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2012 J. Radiol. Prot. 32 455

(http://iopscience.iop.org/0952-4746/32/4/455)

IOP PUBLISHING JOURNAL OF RADIOLOGICAL PROTECTION

J. Radiol. Prot. **32** (2012) 455–464 doi:10.1088/0952-4746/32/4/455

On the operational quantity $H_p(3)$ for eye lens dosimetry

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Received 9 July 2012, in final form 28 September 2012, accepted for publication 8 October 2012
Published 12 November 2012
Online at stacks.iop.org/JRP/32/455

Abstract
In the past the operational quantity $H_p(3)$ has been defined for calibration purposes in a slab phantom. Recently, an additional phantom in the form of a cylinder was suggested for eye lens dosimetry as a cylinder much better approximates the shape of a head than a slab. Therefore, this work investigates whether the quantity $H_p(3)$, when defined in the respective calibration phantom, adequately estimates the eye lens dose (or is at least conservative) depending on the phantom: it turns out that in most cases both calibration phantoms are similarly well suited. Finally, the definition of the eye lens dose is discussed together with possible consequences on the definition of $H_p(3)$: the consideration of only the radiation sensitive volume of the lens causes $H_p(3)$ not to be conservative in beta radiation fields.

1. Introduction

Monitoring of the eye lens may become more important than in the past in order to make sure that the new annual dose limit of 20 mSv recommended by the ICRP [1] is not exceeded. The appropriate operational dose quantities to monitor the eye lens are the personal and directional dose equivalents at 3 mm depth, $H_p(3)$ and $H'(3, \Omega)$, respectively [2, 3]. For mono-energetic photon radiation no conversion coefficients from air kerma to $H'(3, \Omega)$ are available; therefore, in this paper only $H_p(3)$ is considered, although in the future also $H'(3, \Omega)$ may be important for area monitoring.

In the past, for $H_p(3)$ a slab phantom has been recommended, made of ICRU tissue for the calculation of conversion coefficients [2] and made of water-filled polymethyl methacrylate (PMMA) for calibrations [4]. However, a short time ago a cylinder phantom was suggested as it much better approximates the shape of a human head—again made of ICRU tissue for the calculation of conversion coefficients and made of water-filled PMMA for calibrations [5–8]. In this work the following question is investigated: which phantom, slab or cylinder, when

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used for calibration and type testing, leads to a more adequate $H_p(3)$ to estimate the eye lens dose, H_{lens}, and which one leads to an at least conservative $H_p(3)$ (i.e. larger than H_{lens})? This question is answered by comparing the corresponding conversion coefficients from fluence and air kerma for electrons and photons, respectively; i.e. for electrons $h_{p\Phi}(3) = H_p(3)/\Phi$ and $h_{lens\Phi} = H_{lens}/\Phi$ are compared and for photons $h_{pK}(3) = H_p(3)/K_a$ and $h_{lensK} = H_{lens}/K_a$ are compared[1]. As this comparison is made for both types of calibration phantom, the slab and the cylinder, the corresponding quantities are denoted by the indices 'slab' and 'cyl', respectively: for electrons $h_{p\Phi}(3)_{slab} = H_p(3)_{slab}/\Phi$ and $h_{p\Phi}(3)_{cyl} = H_p(3)_{cyl}/\Phi$ and for photons $h_{pK}(3)_{slab} = H_p(3)_{slab}/K_a$ and $h_{pK}(3)_{cyl} = H_p(3)_{cyl}/K_a$.

Neutron radiation is not discussed in this paper as, in neutron dosimetry, usually the measurement of the whole body dose estimates the eye lens dose sufficiently well [9].

2. Materials and methods

2.1. General method

An ideal dosemeter for the quantity $H_p(3)$ always indicates the correct value in arbitrary radiation fields and is consequently represented by the corresponding conversion coefficient from air kerma and fluence for photons and electrons, respectively: $h_{pK}(3)$ and $h_{p\Phi}(3)$. Accordingly, the equivalent dose to the eye lens, H_{lens}, is represented by the corresponding conversion coefficient from air kerma and fluence for photons and electrons, respectively: $h_{lensK}(3)$ and $h_{lens\Phi}(3)$. To answer the question of whether an operational quantity is suited to adequately estimate the eye lens dose the corresponding conversion coefficients are compared with each other for mono-energetic photons and electrons.

2.2. Overview of available conversion coefficients

Data for the slab phantom: for mono-energetic photon radiation no internationally agreed conversion coefficients from air kerma to $H_p(3)$ and $H'(3, \Omega)$ are available; however, values for $H_p(3)$ can be found in the literature [10]. For mono-energetic electrons, internationally agreed conversion coefficients from fluence to $H_p(3)$ and $H'(3, \Omega)$ have long been available [11]; these data were calculated for the ICRU slab phantom but are (according to the ICRU) assumed to be equivalent to both $H_p(3)$ and $H'(3, \Omega)$, see paragraphs (268) and (269) in ICRP 74. For x and gamma radiation qualities according to the standard ISO 4037 [12] conversion coefficients have recently been published [13].

Data for the cylinder phantom: up to now, no internationally agreed data are available but conversion coefficients to $H_p(3)$ for mono-energetic photons and electrons are available [14–16] as well as values for x and gamma radiation qualities [17].

2.3. Photon radiation: method and data base

The conversion coefficients from air kerma to $H_p(3)_{slab}$ and $H_p(3)_{cyl}$ are compared with the conversion coefficients from air kerma to H_{lens}. The data were taken from Till *et al* [10] for $h_{pK}(3)_{slab}$, from Vanhavere *et al* [14] for $h_{pK}(3)_{cyl}$, and from ICRP Publication 116 [18] for

[1] This is equivalent to comparing the quantities themselves as the denominator is in both cases the same: Φ for electrons and K_a for photons.

h_{lensK} for angles of incidence of $\alpha = 0°$ (AP geometry), 90° (LAT geometry) and 180° (PA geometry), and for other values of α from Behrens and Dietze [19][2,3].

2.4. Electron radiation: method and data base

The conversion coefficients from fluence to $H_p(3)_{slab}$ and $H_p(3)_{cyl}$ are compared with the conversion coefficients from fluence to H_{lens}. The data were taken from ICRP Publication 74 [11] for $h_{p\Phi}(3)_{slab}$, from Ferrari and Gualdrini [16] for $h_{p\Phi}(3)_{cyl}$, and from ICRP Publication 116 [18] for $h_{lens\Phi}$ for angles of incidence of $\alpha = 0°$ (AP geometry) and 180° (PA geometry), and for other values of α from Behrens [21].

3. Results

3.1. Photon radiation

3.1.1. Comparison of quantities. For this comparison, the respective conversion coefficients from air kerma to the different quantities, $h_{pK}(3)_{slab}$, $h_{pK}(3)_{cyl}$ and h_{lensK}, are shown in figure 1 for mono-energetic photons (filled symbols; the half-open symbols are explained below in section 3.3). Conservatism occurs when the conversion coefficient to the operational quantity is larger than the conversion coefficient to the eye lens dose.

Observations for photon energies below about 1–2 MeV are as follows.

- Firstly, it can be seen in figure 1 that for $\alpha \leq 75°$ the values for both the slab and the cylinder phantom are conservative, and that $H_p(3)$ based on the cylinder phantom slightly better approximates H_{lens}.
- Secondly, figure 1 ($\alpha = 90°$) clearly reveals the effect that the slab phantom produces an extreme angular dependence around $\alpha = 90°$ as, at this angle of incidence, 15 cm of ICRU tissue lies between the phantom surface and the point of definition of the operational quantity $H_p(d)_{slab}$. This is the case for all depths d (0.07, 3 and 10 mm). Of course, this behaviour does not describe the angular dependence of the eye lens dose, H_{lens}, which is much better estimated by $H_p(3)_{cyl}$, as can clearly be seen in figure 1. However, this strong angular dependence is present for all values of d. Therefore, no type tests have been performed in the past at $\alpha = 90°$ for $H_p(0.07)$ and $H_p(10)$; another reason is that no internationally agreed conversion coefficients are available in ICRP Publication 74 [11] but only in the literature [10]. However, such type tests could be necessary for dosemeters for $H_p(3)$ according to typical workplace situations in interventional radiology [14].
- For the sake of completeness, figure 1 also gives the data for $\alpha > 90°$ up to $\alpha = 180°$. It can be seen that the values for the cylinder phantom are closer to the eye lens dose than those for the slab phantom except for $\alpha > 150°$.
- Finally, data for rotational geometry are shown for a rotation from $\alpha = 0°$ up to $\pm 75°$, $\pm 90°$and $\pm 180°$. It can be seen that for all three ranges both $H_p(3)_{slab}$ and $H_p(3)_{cyl}$ adequately estimate the eye lens dose. These geometries represent a person moving in a

[2] The data of Behrens and Dietze served (besides others) as input for ICRP Publication 116.

[3] Photon data for the lens dose are given in ICRP 116 and in Behrens and Dietze in terms of absorbed dose per fluence, D/Φ, and equivalent dose per fluence, H/Φ, respectively. The conversion from absorbed dose to equivalent dose is trivial for photons and electrons: $H = D \times 1$ Sv/Gy; the subsequent division of the dose per fluence, H/Φ, by the kerma factor, K_a/Φ, leads to the conversion coefficient from air kerma to equivalent dose: $h_{lensK} = (H/\Phi)/(K_a/\Phi) = (H/\Phi)/(\mu_{en}/\rho)E$, with the energy absorption coefficient of air for photons, (μ_{en}/ρ), taken from Hubbell and Seltzer [20] and with the photon energy E.

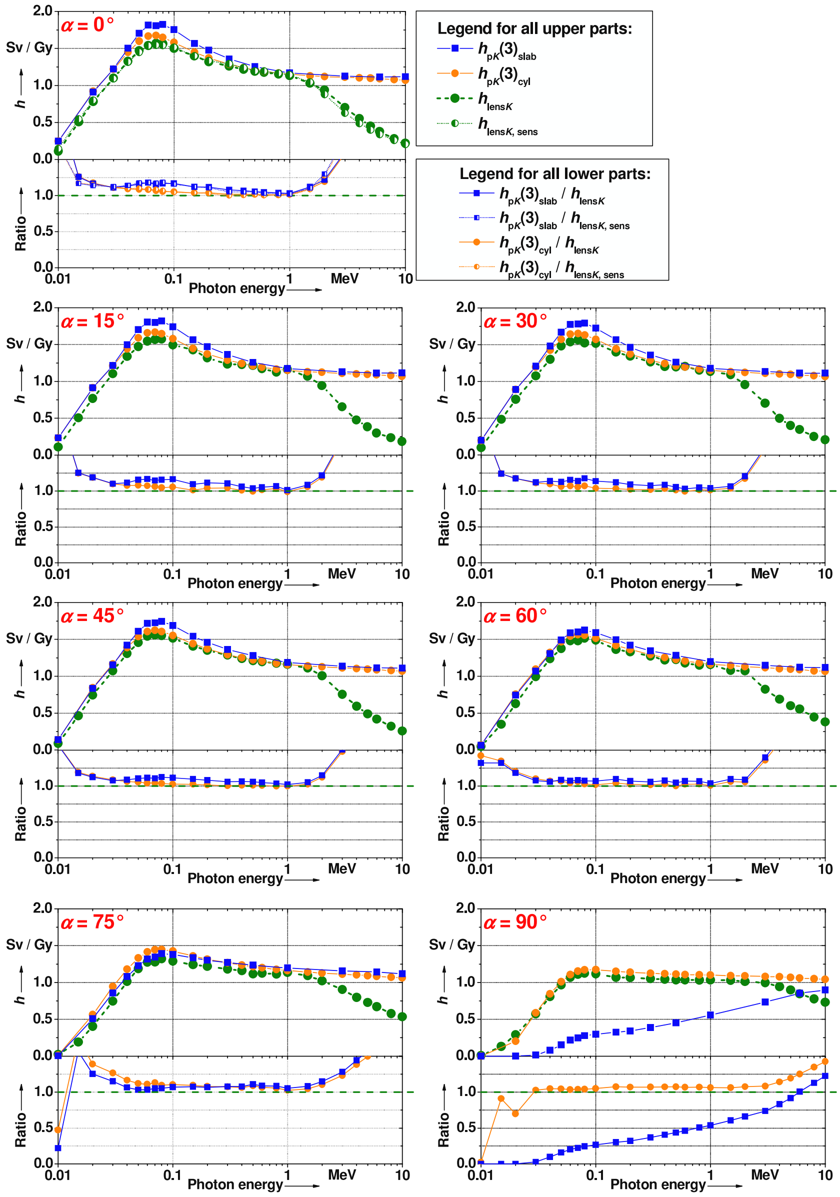

Figure 1. Conversion coefficients from air kerma to the quantity $H_p(3)$ for the slab phantom and the cylinder phantom (representing the performance of an ideal dosemeter for the respective operational quantity) in comparison with the respective value for the eye lens dose for photon radiation as defined in [18]. In addition, the values relative to the eye lens dose are given in the lower parts of the figures: ratios larger/smaller than unity represent conservative/non-conservative quantities, respectively. The filled symbols represent data for the lens dose calculated for the complete eye lens, H_{lens}, and the half-open symbols relate to the lens dose calculated for the radiation sensitive cells of the lens, $H_{lens,sens}$ (the latter only at a 0° angle of radiation incidence).

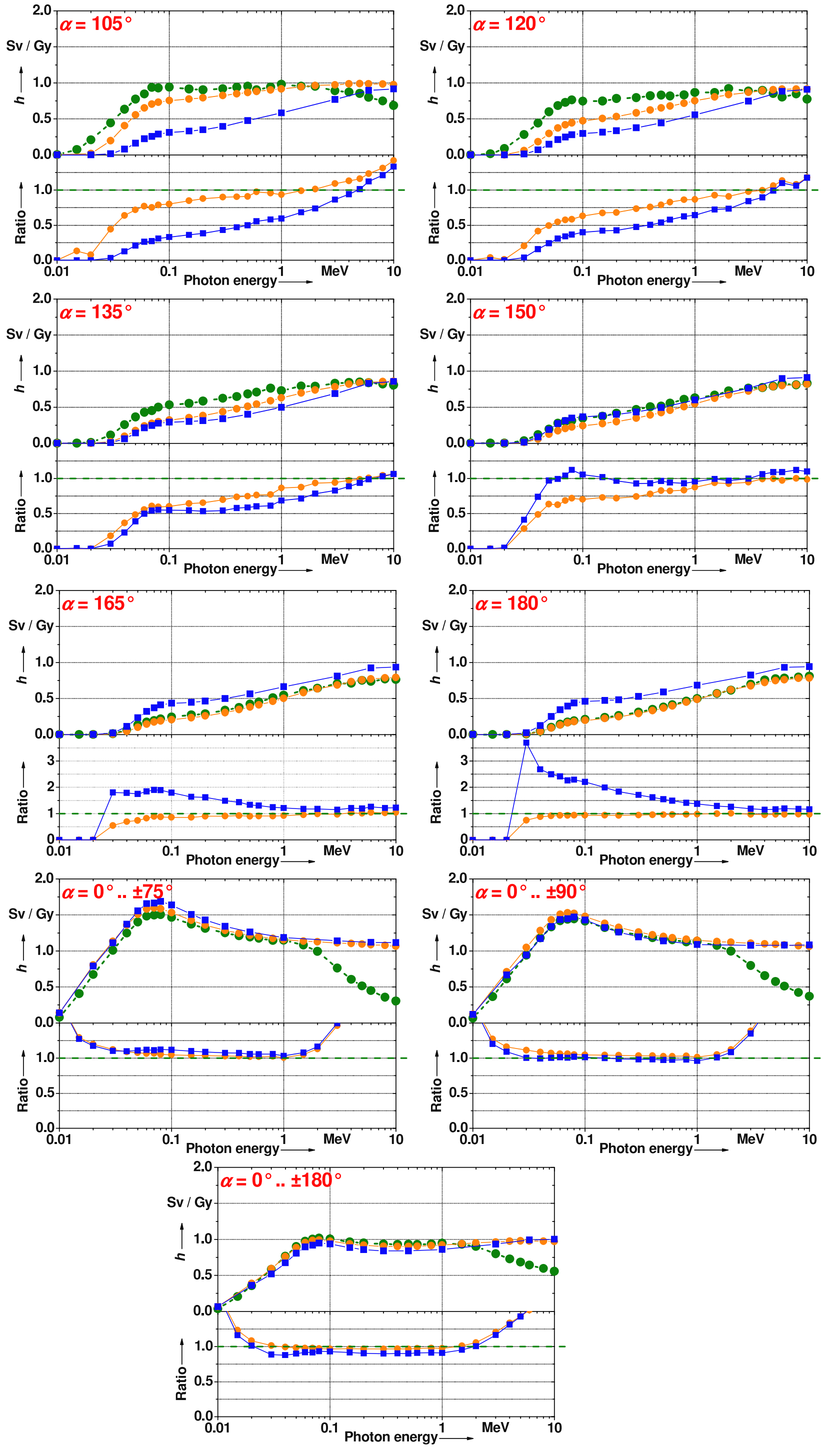

Figure 1. (Continued.)

radiation field or working in different radiation fields within a monitoring period (usually one month).

Observations for photon energies above about 1–2 MeV are as follows.

- Except for very large angles of radiation incidence ($\alpha \geq 120°$), the eye lens dose is strongly overestimated by $H_p(3)_{slab}$ and $H_p(3)_{cyl}$. The reason is that h_{lensK} was calculated with full electron transport (i.e. no kerma-approximation) [18, 19] while $h_{pK}(3)_{slab}$ and $h_{pK}(3)_{cyl}$ were calculated without any electron transport (kerma-approximation) [8, 10]. The consequence is that for energetic photons the dose build-up in the eye lens is not complete (resulting in the smaller values of h_{lensK} the higher the photon energy is), while the results of the kerma-approximation yield doses as if the dose build-up were complete (resulting in values of $h_{pK}(3)_{slab}$ and $h_{pK}(3)_{cyl}$ almost independent of the photon energy). In real radiation fields the values of h_{lensK} (i.e. the real eye lens dose) are assumed to be larger than the given ones, as photons are usually accompanied by secondary electrons (at least some), while the values of $h_{pK}(3)_{slab}$ and $h_{pK}(3)_{cyl}$ (i.e. the indications of dosemeters) are assumed to be smaller than the given ones, as the dosemeters' housings are not thick enough to complete the dose build-up. As a consequence it is assumed that in real radiation fields similar characteristics are valid for energetic photons to those described above for photons with energies below about 1–2 MeV.

3.1.2. Summary for photon radiation. In summary, it can be said for photon radiation that for calibrations ($\alpha = 0°$) and for type tests up to $\alpha \leq 75°$ both types of phantom are nearly equally well suited ($H_p(3)_{cyl}$ slightly better estimates the lens dose), whereas at larger angles of incidence the cylinder phantom is clearly superior to the slab phantom. For rotational geometries only minor differences occur and both $H_p(3)_{cyl}$ and $H_p(3)_{slab}$ appropriately estimate the lens dose. Thus, in cases where type tests are also performed for $\alpha > 75°$, the cylinder phantom is necessary.

Finally, some practical considerations are given. Some situations may occur where a person is mainly exposed from one side ($\alpha = 90°$) during the complete monitoring period, for example, one month. In these cases, $H_p(3)_{cyl}$ is the only choice to adequately estimate the lens dose if the dosemeter is worn pointing in the forward direction. However, all dosemeters must be worn on the representative part of the body which would, in such cases, be the side from which the radiation impinges on the person. In this case the radiation comes from in front of the dosemeter and, therefore, $H_p(3)_{slab}$ will adequately estimate the eye lens dose and could consequently be used. In addition, real dosemeters for $H_p(3)_{slab}$ will better estimate the lens dose than $H_p(3)_{slab}$ at $\alpha = 90°$ as their housing will be much thinner than the 15 cm material as present in the slab phantom in the 90° direction. This should be investigated in a separate study by irradiating real dosemeters on slab and cylinder phantoms and comparing the results with the corresponding eye lens doses. The same arguments apply for the inverse situation: the dosemeter is worn on the side of the head (90° position), but the radiation impinges from the front. However, of course, the more appropriate way is to use $H_p(3)_{cyl}$ if type tests at $\alpha \geq 90°$ are considered to be necessary.

3.2. Electron radiation

3.2.1. Comparison of quantities. For this comparison, the respective conversion coefficients from fluence to the different quantities, $h_{pK}(3)_{slab}$, $h_{pK}(3)_{cyl}$ and h_{lensK}, are shown in figure 2 (filled symbols; the half-open symbols are explained in section 3.3).

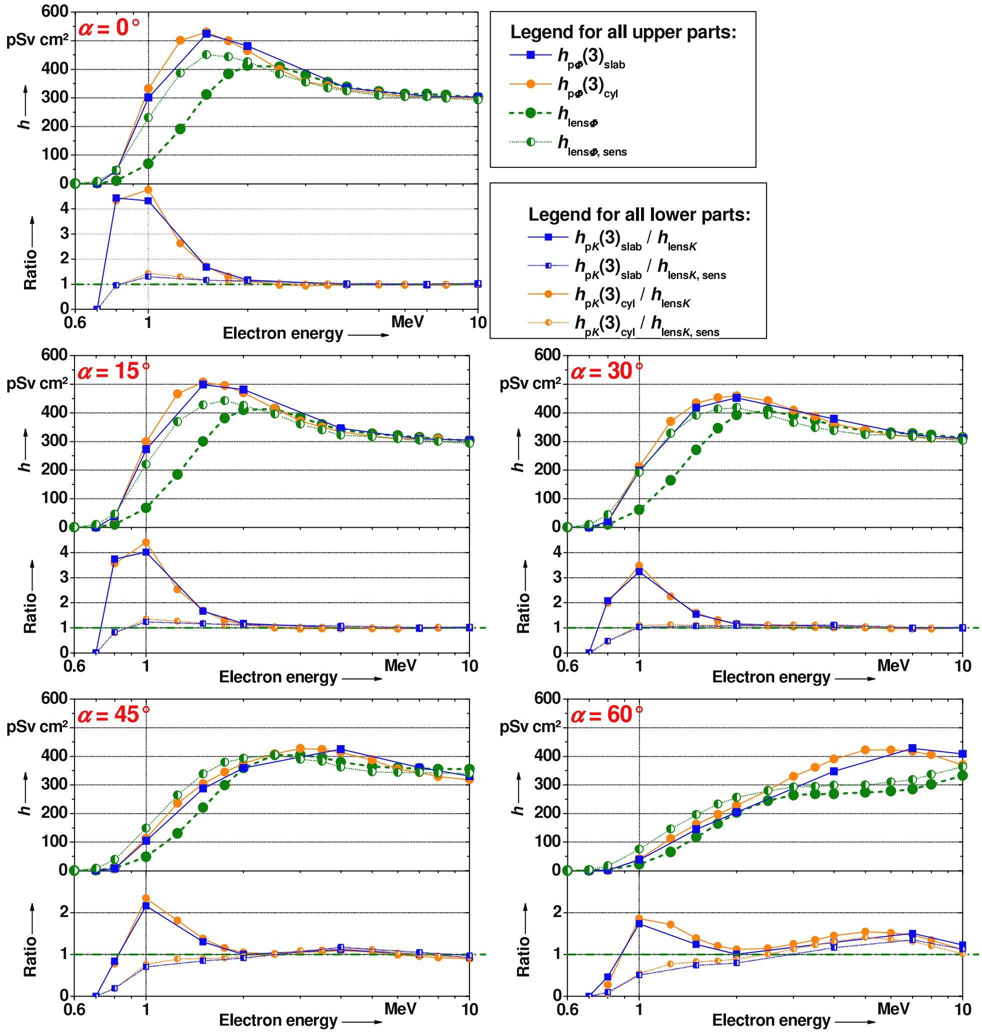

Figure 2. Conversion coefficients from fluence to the quantity $H_p(3)$ for the slab phantom and the cylinder phantom (representing the performance of an ideal dosemeter for the respective operational quantity) in comparison with the respective value for the eye lens dose for electron radiation as defined in [18]. In addition, the values relative to the eye lens dose are given in the lower parts of the figures: ratios larger/smaller than unity represent conservative/non-conservative quantities, respectively. The filled symbols represent data for the lens dose calculated for the complete eye lens, H_{lens} (as for photons), and the half-open symbols relate to the lens dose calculated for the radiation sensitive cells of the lens, $H_{lens,sens}$.

It can be seen in figure 2 that for $\alpha \leq 60°$ the values for both the slab and the cylinder phantom are conservative. In addition, figure 2 shows that for $\alpha = 75°$ the values for both phantoms are quite similar but slightly underestimate the eye lens dose (about 20% and 30% for the cylinder and the slab phantom, respectively). Here, it must be kept in mind that most beta dosemeters for H_p (0.07) only perform well at $\alpha \leq 60°$. Values for $\alpha = 90°$ are not available for $H_p(3)_{slab}$, but it is obvious that $H_p(3)_{cyl}$ strongly underestimates the eye lens dose, and this is expected to be the case even more extremely for $H_p(3)_{slab}$ (due to the edge effect described in

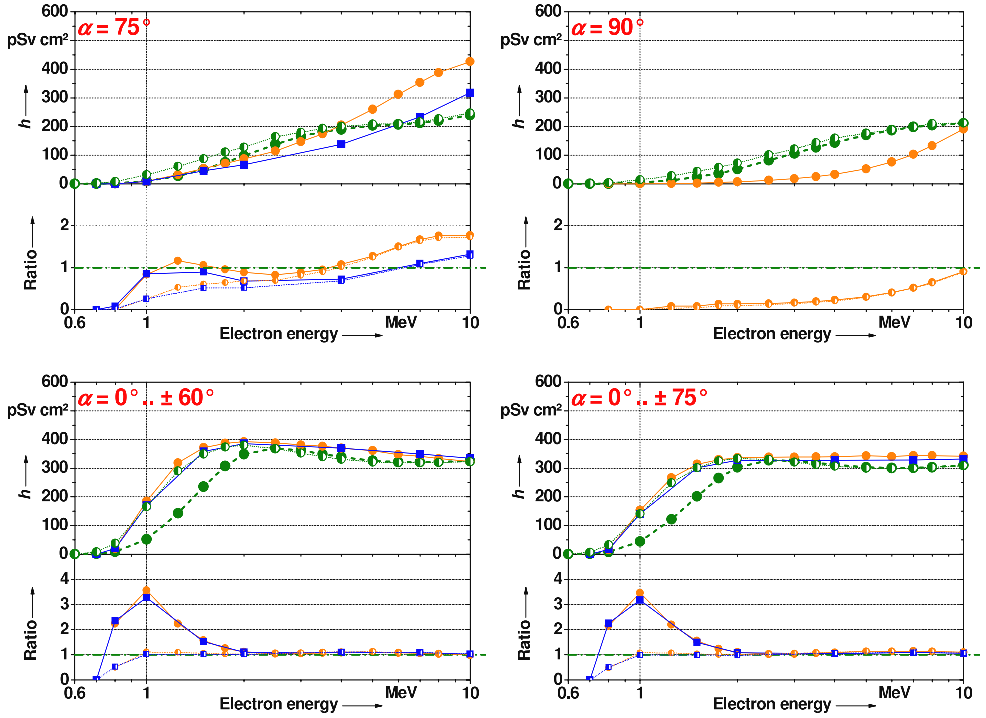

Figure 2. (Continued.)

section 3.1). Values for $\alpha \geq 90°$ are not available for $H_p(3)$ for either type of phantom, therefore no comparison is possible here.

Finally, data for rotational geometry are shown for a rotation from $\alpha = 0°$ up to $\pm 60°$ and $\pm 75°$. The data are quite similar to those for $\alpha = 30°$, namely both $H_p(3)_{cyl}$ and $H_p(3)_{slab}$ adequately estimate the eye lens dose and are conservative.

3.2.2. Summary for electron radiation. In summary, it can be said for electron radiation that for the angular range relevant for calibration ($\alpha = 0°$) and for type tests up to $\alpha \leq 60°$ both types of phantom are equally well suited for use. This is also the case for rotational geometries up to $\pm 75°$.

3.3. Eye lens dose definition and $H_p(3)$

Up to now, the equivalent dose to an organ has been based on the absorbed dose averaged over the complete organ [18]. However, it is well known that there are strong differences of sensitivity to ionising radiation exposure with respect to cataract induction within the eye lens [22]. This is of special importance for weakly penetrating radiation, such as electrons and photons of low energy, as strong dose gradients occur within the eye lens. Therefore, in figures 1 and 2, data for the lens dose are not only shown for the complete lens (filled symbols, $h_{\text{lens}\Phi}$) but also for the radiation sensitive region of the eye lens (half-open symbols, $h_{\text{lens}\Phi,\text{sens}}$); the respective data are contained in the same publications as the values for the complete lens [19, 21]. In figure 1 it can be seen that $H_{\text{lens,sens}}$ is quite similar to H_{lens} for photon radiation for $\alpha = 0°$ (this is also the case for other values of α), whereas figure 2 reveals strong differences for electrons. Here, $H_{\text{lens,sens}}$ is only estimated adequately by $H_p(3)$ at electron energies above

1 MeV and for $\alpha \leq 45°$. For smaller energies and larger angles of radiation incidence, $H_{\text{lens,sens}}$ is strongly underestimated by $H_p(3)$. The reason is that the front part of the eye lens (where the radiation sensitive cells are located) is covered by less than 3 mm of tissue. This situation would be improved by selecting a reference depth smaller than 3 mm ($d < 3$ mm), leading to an operational quantity $H_p(d < 3)$. This demonstrates that further discussion is needed about whether the complete lens or only the radiation sensitive region is taken as the basis for the determination of the lens dose. This discussion is beyond the scope of this paper but is currently occurring within the ICRP, see paragraph (F3) in [18].

4. Discussion and conclusions

The comparison of the lens dose and the operational quantity $H_p(3)$ reveals the following.

- For calibration (at normal radiation incidence) and type testing of photon and electron dosemeters in terms of $H_p(3)$ up to 75° radiation incidence, the definition of $H_p(3)$ in a cylinder phantom has only small advantages (about 10% over response) compared with the definition of $H_p(3)$ in a slab phantom (about 20% over response).
- The definition of $H_p(3)$ in a cylinder phantom has a strong advantage at 90° radiation incidence compared with definition of $H_p(3)$ in a slab phantom, as $H_p(3)_{\text{cyl}}$ quite adequately estimates the eye lens dose for photons, whereas $H_p(3)_{\text{slab}}$ strongly underestimates H_{lens}. However, this is expected to be practically relevant only in a very limited number of cases, namely in cases where the radiation is coming only from the left and the right ($\alpha = \pm 90°$) during most of the monitoring period (usually one month). Once the radiation impinges from different directions (rotational geometry) both $H_p(3)_{\text{cyl}}$ and $H_p(3)_{\text{slab}}$ are appropriate (for both photons and electrons). Once the radiation impinges only from one side (left or right) it is possible to wear the dosemeter facing the radiation source leading to $\alpha = 0°$ (where again both $H_p(3)_{\text{cyl}}$ and $H_p(3)_{\text{slab}}$ are appropriate).
- At angles of radiation incidence larger than 90° the definition of $H_p(3)$ in a cylinder phantom is also clearly superior to the definition in a slab phantom. However, it is assumed that only in a very limited number of cases will type tests at angles larger than 90° become necessary.
- More important than the choice of reference phantom is the question which part of the eye lens should be considered for the definition of the equivalent dose to the lens. If only the radiation sensitive part of the lens served as the basis for the lens dose, the reference depth of 3 mm would be too large, resulting in the necessity to implement a quantity $H_p(d < 3)$. As mentioned earlier, this topic is currently under discussion within the ICRP.

Acknowledgment

The author wishes to thank Peter Ambrosi from PTB for his valuable contributions to the manuscript.

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