated earlier by Behrens and Dietze[16]. Once irradiations or calibrations should be performed in terms of $H_p(3)$, corresponding conversion coefficients for photon radiation qualities will be available for both the slab[17] and the cylinder phantom[18]; in addition, a secondary standard irradiation facility for beta radiation (BSS 2) was recently extended for the quantity $H_p(3)$[19].

4. Conclusions

In short, it can be said that in pure photon radiation fields, $H_p(0.07)$ dosemeters may be used when worn near the eye, in case beta radiation significantly contributes to the dose, $H_p(3)$ dosemeters are advisable. The question as to which type of calibration phantom, slab or cylinder, should be used for $H_p(3)$ dosemeters is not important compared to the question as to which part of the eye lens should be used to define the eye lens dose (the total volume of the eye lens as it has been up to now or only the radiation-sensitive volume, namely the significant volume). However, this discussion is beyond the scope of this paper and is more appropriate within the ICRP. Furthermore, the discussion on whether a new quantity, e.g. $H_p(2.8)$, or even a quantity with a smaller depth d, being conservative to the eye lens dose based on the significant volume of the lens should be defined or not is also beyond the scope of this paper and is more appropriate within the ICRU.

Regarding the question of which calibration phantom is to be used for eye lens dosemeters (irrespective whether for the quantity $H_p(3)$ or smaller depth d), it should also be kept in mind that the slab phantom is widely available and has been in use in many calibration laboratories for many years, whereas cylinder phantoms would have to be produced and bought by most calibration and testing laboratories

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