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New eye lens dosemeters for integration in radiation protection glasses

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Abstract

With the annual dose limit for the lens of the eye being lowered to 20 mSv from 2019, both new efforts to improve radiation protection for this part of the body and new approved dosemeters for official dose monitoring are required. The individual monitoring services at the Helmholtz Zentrum München and Dosilab AG, together with MAVIG, have developed a mechanical interface to integrate eye lens dosemeters into radiation protection glasses. MAVIG has designed a new type of radiation protection glasses featuring this dosemeter interface. The two individual monitoring services have independently developed two new types of eye lens dosemeters for the interface. The Munich solution for the eye lens dosemeter is a BeOSL dosemeter for photon radiation with a new detector element introduced by Dosimetrics GmbH in 2018. The Dosilab approach is based on a TLD dosemeter for photon and beta radiation. This work describes the concepts for radiation protection glasses and interface, the new dosemeters, and presents the performance characteristics of the dosemeters in accordance with IEC requirements.

Keywords
Eye Lens Dosemeters; Radiation Protection Glasses; BeOSL; ezClip; TLD;

Highlights

- A new type of RP glasses with 0.5 mm lead equivalent protection is introduced.
- A BeOSL eye lens dosemeter for photon radiation is characterized.
- A TLD eye lens dosemeter for photon and beta radiation is introduced.
- Dosemeters are integrated in the frame of the glasses behind the lead shielding.
- A standardized mechanical interface between dosemeter and RP glasses was introduced.

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1 Introduction

The individual monitoring service (IMS) at the Helmholtz Zentrum München (HMGU) is the largest dosimetry service in Germany and monitors approximately 170 000 customers per month by means of OSL-, film- and TLD-dosemeters. 10 000 customers per month are supplied with extremity dosemeters such as photon and beta rings. With the new European basic safety standard 2013/59 [1] being translated into national German law going into effect in 2019, the dose limit for the lens of the eye will be lowered to 20 mSv per year. Therefore, eye lens dose monitoring will become mandatory for some customers. Additionally, $H_p(3)$ is introduced as a new legal operational dose quantity in Germany. Consequently, the IMS is required by law to supply eye lens dosemeters (ELDs) calibrated in $H_p(3)$ for its customers. In order to provide eye lens dosimetry fulfilling both the requirements of the new regulations and the needs of the customers, the IMS has developed a new dosemeter. This dosemeter is intended to be integrated in personal safety equipment such as radiation protection (RP) glasses and visors. In particular, it is designed to fit into a new type of radiation protection glasses developed specifically for the purpose of eye lens dosimetry and protection together with MAVIG, a German manufacturer of RP equipment and Dosilab, the largest private IMS in Europe with headquarters in Switzerland.

The first section of this article provides a summary of the current situation in eye lens dosimetry, mentioning the most affected medical applications, for which a number of national and international studies indicate the necessity to monitor the eye lens dose. After a brief discussion of the operational dose quantity $H_p(3)$ the section concludes with the objectives set for the development of the new dosimetry system. In the second part of the paper a new type of RP glasses is presented with a dedicated solution [2] for the fixation of the dosemeters. Subsequently, a first solution for an ELD developed by the IMS in Munich for use with a BeOSL [3] detector element for extremity dosimetry [4] introduced by Dosimetrics is described. A second solution was developed by Dosilab based on the UD-807 TL dosemeter from Panasonic [5], which is widely used as extremity dosemeter. The performance characteristics of the dosemeters were obtained from radiological tests in preparation of the official type testing by the Swiss and German authorities, performed at the secondary standard irradiation facilities of the IMS in Munich.

2 Motivation for the development of dosemeters integrated in RP glasses

2.1 Relevance of eye lens dosimetry in medical applications

The introduction of the new limit for the eye lens dose is a consequence of the observation of an increased rate of occurrence of radiation-induced cataracts [6]-[10]. In the last few years a number of studies have investigated which medical or industrial work places are the most affected by the problem and if the new dose limit of 20 mSv is actually reached or even exceeded [11]-[20]. The studies have identified certain types of medical workplaces, such as

interventional radiology or cardiology, for which higher exposures of the lens of the eye are much more likely than for others, i.e. nuclear medicine. However, there is unfortunately no strict correlation between high exposures and a given workplace. Especially in radiology, the measured doses depend strongly on the individual experience of doctors and staff, the quality of the local radiation protection procedures, the used devices and structural radiation protection in their vicinity and on the use of personal radiation protection and safety equipment such as glasses or visors.
These individual factors lead to maximum doses increased by up to a factor of 100, even though average and most likely doses are well below the new dose limit. Generally, the dose limit should not be exceeded, if personal safety equipment, i.e. RP glasses are used and good radiation protection practice is followed in the clinical routine. The use of RP glasses in particular reduces the eye lens dose very efficiently. For photon radiation, lead glasses with 0.5 mm Pb equivalent shielding offer adequate protection, provided the shielding is close-fitting and extends beyond the glasses to cheekbones and temples[18], [21]. Additional shielding beyond 0.5 mm Pb equivalence does not effectively improve dose reduction due to a constant backscatter component of the head, but decreases wearing comfort due to weight. In other applications of radiation, such as nuclear energy, industry and research, much less evidence for higher eye lens doses has been found. If beta radiation occurs, it is very efficiently shielded by RP glasses or even by ordinary laboratory safety glasses in the case of low energy beta radiation.

2.2 Operational dosimetric quantity $H_p(3)$

In parallel to the studies concerning the prevalence of significant eye lens doses at work places the international radiation protection community has been working to develop the tools for eye lens dosimetry. The new operational radiation protection quantity $H_p(3)$ [22] was established and a new cylinder phantom was proposed in the ORAMED project [11] to be used in calibrations of ELDs with corresponding conversion coefficients [23], which have been introduced in the latest versions of the ISO 4037 standard [24]-[26]. Furthermore, requirements for ELDs have been included in IEC 62387 [27] and protocols and recommendations [29],[30],[31] for eye lens dosimetry have been published. As a possible alternative to dedicated ELDs worn on the head near the eye, alternate methods like dosimetry on the collar, or conversions of whole body dosemeter readings into eye lens dose by means of correction factors have been investigated. However, these methods are only useful in homogeneous fields and not generally recommended [29], as the most affected workplaces suffer from highly inhomogeneous radiation fields, e.g. in interventional radiology.
A dedicated ELD designed to measure $H_p(3)$, correctly estimates the dose to the lens of the eye for both beta and gamma radiation. However, it is important to note, that for photon radiation $H_p(0.07)$ is an appropriate measure for the eye lens dose as well [32][33]. This has also been confirmed by the first intercomparison exercises in eye lens dosimetry in Germany [34] and by EURADOS [35] in which $H_p(0.07)$ dosemeters performed well in photon fields. Those findings have implications for the optimization of an ELD intended for use

only in photon fields, as described below. Dosemeters such as EyeD™ [36] developed in the framework of the ORAMED study have been optimized for $H_p(3)$ and perform well both for photon and beta radiation. However, this dosemeter is not optimized for use as an official dosemeter, as the detector is not sufficiently protected from user interference and environmental influence factors under German regulations.

2.3 Objectives for the development of a new eye lens dosimetry system

Personnel in the medical sector are usually quite busy and under pressure while being required to satisfy many stipulations. Radiation protection may feel like one of the annoying duties. Therefore, it is of capital importance to support, educate and help the workers to protect themselves using safe and easy procedures. Based on the needs and requirements for eye lens dosimetry described above, the following objectives for the development of a new dosemeter have been defined:

- As the new dose limit is likely to be reached at the most affected work places, the most important issue for the affected staff is to actually ensure appropriate protection by means of RP glasses. Those using RP glasses should have the benefit of dosimetry for almost no extra effort. The primary target of new dosimetry concepts should therefore be an integration of dosemeters into RP glasses and to promote the use of such glasses.
- Monitoring of the eye lens dose needs to be performed at a well defined position close to the eye to produce comparable results. This is satisfied with a dosemeter integrated in RP glasses.
- A mechanical interface for the fixation of the dosemeter behind the lead shielding of the RP glasses has to be developed, that can be used with different types of existing and future passive dosemeters, which are lightweight and by far the best choice economically and technologically for eye lens dosimetry. The coupling between dosemeter housing and RP glasses should be standardized to ease access for other IMS.
- The mechanical interface and the new dosemeters should ensure that the wearing comfort is optimized. Therefore, the dosemeter should be small, thin, and sunken in the frame of the glasses.
- Adapters with the same mechanical interface should allow to upgrade older RP glasses or visors.
- The mechanical interface should not interfere with the incident radiation within the angular acceptance of the dosemeter.
- If possible, the dosemeter should be constructed symmetrically with regard to radiation incidence from the front and from the back to ensure equal response to direct radiation and backscatter from the head.

In addition to the objectives above, the IMS in Munich decided to develop its new BeOSL dosemeter only optimized for photon response for use in interventional radiology and cardiology. A beta optimized $H_p(3)$ dosemeter with equal forward and backward response would require a total thickness of approximately 5-6 mm of tissue equivalent material in the enclosure, thus creating problems for the integration in the frame of RP glasses or with wearing comfort. A photon only optimized version can be constructed much thinner, as theoretically even a $H_p(0.07)$ dosemeter is sufficient. While such a photon dosemeter suffers from an over response to high energy betas such as $^{90}Sr/^{90}Y$, this is not an issue inside the RP glasses as they absorb beta radiation and there is no backscatter from the head for beta radiation. Consequently, the dosemeter can also be used at workplaces in nuclear medicine or in nuclear energy, provided it is worn inside glasses or visors. In contrast, Dosilab decided to implement a solution, which is capable to correctly measure both gamma and beta radiation.

3 Development of dosemeter, interface and RP glasses

3.1 RP glasses

Typically, RP glasses are classified as personal protection equipment (PPE) class III [37] protection against ionizing radiation. Besides their main purpose as radiation protection device, RP glasses offer other features like any other type of glasses such as the correction of the refractive error. These requirements have been addressed accordingly, during the development of the new type of RP glasses. Unfortunately, previous findings indicate that some commercially available RP glasses lack lateral- or side protection against ionizing radiation [38]. This is due to the way interventional procedures are performed in daily routine. Unlike in other medical disciplines the physicians do not look mainly at the patient but instead at a monitor visualizing X-ray images or other patient related data. For this viewing angle X-rays scattered by the patient can enter the eye of the user without any protection [39]. In the development of the RP glasses this lack in radiation protection was improved by an increased lateral protection area. Figure 1 shows the new RP glasses (BR330). It is important to mention that the lateral radiation protection embedded in the frame overlaps with the leaded glasses. This new concept is realized for the first time in the design of BR330. Because of the increased protection area, BR330 weighs slightly more than other RP glasses (approx. 115 g without prescription). Independent of the RP glass type MAVIG recommends using a headband for wearing the RP glasses in order to provide better fixation to the user's head and avoid the risk of the glassed sliding off the nose of the wearer. The headband also improves wearing comfort.

Figure 1 Prototype BR330 radiation protection glasses.

To ensure an optimal fit of the glasses for each individual physician or user, nose pad and temples of BR330 can be adjusted to their needs. A key feature to do so is the joint between temple and front of BR330. The joint allows for a vertical rotation of the temples and as a consequence for a change in position of the BR330 front. In this way the gap between RP glass and user face can be reduced, leading to a further decrease in dose to the eye lens.
Likewise, hygiene, as one of the major topics in the medical field, was addressed with the BR330. The number of edges and cavities was reduced to a minimum, albeit the integrated dosemeter interface adds a new type of complexity to the RP glasses. Furthermore, the frame material was chosen to provide good mechanical properties and on the other hand to allow for easy cleaning and disinfection.

3.2 Mechanical interface

In addition to requirements described in section 2.3, the mechanical fixation of the dosemeter to the RP glasses has to facilitate a convenient periodic replacement (typically once a month) of the dosemeter with minimum effort. At the same time, the fixation has to be absolutely safe to prevent any loss during operations. The coupling was designed as an integral part of the new RP glasses in the form of a bayonet [2] – see Figure 2. While both the IMS at HMGU and Dosilab use different detector technologies, they access the same coupling via standardized detector housing geometries. This synergy enables cross exchange of RP glasses and dosemeter technologies with a minimum of investment for IMS and for RP equipment manufacturing.

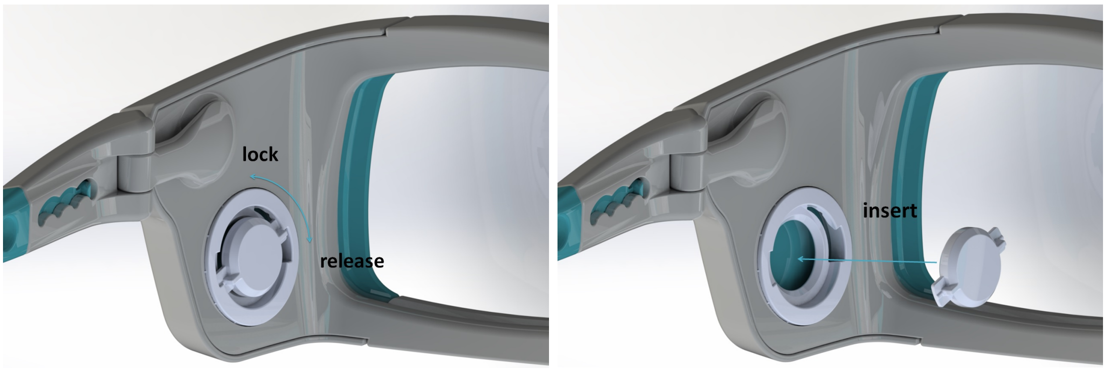

Figure 2 Bayonet coupling between RP glasses and BeOSL ELD. Left: Open coupling, showing the recesses engaging with the small fins which protrude from the dosemeter housing. Right: Quick and safe locking and releasing of the dosemeter by means of the bayonet mechanism.

3.3 New BeOSL detector for extremity dosimetry

The new detector element for extremity dosimetry developed by Dosimetrics, the so called ezClip, contains the same 4.7x4.7x0.5 mm^3 BeO chip [3] used inside the BeOSL whole body dosemeter badge described in [40]. The only difference is the plastic enclosure of the BeO chip, shown in Figure 3, which is labelled with a 2D code to identify the detector element. Depicted in Figure 3, the detector element can be placed in a readout carrier, which in turn fits into a badge called ezCases. The latter has the same form factor as the standard whole body dosemeter. Consequently, the detector element can be evaluated using the identical read out infrastructure used for the whole body system, which includes readers, erasers, and robotic manipulation tables as described in [40]. The only requirement for the user is a software update and the only additional step in the readout process is the unpacking from the extremity dosemeter and the transfer to the readout badge. This procedure includes the scanning of the codes of the dosemeter, of the ezClip, and of the ezCase, which are then sent to the production database.

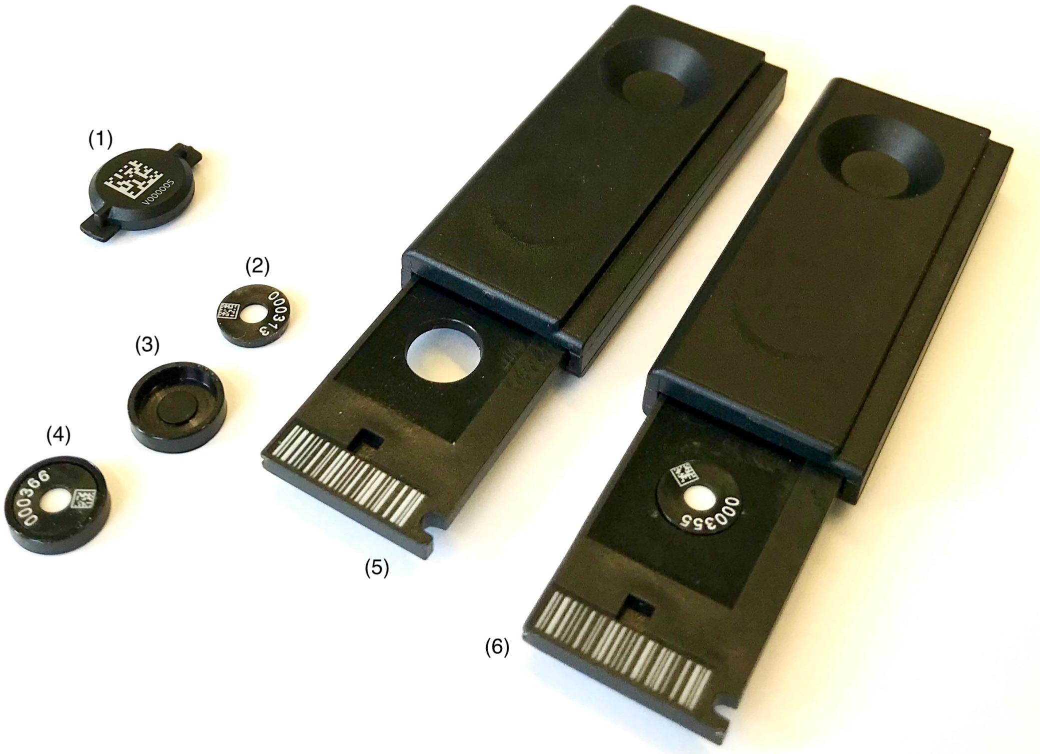

Figure 3 ELD with BeOSL detector element and readout badge: (1) ELD front enclosure, (2) ezClip detector element, (3) detector tray, (4) tray with ezClip inside, (5) readout badge ezCase, (6) ezCase with ezClip inserted.

As the measurement is practically identical to the whole body dosimetry system the following paragraph lists only the minor differences in the measurement process leading to only slightly changed performance characteristics.

Overall sensitivity of the detector element

Due to the plastic enclosure of the ezClip (Figure 3) which is mostly required to accommodate the 2D code of the detector, less detector surface is available for light stimulation on the bottom of the detector and less surface is available for the OSL light to be collected on the top of the detector. This leads to a decrease in overall sensitivity of the individually calibrated detector element in comparison to the whole body dosemeter by about 50% on average.

Rotational degree of freedom in the readout badge

When placed into an ezCase, the detector element has a rotational degree of freedom in the horizontal plane, which does not exist for the detectors in a whole body dosemeter. Therefore, it was necessary to test, if this new degree of freedom introduces additional uncertainty in the dosemeter readout. A series of reproducibility tests with approximately 15-20 repeated irradiations of both whole body dosemeters and a number of ezCases with the ezClips intentionally rotated by up to 360° was carried out. In these tests ezClips were irradiated inside the ezCases. No difference in the reproducibility (≈2.5%) of the results with either kind was found despite intentional rotations.

Reusability of irradiated elements
BeOSL sensitivity is known [41] to decrease slightly with accumulated lifetime dose. At the same time the zero signal of the detectors increases. This might be more of an issue for extremity dosemeters than for whole body dosemeters. Therefore, the reproducibility tests described above were also evaluated to confirm that the sensitivity decrease of the detector elements is less than 3% for accumulated doses up to 150 mSv.

Exposure to ambient light
The working principle of a BeO detector chip is optical stimulation of the luminescence signal. The material is most sensitive to stimulation with blue light up to 500 nm wavelength. For longer wavelengths the traps occupied due to radiation effects cannot be depleted. Nevertheless, exposure to the spectral distribution of ambient light would lead to an unwanted stimulation and loss of dose information. Whole body dosemeters are made of opaque material and are opened only inside the reader; therefore, light exposure is not an issue. In the case of extremity dosemeters, however, the ezClips need to be unpacked from their enclosure (rings or ELDs) and transferred to the readout badge. The whole process takes no more than 10-20 seconds during which the detector is exposed to ambient conditions. The risk of signal loss is limited. A series of tests with intentional exposures of irradiated chips showed that a 5% signal loss occurs for artificial light sources under standard laboratory conditions in approximately 4 minutes and for an exposure to daylight within 1 minute. However, the problem can be fully neutralized by means of UV protection filters, such as the Lithoprotect® UV-protective yellow foil Y520E212 [42], which are widely used for lithography applications in semiconductor industries. The IMS has equipped a new laboratory with UV protection filters both on windows and on artificial light sources. Under these yellow light conditions, no signal loss within the uncertainty of the measurement was found in exposures of the BeO detector element up to 80 minutes.

3.4 BeOSL eye lens dosemeter

Based on objectives listed in 2.3 and to fit the mechanical interface described in 3.2 the two-part dosemeter enclosure shown in Figure 4 was designed by the IMS in Munich to accommodate the new ezClip detector. In this design the ezClip is located inside a tray. The dosemeter is sealed by pressing the tight-fitting coded dosemeter front enclosure onto the tray, using a pneumatic tool. This method of enclosure results in a waterproof seal up to 3 bar water pressure. The choice of a symmetrical material thickness of 1.5 mm both for tray and front enclosure ensures equal response for forward and backward irradiations. The thickness is a compromise between minimum space usage, mechanical stability against the pneumatic opening/closing tool, opacity to blue light and photon energy and angular response based on $H_p(3)$. In the design process for the new ELD Monte Carlo simulations were used to predict the energy and angular response of the dosemeter before ordering the expensive tools for injection molding to produce the dosemeter parts. The results of this Monte Carlo study published in [4]showed the design is fulfilling the corresponding IEC requirements easily and supported the choice of material. The final dosemeter is made from polyamide and encoded with a 2D data matrix code and a user readable ID.

Figure 4 BeOSL ELD: the top row shows the inside (left) and outside (right) of the dosemeter front enclosure and the bottom row the detector tray without (left) and with (right) the ezClip inside.

3.5 TLD eye lens dosemeter

Dosilab is currently using TLD technology from Panasonic. The single element detectors, which are also in use as extremity dosemeters, are of the type UD-807, comprising a layer of $Li_2B_4O_7$:Cu crystals (approx. 15 mg/cm^2 of $Li_2B_4O_7$:Cu thermoluminescent phosphor)[5]. The detector material is virtually tissue equivalent (Z_{eff} = 7.26), which allows to adequately determine the accumulated dose over a broad energy range with one single detector element. However, due to the thin phosphor layer of roughly 15 mg/cm^2 an extra absorption material is required for $H_p(3)$ measurement. The detector housing designed by Dosilab is shown in Figure 5. The detector part exposed to radiation (facing the head of the wearer) has a cap of essentially 3mm of water equivalent material (Polyamide variant with density 1.0 g/cm^3). The dosemeter bottom was chosen to be relatively thin (0.4 mm) in order not to increase the overall thickness, which is perfectly acceptable owing to the fact that the dosemeter is shielded by 0.5 mm

Pb equivalent from that side. The design shown in Fig. 5 ensures correct positioning and orientation of the detector owing to the unambiguous coupling with the bayonet socket."

Figure 5 The schematic assembly of the dosemeter (left) comprises the 3mm front cap (1) where the TL detector (3) is inserted, followed by a label (4) with information like personal name, wear month, detector ID, finally being enclosed and hermetically sealed with the thin back cap (2) through ultrasonic welding. The photograph (right) shows both housing sides and the assembled $H_p(3)$ dosemeter. A key is supplied for safe and easy manipulation.

3.6 Adapters

Adapters such as headband adapters or adhesive adapters (see Figure 6 and Figure 7) had to be developed in order to provide alternative wearing options. Headband adapters were chosen as they can be worn independently from glasses and they are also required for the formal certification process in Germany by Physikalisch-Technische Bundesanstalt (PTB) Braunschweig, even though most users dislike this wearing option. Adhesive adapters are necessary to provide an upgrade solution for customers already using glasses and unwilling to purchase new ones at this time. They work only with a limited number of RP glasses and visors depending on space constraints on the insides of these devices. All adapters employ the same fixation mechanism described in section 3.2.

Figure 6 Headband adapter (a) and insertion tool (b) for the BeOSL dosmeter, adhesive adapter (d) and adhesive adapter in various RP glasses (c).

Figure 7 Adhesive adapter (a) with Dosilab TLD ELD (b) and insertion key (c).

4 Radiological characterization of the dosemeters

4.1 Equipment and methods of radiological characterization

All radiological tests required to demonstrate conformity with IEC [27] requirements were carried out in the secondary standard irradiation facilities of the IMS in Munich [43], [44]. Calibration procedures in these labs are in accordance with the recommendations of the ISO 4037 [24]-[26] series. For the evaluation of the energy and angular response for photons, irradiations with doses of approximately 3 mSv $H_p(3)$ have been carried out with N-series radiation qualities as well as S-Cs and S-Co. ISO phantoms used were the cylinder phantom and in some cases the slab phantom. (BeOSL Dosemeters were all irradiated on the cylinder phantom and for TLDs all large series irradiations were performed on the slab phantom and validated with lower statistics by irradiations on the cylinder phantom over the entire angular range.)
Beta response was tested with $^{90}Sr/^{90}Y$ and ^{85}Kr irradiations on a PTB beta standard BSS2 [45] following ISO 6980 recommendations[46]. ^{85}Kr irradiations have been used to verify that the $H_p(3)$ readings from ^{85}Kr are less than 10% of the $H_p(0.07)$ dose in accordance with IEC 62387. Both new dosemeters passed this test.
Usually five to ten dosemeters were irradiated and evaluated for each radiation quality and angle of incidence and the arithmetic mean of the individual dosemeter results was used in the following presentation of results (Figure 8 to Figure 14).

4.2 Performance results for the BeOSL eye lens dosemeter

In the following paragraphs the results of radiological tests of the properties of the ELDs concerning energy and angular response, linearity, coefficient of variation are given. In addition to the radiological characterization, the dosemeter enclosures have also successfully been tested for water tightness up to pressures of 3 bar, for opacity in intense illuminations with blue light (Royal Blue LEDs at 455nm, 12 h × 0.1 W/cm^2) and against mechanical shock.

4.2.1 System calibration for $H_p(3)$

The first tests carried out with the new ELDs served to derive a system calibration for the quantity $H_p(3)$ by measuring energy response at 0° and 60° and choosing an appropriate calibration point. As a result of this exercise N-150 was selected as the reference radiation quantity and the system calibration factor input into the readout software was chosen to produce a response equal to unity for N-150, 0°. The choice of N-150 provides both an optimization in terms of energy response, as shown below, and in terms of calibration efficiency, as the X-ray facilities can produce relatively high dose rates at this radiation quality.

4.2.2 Energy and angular response

The energy response of the dosemeter was measured with radiation qualities from N-15 to S-Co at 0° and 60° angle of incidence by means of irradiations on the cylinder phantom. The results plotted in Figure 8 show a very flat energy response close to unity in the energy range from 20 keV to 200 keV, which covers all the energies of interest in radiology. IEC requirements can easily be fulfilled in the range from 16 keV to 1.3 MeV and for angles of incidence up to 60°. As the latest IEC Draft [28] uses extended limits of 0.5 to 2 for radiation energies lower than 20 keV, even N-15 (12 keV) would be fulfilled. Higher photon energies > 1.3 MeV will be tested by PTB, but compatibility with IEC requiremnets can be inferred from the known high energy photon response of the BeOSL detectors [40]. A comparison with the energy response of the EYE-D™ dosemeter from the ORAMED study, which has been used at the IMS in Munich for evaluation purposes, shows the response of the BeOSL ELD to be more accurate in the lower energy photon range relevant for radiology. Due to its symmetrical design the dosemeter response is the same (Figure 9) for forward irradiation (through the front enclosure) and backward irradiation (through the detector tray), i.e. to direct radiation and backscatter from the head, no matter how the dosemeter is worn.

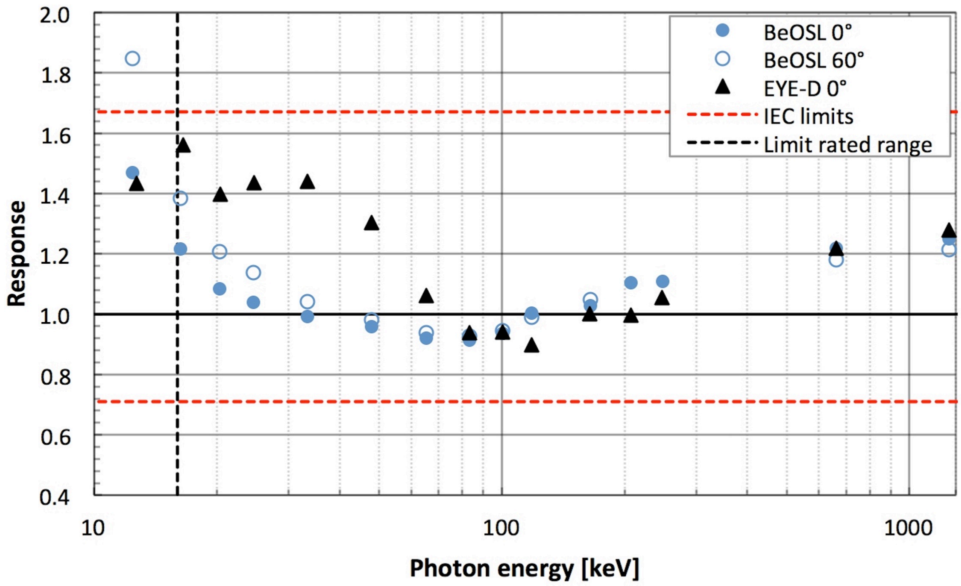

Figure 8 Energy response of the BeOSL ELD for 0° and 60° photon incidence.

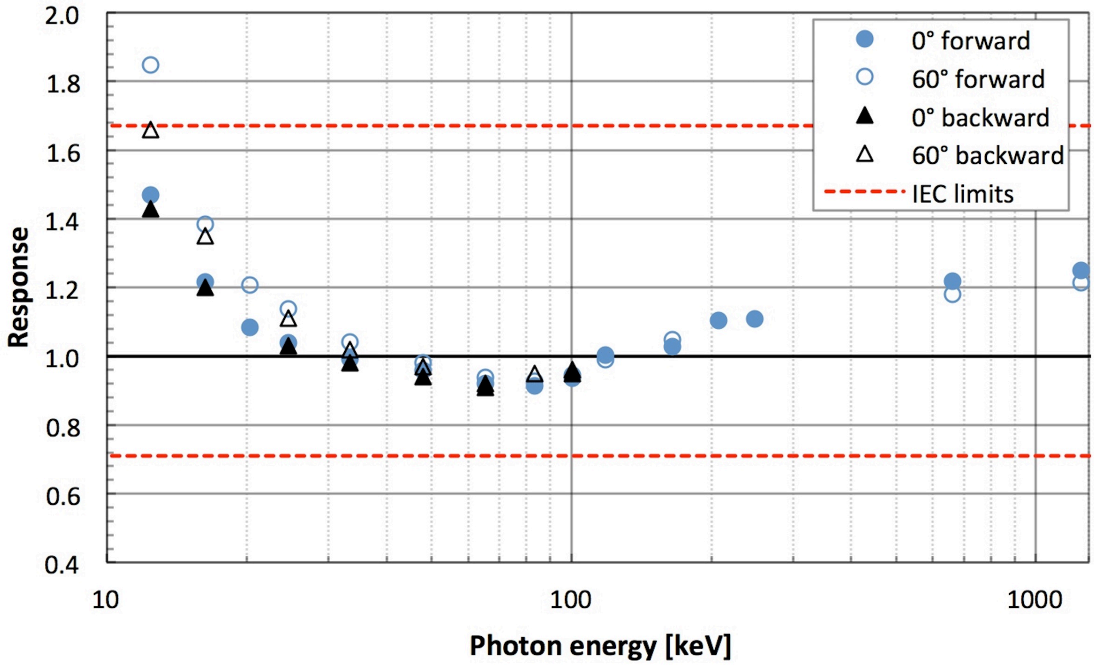

Figure 9 Energy response for backward and forward irradiation: there is no difference in response due to the symmetrical design.

4.2.3 Performance with adaptors

The mechanical interface described above has been designed specifically not to interfere with the radiological characteristics of the dosemeter, as there is no additional material within the ± 60° angular acceptance of the dosemeter for both forward and backward incidence. The headband adaptor does not affect energy response and, more importantly, the angular response up to 75° incidence, as shown in Figure 10.

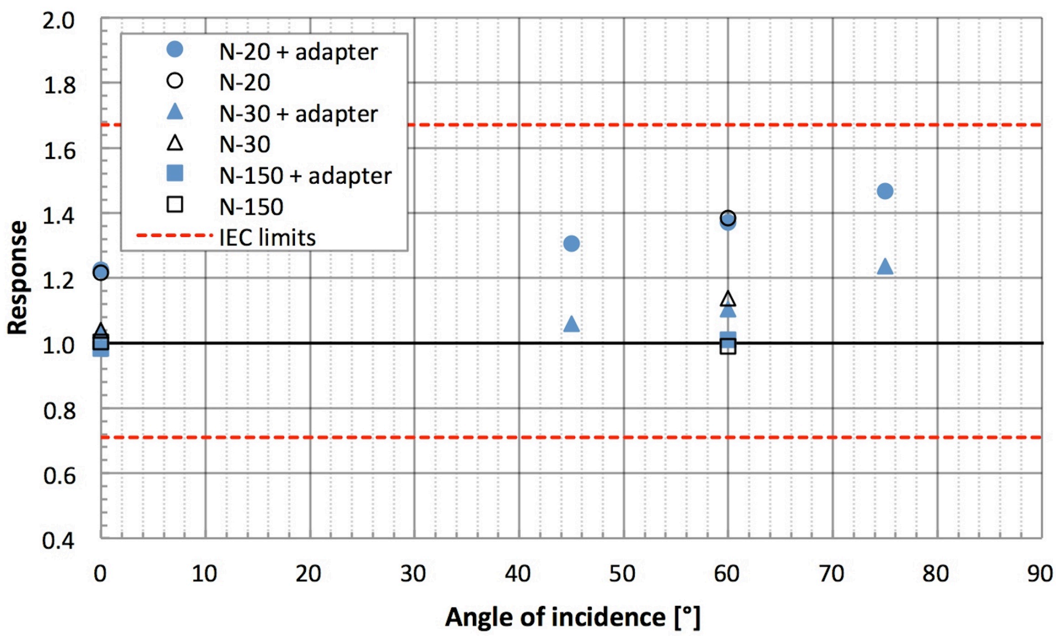

Figure 10 Angular response of dosemeters irradiated in the headband adaptor is the same as without the adaptor.

4.2.4 Linearity and coefficient of variation

The linearity and coefficient of variation of the new ELDs was established by means of S-Cs irradiations with doses from 0.1 mSv to 1 Sv following IEC [27] recommendations. In irradiations with doses > 0.4 mSv seven dosemeters were used to calculate the coefficient of variation, in irradiations <= 0.4 mSv ten dosemeters. The coefficient of variation is less than 2.5% for doses > 1 mSv and less than 6% down to 0.1 mSv – see Figure 11. As expected, these results are comparable to the performance of the whole body dosemeter. Deviations from linearity are less than 2% up to 1 Sv – see Figure 12.

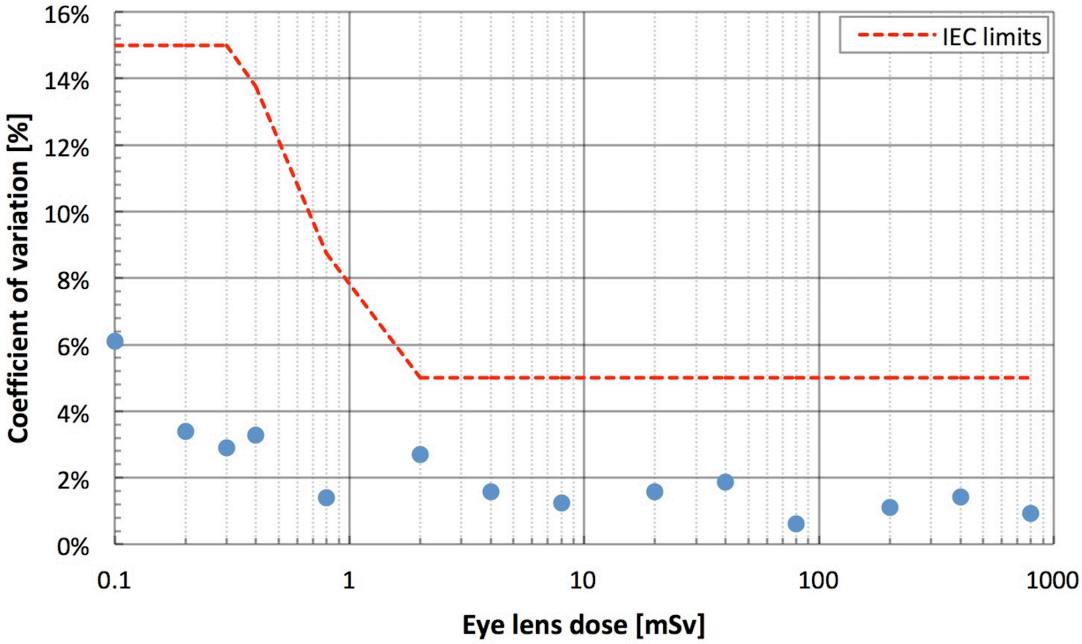

Figure 11 Results for the coefficient of variation.

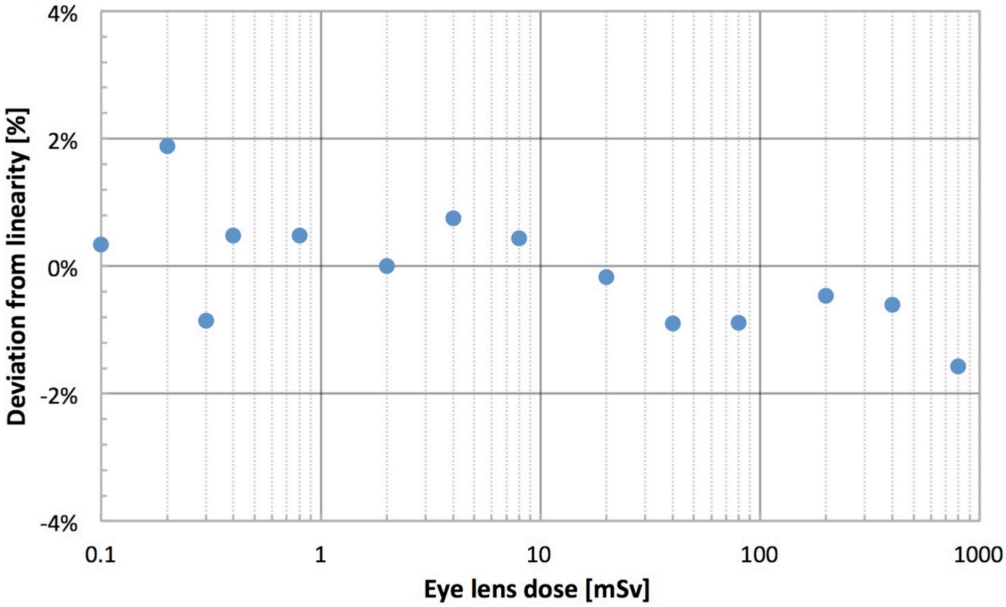

Figure 12: Dose linearity: the ELDs deviate less than 2% from linearity for doses from 0.1 mSv to 1 Sv. IEC limits are -13% to +18%.

4.3 Performance results for the TLD eye lens dosmeter

The TL detectors from Panasonic are widely known and well characterized for $H_p(10)$ and $H_p(0.07)$. Here the results from test series performed on the new $H_p(3)$ dosemeter (paragraph 3.5) are shown. The dosemeters were irradiated with X-ray raditation qualities N-20 to N-300, with Gamma qualities S-Cs and S-Co and with the beta quality $^{90}Sr/^{90}Y$. The energy response of the dosemeters at zero incident angle is shown in Figure 13. The results for the $H_p(3)$ dosemeters, which are referred to as dosiEYE, are represented with full dots, while the error bars reflect the statistical uncertainty. The response of the dosemeter is found to be very well within the IEC limits indicated by dashed lines. For comparison, the response of our $H_p(0.07)$ dosemeters, referred to as dosiCLIP (full triangles) is shown as well. As expected, a significant deviation and over response is observed below 30 keV due to the thinner absorber.

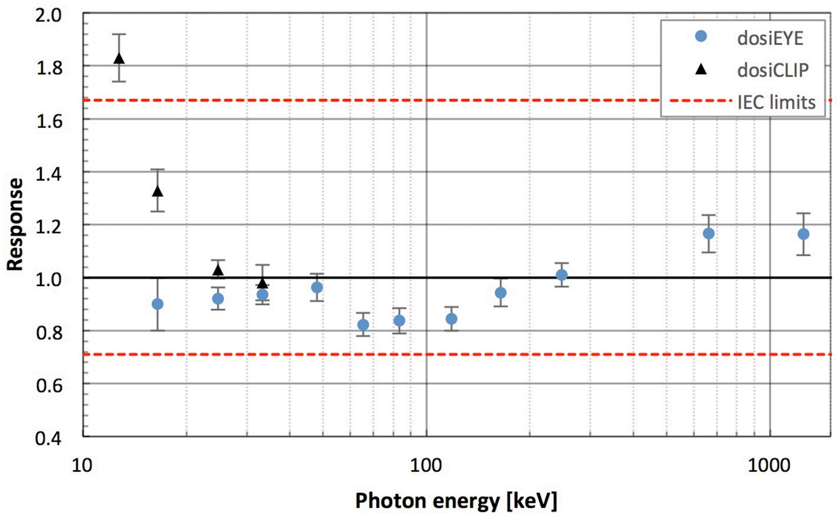

Figure 13 Energy response of the $H_p(3)$ dosemeter (dosiEYE, solid circles). For comparison, the response of a $H_p(0.07)$ dosemeter (dosiCLIP, solid triangles) is also shown. The dashed lines denote the IEC limits.

Angular response is also most critical at lower energies. Figure 14 shows the response to N-20, N-30 and N-40 over the angular range from -75° to +75°. In addition, the response to betas with E_{mean} ≈ 0.8 MeV from $^{90}Sr/^{90}Y$ is shown (open triangles). All results are consistent with simulations and they satisfy the constraints imposed by the IEC standard [27].

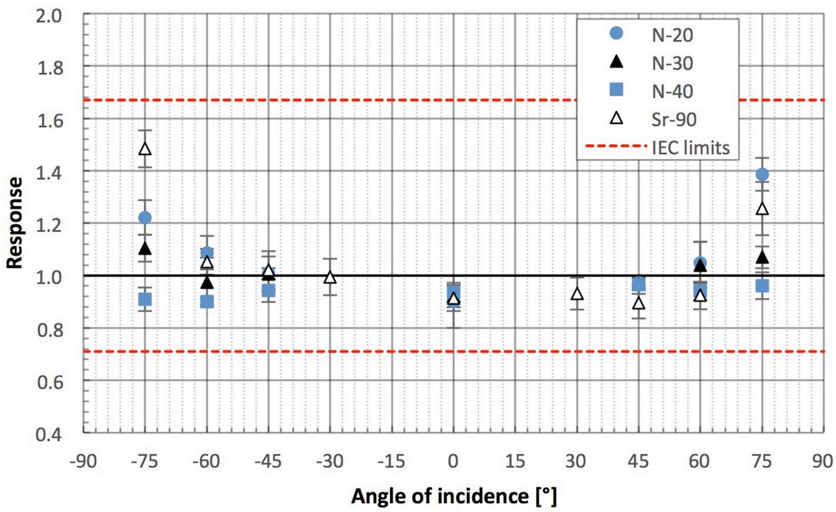

Figure 14 Response to the lowest photon energies N-20, N-30, N-40 and to 0.8 MeV betas from $^{90}Sr/^{90}Y$, measured over an angular range of incidence of ±75°. The dashed lines denote the IEC limits.

Dose linearity is essentially a function of the detector technology and does hardly depend on dosemeter housing. Therefore, it remains satisfied for the UD-807 over the response range 100 μSv – 10 Sv. Type testing and homologation of Dosilab's entire dosimetry system including whole body, extremity and eye lens dosemeters is certified by the Federal Institute of Metrology METAS and accredited by the Swiss Accreditation Service SAS. Dosilab participates in the annual Swiss intercomparisons as well as in periodic intercomparisons conducted by other organisations (EURADOS, IRSN).

5 Conclusion and outlook

Using a standardized mechanical interface for the fixation of ELDs to RP glasses, a new type of RP glasses and two different types of ELDs, based on different detector technologies (OSL and TLD) have been developed. Adapters have been developed to provide upgrades for existing RP glasses and visors and to provide an alternative wearing option on a headband. The results of the radiological characterization of both dosemeter types show conformity with IEC requirements for $H_p(3)$ dosemeters.
The rated range of use of the BeOSL ELD for photon radiation will be from 16 keV to 7 MeV with an angle of incidence ±60° and for doses from 100 μSv to 1 Sv.
For Dosilab's dosiEYE comprising a TLD the rated range for photons is 16 keV to 1.25 MeV whereas for beta radiation the tests were performed with 0.8 MeV. The rated dose range for both photons and betas is from 100 μSv to 10 Sv over an angular range of ±75°.
The glasses have been submitted to a PPE approval process, and the OSL ELD is in the process of certification as an official dosemeter in Germany by PTB. Currently first workplace evaluation measurements in clinical applications are carried out with the new BeOSL ELD. Additional studies focusing on the performance of the dosemeter behind the RP galsses are being carried out with dosemeters and glasses on an Alderson phantom in the calibration facilities in Munich. The new results will be presented later this year at the SSD19 conference in Hiroshima [47].

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