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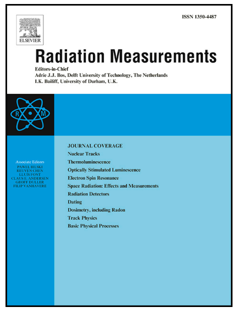

3D-printed eye lens dosemeter holder for use in interventional radiology and interventional cardiology

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3D-printed eye lens dosemeter holder for use in Interventional Radiology and Interventional Cardiology

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Abstract

Mandatory eye lens monitoring for exposed workers who are liable to receive an equivalent dose to the lens of the eye higher than 15 mSv in one year, required by the new European Basic Safety Standard 2013/59 and the recommendation given by the International Commission on Radiological Protection to lower the annual dose limit for the lens of the eye to 20 mSv, have put dosimetry services using Panasonic dosemeters in a difficult position. There are no commercially available eye lens dosemeter holders to fit Panasonic TLD pellets. Therefore, we designed and 3D printed inexpensive, splash proof, reusable and comfortable holders to fit a Panasonic $^{n}Li_2{}^{n}B_4O_7$:Cu pellet. The eye lens dosemeter consists of an acrylonitrile butadiene styrene (ABS) plastic holder with a slot for a TLD pellet. The slot with the TLD pellet is covered by a heat-shrink tube and shortly heated with hot air to shrink wrap. Results of combined energy/angular

response measurements, for all photon radiation qualities used, relative to N-100 at 0˚ as the reference energy, were within IEC 62387:2012 limits. Additionally, electron spin resonance spectroscopy was used to test the effect of irradiation to the degradation properties of the plastic ABS holder. The dosemeter is to be worn fixed to a headband, close to the eye, on the left side of the head or in the middle of the forehead.

Keywords: Eye lens dosimetry, *H*p(3), $Li_2B_4O_7$, eye lens dosemeter holder, personal dosimetry

1. Introduction

The lens of the eye is one of the most radiosensitive organs in the body (Ainsbury et al., 2009). Cataracts are a condition in which eye lens opacity occurs and has been documented as an ocular complication associated with exposure to ionising radiation (Chodick et. al., 2008). Besides ionizing radiation, there are many risk factors for cataracts such as age, exposure to sunlight, alcohol and nicotine consumption, diabetes and use of corticosteroids (Ainsbury et al., 2009). The research in the first decade of this century has indicated that radiation-associated opacities of the lens of the eye occur at lower doses than previously stated (Ainsbury et al., 2009; Shore et al., 2010). In light of new research data, the International Commission on Radiological Protection (ICRP) has reduced the annual dose limit for the equivalent dose to the lens of the eye from 150 mSv to 20 mSv (20 mSv/y, averaged over 5 years, with no single year exceeding 50 mSv) (ICRP, 2011, 2012). The International Atomic Energy Agency (IAEA) also recommends to monitor the eye lens dose for exposed workers who work in non-uniform radiation fields (IAEA, 2014). Occupational exposures to the lens of the eye may occur in nuclear power plants, research or industrial facilities and medicine (Hoedlmoser et.al. 2019 and the references cited therein). During interventional radiology (IR) and interventional cardiology (IC) procedures, the medical staff and the patients experience prolonged exposure to non-uniform radiation fields. In such procedures, physicians and other medical personnel remain close to patients and are exposed to high levels of scattered radiation up to several hours a day (Vano et al., 2009, Vano et al., 2010). Some of the highest occupational doses in medicine are received by physicians (interventional radiologists and cardiologists) performing fluoroscopically guided interventions (Vano et al., 2010). In the ICRP Publication 139 (ICRP, 2018), it was suggested that in IR or IC practices when protective glasses are not worn, the use of collar dosemeter placed over the protective apron on the side adjacent to the x-ray tube is only an indicator of the eye dose. Therefore, it is recommended to improve the accuracy of the measurement by wearing an eye dosemeter adjacent to the most exposed eye. A number of studies (Efstathopoulos et al., 2011; Ishii et al., 2019; Principi et al., 2014; Vanhavere et al., 2012) have investigated the position where an eye dosemeter should be worn, in situations when no eye protection (protective glasses, ceiling-suspended screens, etc.) is used. The evaluated positions were the left eyebrow ridge or the middle of the forehead. The overall conclusion is that the optimum position strongly depends on the procedure and practice of the operator. A recently published study (Ishii et al., 2019) suggested that the placement of the dosemeter on the left side of the head, near the eye, provides good estimates for physicians, and the forehead position is more suitable to monitoring nurses. Furthermore, the new European Basic Safety Standard 2013/59 (European Council Directive) requires mandatory eye lens monitoring for exposed workers liable to receive an equivalent dose for the lens of the eye higher than 15 mSv in one year. The aforementioned requirements and recommendations have put dosimetry services using Panasonic dosemeters in a difficult position. There were and there still are no commercially available inexpensive eye lens dosemeter holders that could fit a single Panasonic thermoluminescent dosemeter (TLD) pellet. Panasonic single

TLD pellets are comprising a thin layer of $Li_2B_4O_7$:Cu crystals, a highly sensitive TL material with an effective atomic number Z_{eff}=7.3 very close to that of soft biological tissue (Z_{eff}=7.4) (Yamamoto et al., 1982; Prokić, 2002). There is one model recently developed by Dosilab AG, Switzerland, described in the literature (Hoedlmoser et al., 2019), but it requires the use of an ultrasonic welding device to seal the dosemeter, which is not affordable for small dosimetry services, and the holder is not reusable. Therefore, we designed and 3D printed an inexpensive, splash proof and reusable holder to fit Panasonic $Li_2B_4O_7$:Cu and other manufacturers' single dosemeter elements. 3D printing technology has rapidly advanced and has entered into various fields due to developments in technology and affordable prices. In medicine, 3D printing of personalized medical devices, implants and external prostheses has been applied and finds many applications in medical imaging (Squelch, 2018). The main aim of this study was to investigate the adequacy of such in-house produced dosemeters to perform reliable Hp(3) measurements for photon fields. In order to examine the possible effect of irradiation on the degradation process in the acrylonitrile butadiene styrene (ABS) plastic holders, electron spin resonance (ESR) spectroscopy has been used as it is a widespread and well established technique for the study of intrinsic properties of polymers, as well radiation-induced changes, especially in cases when the sensitivity of other analytical methods is not sufficient (IAEA, 2016; Naveed et al., 2018).

2. Materials and methods

2.1. Design of the new dosemeter

The new eye lens dosemeter holder consists of an ABS (produced by XYZ printing) or ABS+ (produced by Devil Design) plastic printed on a 3D printer model da Vinci 1.0 Pro. ABS or ABS+ is a common plastic polymer typically used for injection moulding applications and is very popular as a filament for 3D printing, with a density of 1.04 g/cm^3 (water equivalent material). The design of the holder was inspired by the EYE-D™ dosemeter developed in frame of the FP7 ORAMED project (Bilski et al.,2011). The dosemeter holders are designed to be placed next to the left eye (model L) or in the middle of the forehead (model F), as presented in Fig. 1. The holder is attached to a headband and could be worn under radiation protection glasses or visors, if there is enough space to allow the comfortable use of these devices.

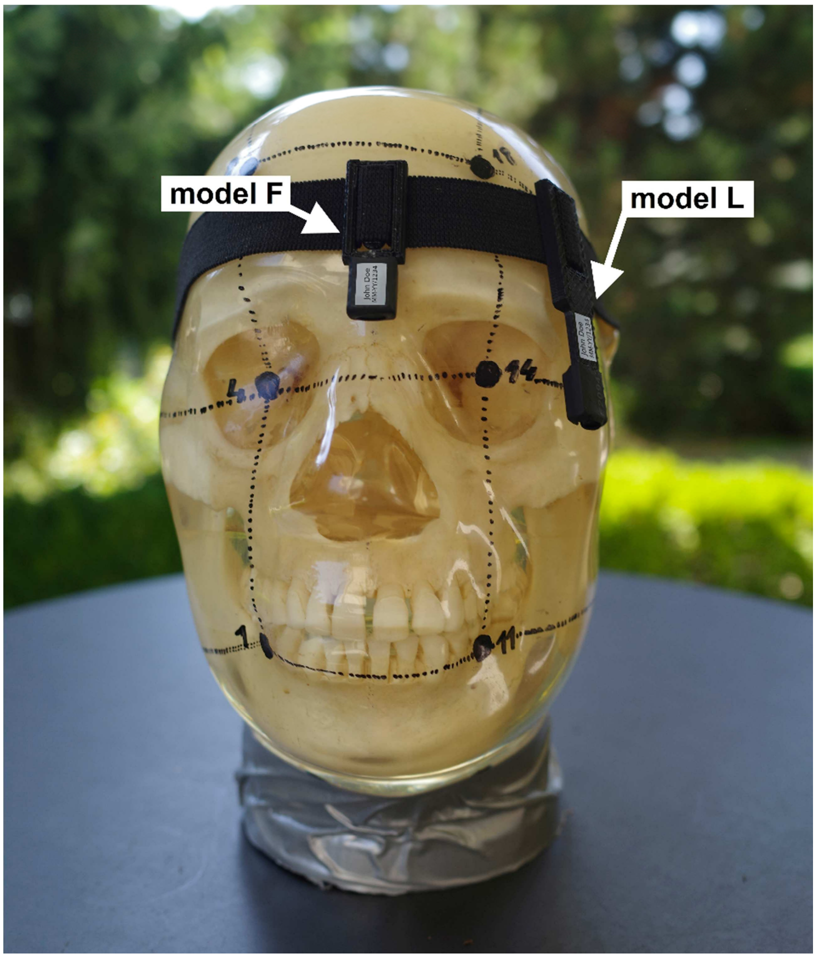

Figure 1: Wearing position of the eye lens dosemeter: model L is to be placed next to the left eye; model F in the middle of the forehead. The label is on the front side of the dosemeter, ensuring correct orientation

Both versions of the holders have an equal quadratic slot for a TLD pellet. The final thickness of the detector slot was chosen as an optimal after evaluation of the energy/angular response of the irradiated prototypes with different thicknesses. Thus, the holder has 2.9 mm front, 1 mm vertical and 1.5 mm horizontal side thickness (Fig. 2). A quadratic slot was chosen rather than a circular one and horizontal sides were made thicker (1.5 mm) to achieve better seal with heat shrink tubing whose function is explained later in text. The quadratic shape also enables use of tweezers for handling pellets, while thicker horizontal sides have an additional important function of increasing the structural strength of the slot. The prototype selection phase is briefly described in the section 2.2.

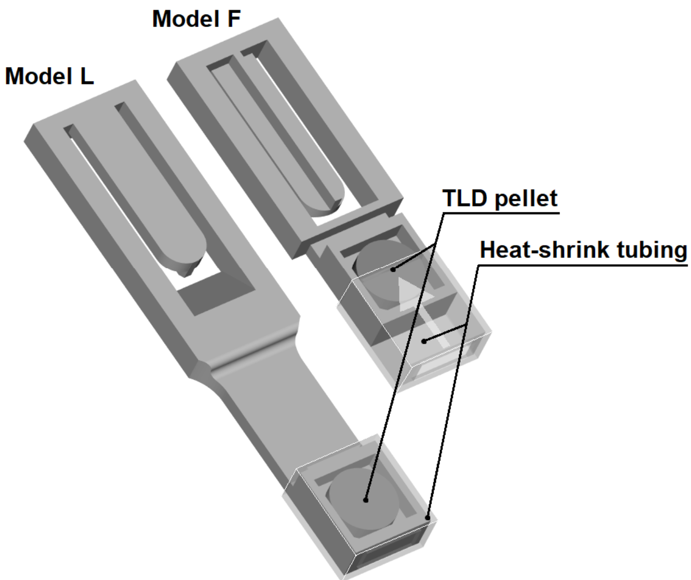

Figure 2: Design of two eye lens dosemeter holder models of, heat-shrink tubing encloses the TLD pellet area

After insertion of the pellet, the slot part was covered by a black widely available heat-shrink tube made of polyolefine and shortly heated with hot air to shrink wrap. Shrink tubing holds pellet in place and provides splash resistance. The thickness of the heat shrink tubing is 0.3 mm so the overall thickness is 3.2 mm (front side), 1.3 mm (sides) and 0.3 mm (head side - only heat-shrink tubing). The label with personal identification and measurement period is pasted on the front side of the dosemeter, additionally ensuring the correct orientation of the dosemeter. In these measurements, we used a single Panasonic UD-807ATN thermoluminiscent (TL) element. The UD-807ATN TL element is producer's name for a single TL pellet containing a mono-layer of $Li_2B_4O_7$:Cu phosphor formed on a substrate polyimide monomers as a binder. On the opposite side of the polyimide film there is a thin carbon layer to increase the absorbancy for irradiation. A transparent Teflon FEP film covers the phosphor layer to keep out the dust, moisture, etc. (Yamamoto et al., 1982). The total thickness of the layers on the front side is 11 mg/cm^2 and that of the back side is 22 mg/cm^2. The $Li_2B_4O_7$:Cu TL pellet is usually used as a detector in plastic ring dosemeters to measure Hp(0.07) for extremity monitoring or as a first and a second element of a 4-element Panasonic whole body dosemeter, but with different added filtration (Yamamoto et al., 1982, Panasonic, 2011). For photon radiation, the personal dose equivalent *H*p(0.07) is also an appropriate dose quantity for monitoring the eye lens (Behrens et.al. 2012b; Behrens and Dietze, 2011). However, for *H*p(3) measurements an extra absorption material should be added due to the thin $Li_2B_4O_7$:Cu phosphor layer (15 mg/cm^2) of the Panasonic UD-807ATN TL element (Yamamoto et al., 1982; Hoedlmoser et al., 2019). Panasonic $^nLi_2{}^nB_4O_7$:Cu TL phosphor is a tissue equivalent (Z_{eff}=7,3) TL material with quite a horizontal energy response and well-documented characteristics (Otto et al., 2010; Panasonic, 2011; Prokić, 2002; Takenaga et al., 1983; Yamamoto et al., 1982). The manufacturer provided type testing data for its whole body dosemeter (commercial name UD-802AT) containing two identical $^nLi_2{}^nB_4O_7$:Cu TL elements and two identical $CaSO_4$:Tm elements for energy discrimination, but with different front and back filtration among particular TL elements (Panasonic, 2011). In the type testing report and reference cited therein, it is stated that the dosemeter output is linear with exposure to 10 Sv, with a stable response up to 7000 irradiations, the residual signal is less than 0.1 % of the previous exposure, the dosemeter is not light sensitive and requires extremes of humidity 90 % at 25˚C for 2-6 months to cause a 10 % loss of signal. These characteristics are a function of the detector technology and are not to be affected by the dosemeter's housing.

2.2. Calibration procedure

Due to limited funds available to our small dosimetry laboratory (we supply around 2000 dosemeters per month), we decided to test the dominant effect of the holder on the dosemeter performance - combined energy and angular response. During the design process we produced prototype holders with various front thicknesses from 1.5 mm to 3.0 mm. The final thickness of the detector slot was chosen as an optimal after evaluation of the energy/angular response of the irradiated prototypes. The prototypes were irradiated with X-ray qualities using the same protocol, described later in the text, as for the final prototype. Thinner prototypes had significant under response at all energies tested.

The combined energy and angular response of the new holder with a single Panasonic UD-807ATN TL element to photon radiation were tested at the Secondary Standard Dosimetry Laboratory of the Ruđer Bošković Institute, Zagreb, Croatia (RBI-SSDL) and the Secondary Standard Dosimetry Laboratory of Institute Jožef Stefan, Ljubljana, Slovenia (IJS-SSDL). The testing was performed using a cylinder phantom with a 20 cm diameter and 20 cm height, water-filled plate of polymethyl methacrylate (PMMA) walls (Gualdrini et al., 2011), developed within the ORAMED project (ORAMED, 2008). Irradiations were performed within photon energy range from 24.6 keV to 661.7 keV for the following available narrow beam radiation qualities: N-30, N-60, N-80, N-100 as a reference, N-120, N-150 and S-Cs, defined in the ISO 4037-1:1996 standard (ISO, 1996), at angles 0˚, 60˚ and 75˚ (due to bilateral symmetry of the dosemeter). Irradiation with energies lower than N-30 were not available in both SSDLs. The source to dosemeter distance was 2 m for S-Cs and 2.5 m for all used narrow beam radiation qualities (EVS-ISO 4037-3:2019). During irradiations with a ^{137}Cs source, a 3 mm build-up plate of PMMA, positioned directly in front of the dosemeters perpendicular to incident beam direction for all irradiation angles, was used to establish a secondary electron equilibrium (ISO, 1996; Behrens et al., 2009). Applied conversion coefficients $h_{pK}(3;R,\alpha)_{cyl}$ from air kerma to *H*p(3) for different *R* and angles of incidence in Sv/Gy were taken from literature (Behrens, 2012a). The reference air kerma rate values for the S-Cs at a defined irradiation distance were measured with the secondary standard TW 30002, 1 l, ionisation chamber traceable to the IAEA (RBI-SSDL). The reference air kerma rate values for the X-ray irradiation at a defined irradiation distance were measured with the secondary standard LS-01, 1 l, ionisation chamber traceable to MKEH Hungary (IJS-SSDL). The combined uncertainty at 95% confidence level, k=2 coverage factor, for air kerma rate is 2.86 % for S-Cs (RBI-SSDL) and 5 % for N radiation qualities (IJS-SSDL). The standard uncertainty of the $h_{pK}(3;R,\alpha)_{cyl}$ is estimated to be less than 1% by R. Behrens (2012a) so this additional contribution was accounted for as an estimation of the measurement uncertainty at 95% confidence level for the used conversion factors (Behrens, 2012a; ISO 4037-3:2019).

A total of 84 dosemeters in groups of 4 were irradiated in 21 separate irradiations with a *H*p(3) value of 2 mSv. The readout of the dosemeters was performed at the dosimetry service of the Institute for Medical Research and Occupational Health (IMROH) on a Panasonic UD-716 AGL 13-C TL dosemeter reader. The reader calibration factor $K_{Hp(3)}$ for *H*p(3) was applied since the reader was calibrated using internal parameters (Panasonic, 1993) for *H*p(10) measurements, due to the accreditation of the IMROH dosimetry laboratory for *H*p(10) measurements in compliance with the ISO/IEC 17025 standard. There were no corrections for energy/angle or fading applied.

2.3. Electron spin resonance spectroscopy testing

To examine the possible effect of irradiation on the stability of the ABS plastic holders, the ESR signals of irradiated ABS plastic holders were studied. The holders would be exposed to the same radiation as the end users. The samples were irradiated simultaneously with TL dosemeters under the same conditions. Afterwards, in order to simulate the repeated use in a realistic situation, samples were additionally irradiated to higher doses using the S-Cs source and the stability for doses up to 20 Gy was studied by ESR spectroscopy during 60 days. Continuous wave (CW) ESR spectra were recorded on a Varian E-109 X-band (≈9.5 GHz) spectrometer equipped with a Bruker ER 4111 VT variable-temperature unit with a flow of N_2 gas in the Laboratory for Magnetic Resonances of the Ruđer Bošković Institute (RBI). CW-ESR measurements were carried out with a magnetic field modulation amplitude of 0.1 mT and 100 kHz field modulation at room temperature. The concentration of radicals, intrinsic and radiation induced, was monitored before and after the irradiation process. The concentration was monitored every 7 days during monitored period of 60 days, after the exposure. A manganese standard reference, Mn^{2+} in MnO, was used to calibrate the magnetic field of the spectrometer.

3. Results and discussion

The *H*p(3) response values were corrected using element correction factors (ECFs) (Plato and Miklos, 1985). The ECF corrected dosemeter response values were normalized to reference radiation quality (ISO N-100 spectrum) at 0 degrees. The combined energy and angular response for the new eye dosemeter in terms of *H*p(3) for the ISO qualities used are given in Fig. 3.

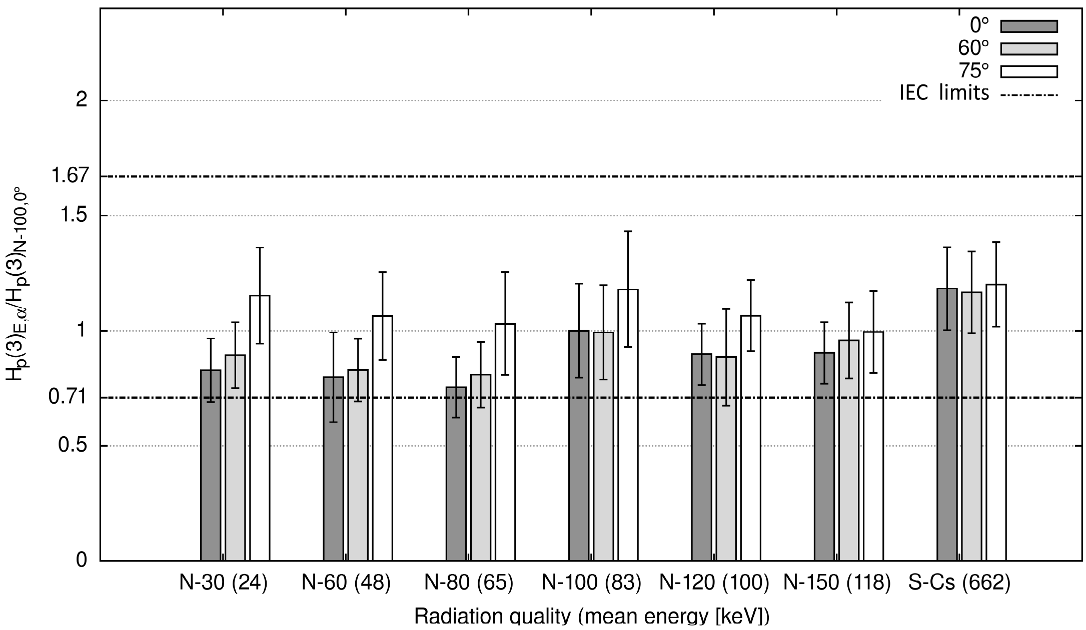

Figure 3: Measured combined energy and angular response for the new eye lens dosemeter with Panasonic UD-807ATN TL element, calibrated in terms of *H*p(3), relative to reference energy N-100 at 0˚. The arithmetic mean value and the standard deviation (error bars) of four dosemeters per irradiation are given. IEC 62387:2012 limits are indicated by dash-dot lines

The error bars in Fig. 3 represent a standard deviation from the mean normalized response dose values of four simultaneously irradiated dosemeters for each energy/angular combination. To evaluate whether the test results complied with the requirements laid down in the IEC 62387:2012 international standard (IEC, 2012), the corresponding limits 0.71≤relative response≤1.67 for energy/angular dependence are marked in the diagram. The measurement results have proven that the energy/angular response of the new home-made eye lens dosemeter with Panasonic UD-808ATN single TL element, for all radiation qualities tested, were within IEC 62387:2012 limits (IEC, 2012): 0.71 ≤ response ≤ 1.67. The angular/energy responses for angles higher than 0˚ confirm that the new holder is appropriately designed for photon irradiation. Although the Hp(0.07) energy response for $^{n}Li_2{}^{n}B_4O_7$:Cu TL element reported by Panasonic (Panasonic, 2011) shows an over response at 30 keV and below, due to the thinner absorber, the results for Hp(3) measurements presented here showed an under response at energies lower than reference energy (N-100). The similar energy response for *H*p(3) dosemeter using the same Pananasonic TLD pellet, developed by Dosilab, was reported by Hoedlmoser et.al. (2019), with N-150 as the reference energy. The under response of the dosemeter should be corrected by an energy/angular correction factor in the dose calculation algorithm. Energies tested (from N-30 up to N-150) generally cover all energies of interest in IR and IC.

The ESR spectra of non-irradiated and irradiated sample of ABS plastic holder did not show any change according to the energy and angular dependence. Furthermore, additional samples have been irradiated up to 20 Gy, to check the stability in the case of accidental overexposure. No ESR signal related to the radiation induced radicals was observed during the monitored period. ESR results confirmed that the degradation of the ABS plastic holder did not occur in the dose range for this kind of application. The results indicate the irradiation from these dose range did not influence the properties of the new holder. This confirms that TL element is protected under the same conditions and therefore the new holder is suitable for use in eye lens dosimetry in IR and IC.

4. Conclusion

The new 20 mSv/y dose limit and the requirements laid in the European Council Directive oblige dosimetry services to provide reliable eye lens dosimetry. 3D-printed eye lens dosemeters with a Panasonic UD-808ATN single TL element, designed at our laboratory, was tested for available photon radiation qualities at two SSDLs. Measurement results have proven that the energy/angular response of the new home-made eye lens dosemeter with $^{n}Li_2{}^{n}B_4O_7$:Cu TL phosphor, for all radiation qualities tested, were within IEC 62387:2012 limits (IEC, 2012): 0.71 ≤ response ≤ 1.67. Angular/energy relative responses for angles higher than 0˚ confirmed that the new holder is appropriately designed for photon irradiation in the range from 24.6 keV to 661 keV. Dose linearity of the new eye lens dosemeter was adopted from the literature (Otto et al., 2010; Panasonic, 2011; Prokić, 2002; Takenaga et al., 1983; Yamamoto et al., 1982), since dose linearity is a property of the detector and is not likely to be affected by the dosemeter's housing.

According to our results, the new dosemeter with a Panasonic UD-807ATN TL element is suitable for use in eye lens dosimetry in IR and IC for workers who do not use radiation protection glasses or visors. The new eye lens dosemeter can also be used under radiation protection glasses or visors depending on their spatial constraints. The dosemeter is to be worn fixed to a headband, close to an eye, on the side of the head (model L) or in the middle of the forehead (model F). The presented use of 3D printing technology can be an affordable solution for small dosimetry services using Panasonic dosemeters to resolve the legal requirements to provide eye lens dosimetry.

Future research will focus on further optimisations of design, calibration with beta sources and photon energies not used in these measurements (energies lower than N-30, and ^{60}Co). The part of the holder used to attach the holder to a head strap could be designed and modified to fit individual needs without affecting the slot for the detector.

This holder could be used with other detectors, but due to their different dosimetric properties further measurements are necessary, possible optimization of filtration and final verification have to be performed for each type of detector.

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Highlights

- an inexpensive and comfortable eye lens dosimeter holder can be 3D printed
- the 3D-printed holder fits a Panasonic TL single dosimeter element
- holders with $Li_2B_4O_7$ TLD are suitable for Hp(3) measurements in IR and IC
- properties of the ABS plastic are not affected by radiation in low range

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: