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Test and optimization of two routine dosemeters for the dose quantity $H_p(3)$

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HIGHLIGHTS

- Whole body dosemeter for $H_p(10)$ and $H_p(0.07)$ can also be used for $H_p(3)$.
- The dose algorithm for whole body dosemeter can be changed for $H_p(3)$.
- Extremity dosemeter for $H_p(0.07)$ can also be used for $H_p(3)$ on the forehead.
- The reference energy has to be changed for $H_p(3)$.

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ABSTRACT

The individual monitoring service Seibersdorf uses two different passive dosemeter types based on thermo luminescence (TL) detectors for monitoring occupationally exposed persons in Austria. Whole body personal dosemeters for the personal dose equivalent quantities $H_p(10)$ and $H_p(0.07)$ worn on the trunk and dosemeters for the extremities for $H_p(0.07)$ worn on a finger or wrist. Both routine dosemeters were calibrated and tested in terms of the personal dose equivalent $H_p(3)$ assuming that the whole body dosemeter is worn on the chest (without or above a lead apron) and the modified ring/wrist dosemeter using a special strap worn on the forehead near the eyes (head band dosemeter). The test results show that it is possible to measure the dose quantity $H_p(3)$ with these dosemeters that were originally not designed for this dose quantity. Only changes in the dose calculation algorithm and in the choice of the reference radiation quality were necessary to fulfil the requirements given in international standards for passive dosemeters in a wide energy (20 keV–1.3 MeV) and angular range (0°–60°).

1. Introduction

The International Commission on Radiological Protection (ICRP) reduced the recommended annual equivalent dose limit in occupational exposure for the lens of the eye significantly from 150 mSv (ICRP, 1991; ICRP, 2007) to 20 mSv (ICRP, 2011; ICRP, 2012). The International Atomic Energy Agency (IAEA) as well as the European Commission followed this recommendation in their recent basic safety standards (IAEA, 2011; European Union, 2014). Studies within the ORAMED (Optimization of RAdiation protection for MEDical staff) project showed that occupationally exposed medical staff can receive significant doses with respect to these new dose limits (Donadille et al., 2011) and that routine monitoring of these personnel is recommended (Vanhavere et al., 2011). Details on the ORAMED project are published by the European Radiation Dosimetry Group (EURADOS) as special EURADOS report (Vanhavere et al., 2012). In addition the IAEA identifies other groups (specific workers in nuclear facilities and industrial radiographers) where elevated doses to the lens of the eye could occur and monitoring might be important (IAEA, 2013). As corresponding dose quantity the personal dose equivalent $H_p(d)$ with a depth $d = 3$ mm is recommended already in ICRU reports 47 and 51 (ICRU, 1992; ICRU, 1993). Due to the high dose limits previously recommended, the measurements of the dose to the eye lens were not of importance for individual monitoring services (IMS) in the past. Even until now only few data were published about new dosemeters that were especially designed for the relevant dose quantity $H_p(3)$ (Gilvin et al., 2013; Bilski et al., 2011). One reason for that is that no internationally recommended calibration procedures (including appropriate calibration phantoms and corresponding conversion coefficients) are available at the moment. Nevertheless the reduction of the annual dose limits requires new dosemeters especially

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designed for the appropriate dose quantity or at least the verification that the specifications of existing dosemeters fulfil the requirements for $H_p(3)$ too. This verification was done for two routine dosemeters of the IMS of the Seibersdorf Labor GmbH and is described in detail in this paper.

2. Existing dosemeters used for routine individual monitoring

The IMS of the Seibersdorf Labor GmbH monitors more than 70% of all occupationally exposed persons in Austria. More than 25,000 different customers per year are individually monitored with a typical monitoring period of one month. In addition workplace and environmental monitoring is offered too by specially designed passive area dosemeters. For routine individual monitoring two different approved dosemeter types based on TL detectors are currently used.

For the estimation of the effective dose and the equivalent dose to the skin a whole body dosemeter for the personal dose equivalent $H_p(10)$ and $H_p(0.07)$ (ICRU, 1993) worn on the trunk is used. For the extremities a ring dosemeter for the personal dose equivalent $H_p(0.07)$ worn on a finger is applied. Both dosemeters are based on commercially available automatically readable 2-element TL detector cards or single element detector ringlets using LiF:Mg,Ti detectors. The whole body badge and the plastic ring were developed and designed by our service (Duftschmid et al., 1996). More details and specifications for these two approved routine personal dosemeters are given in Table 1 (ID: A, B and D).

3. Tested dosemeters for $H_p(3)$

The routine *whole-body dosemeter* for the personal dose equivalent $H_p(10)$ and $H_p(0.07)$ uses a special dose algorithm to calculate both dose quantities from the two TL detector signals. Details about the dosemeter and the algorithm were given by the authors already previously (Stadtmann and Hranitzky, 2008). By adapting the parameters of the existing calculation algorithm the energy response of the dosemeter can be changed without changing the dosemeter design. This approach resulted in an improved energy response of the existing whole body dosemeter also for $H_p(3)$ for a wearing position on the trunk/chest. In how far a whole body dosemeter worn on the trunk/chest is adequate to measure the dose of the lens of the eye will be discussed later.

In addition the design of the *routine ring dosemeter* was adapted already years ago so that it is possible to wear these dosemeters also on the wrist like a watch (Table 1 ID: E). Since the wearing on the wrist is not recommended in Austria this wrist dosemeter was never used for routine monitoring by our service. The new requirement to measure the eye lens dose in the dose quantity $H_p(3)$ raises the question whether this *wrist dosemeter* (which was originally designed for the measurement of $H_p(0.07)$ on the wrist) worn on the forehead near the eyes can be successfully used as routine *head-band eye lens dosemeter* too.

Fig. 1. Four whole-body dosemeters positioned on the front surface of the ISO water slab phantom.

Two dosemeters, the whole body dosemeter (with the new dose algorithm) and the adapted head-band eye lens dosemeter were calibrated and tested in terms of $H_p(3)$ in the secondary standard dosimetry laboratory Seibersdorf. The corresponding dosemeter designs including the wearing positions are listed in Table 1 (ID: C and F).

4. Calibration procedure

Both dosemeters, whole body dosemeter and head-band eye lens dosemeter, were calibrated in the photon energy range from 12 keV to 1.3 MeV. According to international recommendations (IEC 62387, 2012) standard X-ray calibration qualities from the narrow spectrum series N-20 to N-300 and ^{137}Cs and ^{60}Co nuclide calibration sources according to the standard ISO 4037–1, 1996 were used. Due to the different intended wearing positions of both tested dosemeters (chest, head) two different calibration phantoms (ISO water slab phantom representing the chest defined in ISO 4037–3, 1999 and the water filled cylindrical head phantom

Table 1
Detailed description of different dosemeter types and dose quantity combinations. The specifications of the dosemeter types marked bold and with an asterisk (*) are described in detail in this publication and energy and angular responses are given in Figs. 3 and 4.

ID	Dosemeter type	Wearing position	Dose quantity	Dose range	Energy range	Accreditation
A	Whole-body dosemeter	trunk	$H_p(10)$	0.1 mSv–10 Sv	20 keV–1.3 MeV	yes
B	Whole-body dosemeter	trunk	$H_p(0.07)$	0.1 mSv–10 Sv	10 keV–1.3 MeV	yes
C*	**Whole-body dosemeter**	chest	$H_p(3)$	0.1 mSv–10 Sv	20 keV–1.3 MeV	no
D	Ring dosemeter	finger	$H_p(0.07)$	0.5 mSv–10 Sv	12 keV–1.3 MeV	yes
E	Wrist dosemeter	wrist	$H_p(0.07)$	0.5 mSv–10 Sv	12 keV–1.3 MeV	no
F*	**Head-band dosemeter**	forehead	$H_p(3)$	0.5 mSv–10 Sv	20 keV–1.3 MeV	no
G	Area dosemeter	free in air	$H^*(10)$	0.05 mSv–1 Sv	30 keV–1.3 MeV	yes

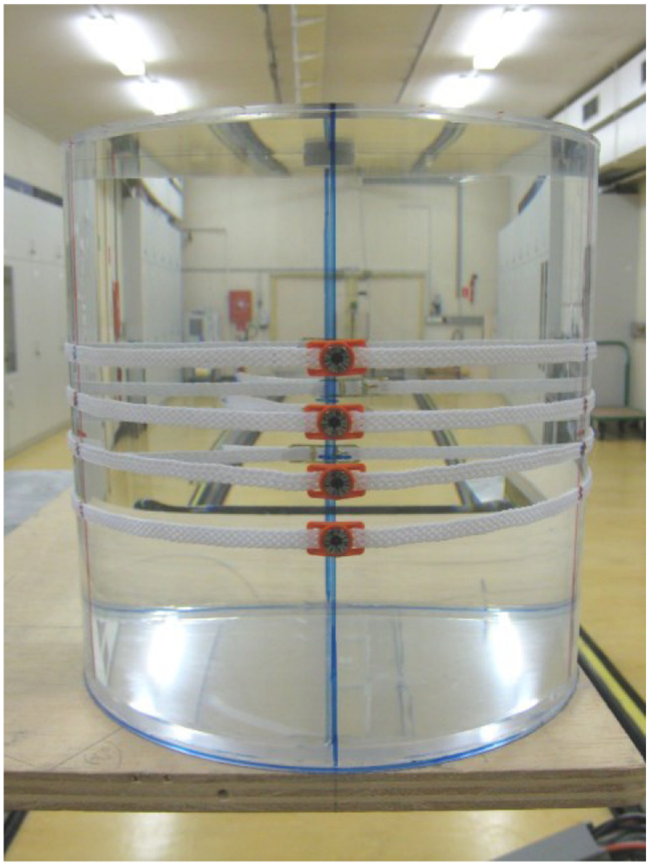

Fig. 2. Four head-band dosemeters positioned on the ORAMED water filled cylindrical head phantom.

as proposed by Gualdrini et al., 2011) were applied during the calibration procedure (Figs. 1 and 2). Details on the calibration setup are given in Table 2. For the test of the angular response the calibration phantoms (and the dosemeters) were irradiated at different irradiation angles (0°, 60°). Unfortunately the conversion coefficients h_{pK} from air kerma K_a to $H_p(3)$ are still under discussion for different calibration phantoms. For the water slab phantom preliminary conversion coefficients were recently published in IEC 62387, 2012. For the cylindrical phantom conversion values from Behrens 2012 were applied. The reference personal dose equivalent $H_p(3)_{ref}$ was calculated by multiplying the reference air kerma value K_a (free in air) by the corresponding conversion coefficient $h_{pK}(3; R,\alpha)$ considering the radiation quality R and the radiation incidence α given by the phantom and dosemeter orientation. The reference air kerma values of the X-ray irradiation (measured with a calibrated monitor transmission chamber) and the dose rates for the nuclide sources at defined irradiation distances were directly traceable to the national primary standards of the BEV (Bundesamt für Eich- und Vermessungswesen).

The typical standard uncertainty of this air kerma value is approximately ±0.8%. The standard uncertainty of the applied conversion factors h_{pK} unfortunately is not stated for all values in the relevant references. Typical standard uncertainties are in the range between ±1% and ±2%, (Behrens, 2012; ISO 4037–3, 1999). In Figs. 3 and 4 the mean response values (ratio of indicated dose to reference dose) and the corresponding standard deviation (indicated as error bar) of four simultaneously irradiated dosemeters are given for selected irradiations. The relative standard deviations are in the range between 1% and 10%. All other influencing quantities (distance, air density correction, current measurement of the monitor chamber signal, etc.) are negligible (standard uncertainty >0.5%) compared to the mentioned components.

The combination of results for different radiation qualities (representing the energy response) and different irradiation directions (representing the angular response) was called “combined energy and angular response” in Figs. 3 and 4.

5. Results

The test results, the relative combined energy and angular response in terms of $H_p(3)$ of both dosemeter types (whole-body and head-band dosemeter) are given in Figs. 3 and 4. All response values are normalized to the reference radiation quality (S–Cs for the whole body dosemeter and N-100 for the head-band dosemeter) at 0° angle of radiation incidence. Due to the non-symmetric design of the whole body dosemeter which uses 2 detectors the response values are given for the reference direction 0° and in addition four different directions of incidence (“left”, “right”, “top” and “bottom”) for an angle of 60°. For the symmetrical head-band dosemeter only the reference direction (0°) and one additional direction of radiation incidence (“left” which is also equivalent to “right” due to the dosemeter and phantom symmetry) for an angle of 60° were tested.

To compare the results with the requirements laid down in the international standard IEC 62387, 2012 the corresponding response limits for angle and energy dependence are marked in addition in both diagrams.

6. Discussion and conclusion

The *whole-body dosemeter* is suitable for $H_p(3)$ measurements on the trunk. According to the tests, the energy and angular response fulfils the requirements of IEC 62387, 2012 in a wide energy range from 20 keV to 1.3 MeV (Fig. 3). For this purpose - as described already–the parameters of the dose calculation algorithm converting mathematically both detector element signals into one $H_p(3)$ dose value were optimised. The reference energy (S–Cs, 662 keV where the relative response is unity) however was not changed compared to the $H_p(10)$ standard calibration of the whole body dosemeter.

The possible wearing position of the whole-body dosemeter on the chest - if possible near to the head – is not optimal for the estimation of the eye lens dose. In addition this dosemeter has to be

Table 2
Detailed description of the calibration/irradiation conditions for the personal dose quantity $H_p(3)$ including the dosemeter IDs from Table 1. Since the cylinder head dosemeter and the head-band dosemeter are symmetrical irradiation from left (+60°) are equivalent to irradiations from right (−60°).

Dosemeter type (ID)	Phantom	Radiation quality	$H_p(3)$ dose (mSv)	Irradiation distance (m)	Phantom/dosemeter orientation
Whole-body dosemeter (C)	ISO water-slab	N-20–N-300	0.7–3.5	2.5	0°, 60° (left, right, top, bottom)
Whole-body dosemeter (C)	ISO water-slab	S–Cs	2.0	2.0	0°
Whole-body dosemeter (C)	ISO water-slab	S–Co	1.0	1.5	0°
Head-band dosemeter (F)	ORAMED cylinder	N-20–N-300	1–2.5	2.5	0°, 60° (left = right)
Head-band dosemeter (F)	ORAMED cylinder	S–Cs	2.5	2.0	0°
Head-band dosemeter (F)	ORAMED cylinder	S–Co	2.0	1.5	0°

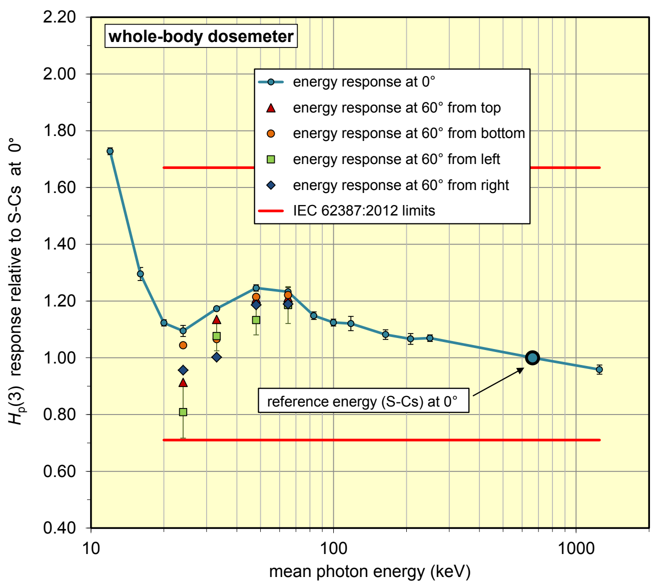

Fig. 3. Measured combined energy and angular response for the *whole-body dosemeters* calibrated on the ISO water slab phantom in terms of personal dose equivalent $H_p(3)$. The mean value (symbols) and the standard deviation (error bar) of four dosemeters are given for selected irradiations.

worn above the shielding apron for this purpose. Whole-body dosemeters for legal individual monitoring are generally worn under a protective apron in Austria. When applying double dosimetry then two dosemeters are used one above and one below the protective apron. This procedure is sometimes applied to estimate the effective dose E from two dosemeter readings more accurately (details are summarised by Jarvinen et al., 2008). In this case it is recommended that the unshielded dosemeter is worn on the neck. The unshielded second dosemeter can be used in addition for the estimation of $H_p(3)$. Further investigations will be carried out to show in how far a wearing position of a dosemeter on the neck could be recommended for eye lens dose measurements and

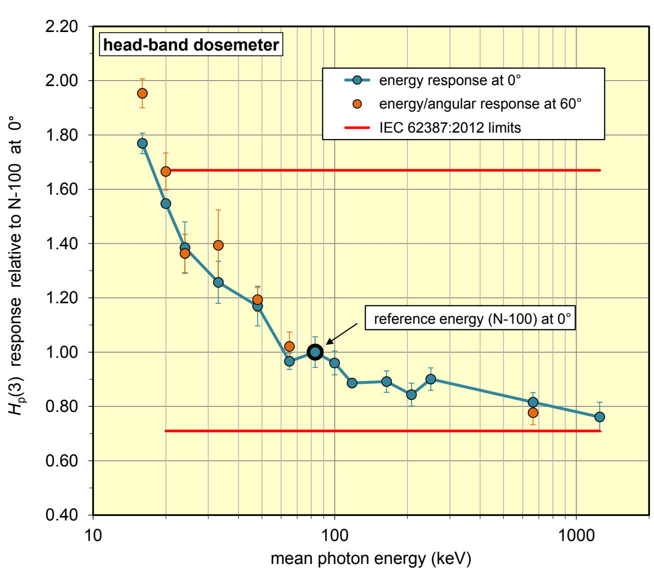

Fig. 4. Measured combined energy and angular response for the *head-band eye lens dosemeter* calibrated on the ORAMED water filled cylinder head phantom in terms of personal dose equivalent $H_p(3)$. The mean value (circle) and the standard deviation (error bar) of four dosemeters are given.

in how far the calibration of this dosemeter on the water slab phantom (representing the trunk/chest) is meaningful. Neck phantoms are not established for external dosimetry at the moment.

The energy and angular response of the *head band dosemeter* also fulfils the requirements of IEC 62387, 2012 in the energy range from 20 keV to 1.3 MeV (Fig. 4). The intrinsic energy response of the detector material LiF:Mg,Ti (e.g. Bilski et al., 2011) and the thin front filter of the head-band dosemeter (this dosemeter was originally designed for the measurement of the personal dose equivalent $H_p(0.07)$) lead to an over response of the head-band dosemeter at low photon energies (Fig. 4). The only way to optimise the energy/angular response with respect to the given response limits (0.71–1.67 from IEC 62387) without changing the dosemeter design (e.g. change of filter thickness) was the choice of an appropriate reference radiation energy. A photon energy of 83 keV as reference energy (for this energy the response is per definition unity) which is the average photon energy of the X-ray radiation quality N-100 leads to an optimised dosemeter response within the given angular and energy response limits. The reference radiation energy and quality is marked in Fig. 4. The possible wearing position of this small dosemeter near the eyes on the head is optimal for the estimation of the eye lens dose.

The results of the paper show that it is possible to measure the dose quantity $H_p(3)$ with different dosemeters that were originally designed for the measurement of the personal dose equivalent $H_p(10)$ and $H_p(0.07)$. Only minor changes in the dose calculation algorithm and in the choice of the reference radiation quality were necessary to fulfil the requirements given in IEC 62387, 2012 in a wide energy and angular range. So no redesign of the dosemeters is necessary to meet the requirements for eye lens dosimetry. Further investigation on the best choice of the wearing position of these dosemeters however needs to be carried out in the future.

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