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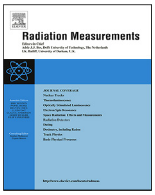

Development of an improved dosemeter for assessments of risk to the eye

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HIGHLIGHTS

- A programme of re-optimization of the current PHE eye dosemeter has been performed.
- A design featuring a truncated hemispherical filter was found to be optimal.
- The shape of the filter better resembles the rotational profile of the eye.
- Response characteristics depend on the calibration conditions taken to provide the best risk estimate.

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ABSTRACT

To develop an improved dosemeter to assess photon and beta exposures of the eye lens, and in response to issues surrounding the preferred values of H_{lens} to be used for guiding operational radiation protection, a programme of re-optimization of the current PHE thermoluminescence dosemeter has been performed. In particular, refinements of the filter located in front of the sensitive ^{7}LiF:Mg,Cu,P element have been considered, so that the dose response characteristics of the device provide a better and more conservative estimate of risk. The investigation was performed using the Monte Carlo modelling software MCNP5, to produce a final design that featured a filter containing a 9.5 mm diameter polypropylene hemisphere truncated to a maximum thickness of 3.0 mm. The responses of this design in photon and electron fields are presented here, contrasted against those of the existing PHE eye dosemeter, with respect to the operational quantity $H_{\text{p}}(3,E,\theta)$ and both current and suggested values for the absorbed dose per fluence risk profile for the lens of the eye.

1. Introduction

In response to updated advice from the International Commission on Radiological Protection (ICRP) regarding the risk to the eye from exposure to ionizing radiation (ICRP 2007; ICRP 2012), the Personal Dosimetry Service (PDS) of Public Health England (PHE) supplies a thermoluminescence dosemeter (TLD) that can estimate doses accrued in the lens of the eye from photons and electrons (Gilvin et al., 2013; Eakins et al., 2013). The dosemeter is intended to be worn by persons occupationally exposed to beta or low-energy photon sources, and is designed to provide accurate measurements of personal dose equivalent, $H_{\text{p}}(d)$, at a depth, d, of 3 mm, which is the currently recommended quantity for eye dosimetry. The PHE TLD device comprises a Harshaw EXTRAD™ 'chipstrate' card covered by a composite filter that is approximately equivalent to 3 mm of tissue. The EXTRAD™ features a ^{7}LiF:Mg,Cu,P 'disc' of cross-sectional area 0.18 cm^{2} and mass-thickness 0.007 g cm^{-2}, which constitutes the sensitive region of the TLD, encased in 0.0165 cm of 1.42 g cm^{-3} Kapton®. The filter comprises a 0.15 cm thick slab of 2.2 g cm^{-3} polytetrafluoroethylene (PTFE) and a 0.01 g cm^{-2} layer of polyvinylchloride (PVC), which forms part of the band by which the dosemeter is secured to the wearer's head. The PTFE slab is approximately 2.4 cm × 0.9 cm in lateral extent and, when the dosemeter is worn with the longest edge horizontal and is viewed from face-on, the TL-element is centred ~0.6 cm from its right-hand edge.

Recent work, however, has proposed that the currently accepted values (ICRP, 2010) for assessing equivalent dose to the eye lens, H_{lens}, do not provide a sufficiently conservative estimate of the risk of cataract induction, and that a value of $d = 3$ mm might not be the optimum depth of tissue for personal dose equivalent (Behrens et al., 2009; Behrens, 2012). Specifically, the suggestion is that the

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sensitive region of the eye is located at shallower depths than the mean depth of the whole lens, upon which the recommended value of 3 mm is based. This issue will be of greatest significance for exposures at low energies, E, and high angles of incidence, θ. Moreover, calculating personal dose equivalent, $H_p(3,E,\theta)$, at a depth of 3 mm in a large slab (or cylinder) of ICRU 4-element tissue might not be considered the most accurate approach for estimating the risk to the lens, because the eye has much greater curvature. In particular, at an exposure angle of θ ($<90°$) the total thickness of material in front of the eye's sensitive region may be much less than $3/\cos(\theta)$ mm.

In an effort to develop an improved device for eye lens dosimetry, a programme of re-optimization of the dosemeter has been performed. Specifically, refinements of the filter have been investigated so that the energy- and angle-dependent dose response characteristics of the device better match the suggested risk coefficients for the eye (Behrens, 2012). The results obtained are presented here, with the responses of both the current and proposed dosemeter designs compared with respect to the operational quantity $H_p(3,E,\theta)$, the presently accepted values for $H_{lens}(E,\theta)$, and the recently advocated risk estimate $H_{sensitive}(E,\theta)$.

2. Methodology

The re-optimization process was achieved using the general-purpose Monte Carlo radiation transport code MCNP5 (X-5, 2005). Various trial designs of dosemeter were modelled. Each dosemeter was located on a water-filled right-cylindrical phantom of radius 10 cm and height 20 cm, which may be considered an acceptable calibration surrogate for an adult human's head (Gualdrini et al., 2011). The overall arrangement was surrounded by vacuum, and was exposed to sets of plane-parallel, monoenergetic electron (1–4 MeV) or photon (20–662 keV, with the latter taken to represent ^{137}Cs) fields, as well as an equal-proportion distribution of 1173 and 1333 keV photons corresponding to a ^{60}Co source. The general method for assessing each trial design was to calculate absorbed dose per fluence data for the ^{7}LiF:Mg,Cu,P element and compare them against the available conversion coefficients appropriate for that source, as detailed in the next section; for the present purposes, an improved design was taken to be one that gave a closer match to the $H_{sensitive}(E,\theta)$ per fluence data.

In the calculations that featured electron sources, the modelling was performed in the full coupled electron-photon transport mode of MCNP, with dose absorption in the ^{7}LiF:Mg,Cu,P element determined using a '**f8:p,e*' pulse-height tally, which accounts for bulk energy deposition in a microscopically realistic way. For the photon source calculations, however, the more computationally-efficient photon-only transport mode was used, with absorbed doses estimated via MCNP '*f6:p*' track-length tallies. The use of the kerma approximation was assumed valid because in the real-world analogues of the exposure conditions being modelled, sufficient air build-up would likely be present between the source and TLD element to produce secondary charged particle equilibrium; in addition, a comparison of **f8:p,e* versus *f6:p* results from photon-only and preliminary electron-photon mode simulations using a 20 keV photon source, for which differences between kerma factors can be large (Hubbell and Seltzer, 1995), found equality to within a few percent. A scaling factor was also required in the photon source calculations to correct the tallied doses for the intrinsic light-conversion efficiency of the ^{7}LiF:Mg,Cu,P material. To this end, an energy-dependent efficiency function, $\eta'(E)$, was applied that was derived by interpolating data determined in previous work on Harshaw TLD-700H ^{7}LiF:Mg,Cu,P material, where Monte Carlo and measured data were compared for ^{137}Cs, ^{60}Co and ISO Narrow Series X-ray fields (Eakins et al., 2007). The values of $\eta'(E)$ used are given in Table 1. For the electron sources, a thermoluminescence efficiency of unity was assumed. In all cases, the doses calculated were normalized to the fluences applied, which were estimated by 'voiding' all materials within the model and defining an MCNP '*f4*' fluence tally on the volume that formerly represented the ^{7}LiF:Mg,Cu,P element.

Table 1
Relative light conversion efficiency, $\eta'(E)$, for photon exposures of ^{7}LiF:Mg,Cu,P.

Energy (keV)	$\eta'(E)$	Energy (keV)	$\eta'(E)$
20	0.730	100	0.725
30	0.766	110	0.738
40	0.778	150	0.798
50	0.764	200	0.857
60	0.732	300	0.910
70	0.716	662	1.00
80	0.711	1253	1.01
90	0.716		

In general, the calculations were performed using default options to control the simulation. Exceptions to this for the electron-source calculations were the use of the Landau energy-straggling logic, which is considered the most accurate option currently available in MCNP5 (X-5, 2005), and the forcing of appropriately small electron 'substeps' to ensure correct simulation of particle trajectories through the thinnest cells in the configuration.

3. Conversion coefficients

As stated earlier, the performances of the dosemeters were appraised by comparing their energy- and angle-dependent response characteristics against the various risk profiles suggested for the eye, i.e. the relevant conversion coefficients. The choice of appropriate conversion coefficient data was not always trivial, however, in part because currently neither values for the operational quantity $H_p(3,E,\theta)$, nor a preferred calibration phantom, are recommended by the International Commission on Radiation Units and Measurements (ICRU) or the International Organization for Standardization (ISO).

For photons above 20 keV, $H_p(3,E,\theta)$ conversion coefficients were taken from the work of Daures et al. (2009), see also Gualdrini et al. (2013), calculated using the kerma approximation for a 20 cm high, 20 cm diameter right-cylindrical phantom composed of ICRU 4-element tissue; an additional datapoint at 10 keV for $\theta = 0°$ was also provided from Daures et al. (2011). For $H_{lens}(E,\theta)$ for photons, conversion coefficients were taken from ICRP 116 (ICRP, 2010). For $H_{sensitive}(E,\theta)$ for photons, conversion coefficients were taken from the work of Behrens and Dietze, (2011). Conversion coefficients for the ^{137}Cs and ^{60}Co sources are not provided in these references for any of the dose quantities; for these sources, values were therefore generated by linearly interpolating the available tabulated data. No $H_{lens}(E,\theta)$ or $H_{sensitive}(E,\theta)$ data are available at exposure angles (θ) between 0° (i.e. anterior-posterior, AP) and 90° (i.e. lateral). However, a comparison with $H_{lens}(E,\theta)$ and $H_{sensitive}(E,\theta)$ per fluence data shows that $H_p(3,E,\theta)$ is the limiting case at 0° in the energy range from 20 to 1253 keV, and from 30 keV at 90° (Fig. 1): in these ranges, a device calibrated in terms of $H_p(3,E,\theta)$ will always provide a conservative estimate of the protection quantities. Moreover, within these ranges the values of the three dose quantities are fairly similar. It may hence be inferred that a TLD device that responds well in terms of $H_p(3,E,\theta)$ may be a adequate estimator of $H_{lens}(E,\theta)$ and $H_{sensitive}(E,\theta)$, for photon exposures at angles up to 90°, in all but very low-energy photon fields.

For electrons, $H_p(3,E,\theta)$ conversion coefficient data were taken from the work of Ferrari and Gualdrini, (2012), calculated using the

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