Performance of radiophotoluminescence personal dosimeters in terms of the ICRU Report 95’s operational quantities

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A B S T R A C T

The objective of this work is to assess the photon energy and angle response of the radiophotoluminescence (RPL) personal dosimetry system used at the Paul Scherrer Institute (PSI) in terms of the operational quantities for external radiation exposure personal dose, \( H_p \), and personal absorbed dose in local skin, \( D_{\text{local skin}} \), defined in the Report 95 of the International Commission on Radiation Measurements and Units (ICRU). The RPL responses in terms of the “new” ICRU Report 95 quantities to a range of photon energies and irradiation angles were calculated using the RPL responses in terms of the personal dose equivalent \( H_p(10) \) and \( H_p(0.07) \) from the ICRU Report 51, previously obtained during commissioning of the RPL system, and the conversion coefficients from air kerma to the various operational quantities. The indicated value provided by the current dosimetry algorithm over-estimates the personal dose, \( H_p \), in the low-energy range (< 33 keV), whereas the estimation for the personal absorbed dose in local skin, \( D_{\text{local skin}} \), with the current system is satisfactory. A new dosimetry algorithm was developed making use of the five signals obtained from the RPL detectors, corresponding to the signal from regions of RPL glass under five different filters, to improve the \( H_p \) estimation by the RPL dosimeters. The results indicate that, in this case, the new algorithm may be sufficient to achieve satisfactory photon energy and angle response in terms of the ICRU Report 95 quantity \( H_p \) without a physical redesign of the dosimeter badges. A few photon mixed fields were also investigated, but a complete algorithm for photon-beta mixed field remains to be developed.

1. Introduction

In 2020, the International Commission on Radiation Units (ICRU) released the ICRU Report 95 “Operational Quantities for External Radiation Exposure” (ICRU, 2020), jointly prepared with the International Commission on Radiation Protection (ICRP). This report proposes new operational quantities to be used in radiation protection, replacing for example the quantities \( H_p(10) \) and \( H_p(0.07) \) defined in the ICRU Report 51 and typically estimated by personal dosimetry systems (ICRU, 1993). The new definitions aim at solving several inconsistencies between the definitions of the protection and operational quantities.

For example, in the antero-posterior (AP) irradiation, \( H_p(10) \) over-estimates the effective dose for photon energies <70 keV. This happens because, in this geometry and for low energy photons, the absorbed dose at the depth of 10 mm will be higher than the average absorbed dose over the entire body. For AP irradiation with photon energies >3 MeV, \( H_p(10) \) can either over- or under-estimate the effective dose, depending on whether \( H_p(10) \) is calculated using the so-called kerma approximation or using full electron transport (Endo, 2016).

The ICRU 95 report extends the range of particles and energies, and defines the operational quantities personal dose, personal absorbed dose in local skin, absorbed dose to the eye lens, and ambient dose. The personal dose, \( H_p(\Omega, E_p) \), replaces the personal dose equivalent \( H_p(d, \Omega, E_p) \) (where \( d \) is the depth in tissue, \( \Omega \), the angle of incidence, and \( E_p \), the energy), and is calculated using an anthropomorphic phantom. \( H_p(\Omega, E_p) \) is defined in the ICRU Report 95 as the product between the particle fluence at a point of the body, \( \phi \), and a conversion coefficient \( h_p \). The conversion coefficient \( h_p \) directly relates the particle fluence to the value of effective dose, \( E \), and is calculated by \( h_p = E/\phi \). Similarly, the personal absorbed dose in local skin, \( D_{\text{local skin}} \), is also defined as the product of the particle fluence incident on the body or extremity, \( \phi \), and a conversion coefficient \( d'_{\text{local skin}} \), with the coefficient \( d'_{\text{local skin}} \) relating particle fluence to the value of the personal absorbed dose in local skin, such as \( d'_{\text{local skin}} = D_{\text{local skin}}/\phi \). The calculation is done on an ICRU slab phantom at a depth between 50 \( \mu \)m and 100 \( \mu \)m.

In practice, the ICRU Report 95 provides conversion coefficients from air kerma or photon fluence to the new operational quantities,

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Fig. 1. (a) Picture of an opened RPL badge type GBFJ-01 (CHIYODA TECHNOL CORP., Tokyo, Japan), with filters’ locations indicated. P₁: plastic 1 (open window), P₂: plastic 2, Al: aluminium, Cu: copper, and Sn: tin. (b) Energy response of each of the glass regions behind the five filters in (a), for irradiations in terms of $H_p$(10) (on phantom).

Fig. 2. RPL energy response (a) in terms of the personal dose $H_p$ (ICRU 95) or $H_p$(10) (ICRU 51), or (b) in terms of the personal absorbed dose in local skin $D_{local\ skin}$ (ICRU 95) or $H_p$(0.07) (ICRU 51). $H_p$ is the indicated value of the dosimetry system, and $H_t$ the conventional true value for the operational quantity in question. The continuous black line indicates unity, the dotted black lines the IEC 62387:2020 limits for $H_p$(10) or $H_p$(0.07).

from which the response of detectors with respect to the ICRU Report 95’s operational quantities can be derived (ICRU, 2020). Typically, for photon energies below 70 keV, the indicated value from current dosimetry systems, designed and optimised to estimate $H_p$(10), will over-estimate the personal dose $H_p$ by up to a factor of 4.5, as $H_p$(10) $\approx E \sim H_p$ in this range (Otto, 2019; Eakins and Tanner, 2019; Eckendahl et al., 2020; Hoedlimoser et al., 2020). To tackle this issue, several dosimetry services have proposed a redesign of their dosimeters’ badges (Eakins and Tanner, 2019; Hoedlimoser et al., 2020; Polo et al., 2022).

Radiophotoluminescence (RPL) dosimeters are now routinely used in individual and area monitoring. They rely on the creation of optically active centres in Ag⁺-doped phosphate glass (P₂O₅) by exposure to ionising radiation (Yamamoto et al., 2011). Upon UV light stimulation, these centres are excited and emit light, the amount of which is proportional to the absorbed dose in the detector. The RPL system implemented at PSI and its performances for personal and environmental dosimetry have already been reported elsewhere (Assenmacher et al., 2017, 2020; Yukihara and Assenmacher, 2021).

RPL dosimeters typically consist of a glass plate housed in a plastic badge. The badge comprises five different windows, each equipped with a different filter: two ABS plastic filters (P₁ and P₂, 0.05 mm and 0.5 mm thick, respectively), the first of which acts as an open window, 0.4 mm of aluminium (Al), 0.3 mm of copper (Cu) and 1.4 mm of tin (Sn); see Fig. 1(a) and Maki et al. (2016). These materials have been chosen because they change the photon energy response of the regions of the glass detector behind them (Fig. 1(b)). During readout, the glass is excited at these five different locations, therefore giving five indications that are then used by the dose calculation algorithm to provide the dose estimates.

The objective of the present work is twofold: (a) to estimate the response of the RPL dosimetry system used at PSI in terms of the new operational quantities defined in the ICRU Report 95, and (b) to test whether an algorithm can be developed based on the five available RPL signals to improve the photon energy and angle response in terms of the new ICRU Report 95 operational quantities, without the need for a physical redesign of the badge. Previous investigations of other personal dosimeters have focused on a redesign of the dosimeters’
badges, adding a different filter combination to correct for an over-response at low-energy due to the photoelectric effect (Eakins and Tanner, 2019; Hoedlmoser et al., 2020; Polo et al., 2022). It would be an advantage if the RPL dosimeter response can be improved only with an algorithm change.

2. Materials and methods

2.1. RPL system and measurement procedure

The dosimetry system used at PSI consists of (37 × 7 × 1.5) mm³ Ag⁺-doped phosphate RPL glass detectors (RPLGDs) of the type FD-7 (AGC TECHNO GLASS CO., LTD., Shizuoka, Japan), dosimeter badges of the type GBFJ-01, reader FDG-660, and dose calculation software CDEC-Easy (CHIYOUDA TECHNOL CORP., Tokyo, Japan).

The data used here corresponds to the commissioning data of the system and consists of 500 RPLGDs irradiated with different photon energies, doses and angles. Each RPLGD was read ten times using two FDG-660 readers (i.e., 20 times for each detector). Detailed information on the irradiation conditions and readouts are provided in Assenmacher et al. (2017). The radiation qualities N-15, N-25, N-40, N-80, N-120, N-200, N-300 and S-Cs, and S-Co were used according to ISO (2019a). The angle response was investigated for the S-Cs and N-80 radiation qualities (662 keV and 65 keV mean energy respectively). The RPL glasses were annealed at 360 °C for 10 min to erase previous signals prior to irradiation and readout to establish the pre-dose signal before use. After irradiation, the RPLGDs were subjected to a 1 h/100 °C thermal treatment to achieve build-up of the RPL signal before the readout (McKeever et al., 2020).

Once measured, the signal for each of the five channels of the detectors are imported into the CDEC-Easy software for dose calculations. The pre-dose signal (measured directly following annealing/regeneration, before irradiation) as well as the signal due to natural background were subtracted from the signal after irradiation. The present algorithm uses a proprietary linear algorithm for the dose calculation (Juto, 2002). The system was designed to perform under the operational quantity definitions of the ICRU Report 51 and was calibrated in terms of $H_p(10)$ and $H_p(0.07)$.

2.2. Calculation of RPL response for $H_p$, $D_{local\ skin}$

The RPL responses in terms of the new ICRU Report 95 quantities were derived using:

$$R_{new} = R_{old} \cdot \frac{h_{old}}{h}, \quad (1)$$

![Fig. 3. RPL angle response in terms of the personal dose $H_p$ (ICRU 95) or $H_p(10)$ (ICRU 51) for (a) S-Cs or (b) N-80 radiation qualities, as well as in terms of the personal absorbed dose in local skin $D_{local\ skin}$ (ICRU 95) or $H_p(0.07)$ (ICRU 51) for (c) S-Cs and (d) N-80 radiation qualities. The continuous black line indicates the unity, the dotted black lines the IEC 62387:2020 limits for $H_p(10)$ or $H_p(0.07)$.]

![Fig. 4. Indicated value for the new algorithm developed in this work (red circles) and the present algorithm (open circles) as an estimation of the personal dose, $H_p$. The continuous black line indicates the unity, the dotted black lines the IEC 62387:2020 limits for $H_p(10)$.]

![Graph showing RPL response in terms of personal dose $H_p$ and absorbed dose in local skin $D_{local\ skin}$ for different radiation qualities and angles. The graph includes data from both the new and present algorithms, with comparison to IEC 62387:2020 limits.]
where $R_{\text{new}}$ and $R_{\text{old}}$ are the responses of the detectors in terms of the “new” (ICRU Report 95) and “old” (ICRU Report 51) operational quantities respectively, and $h$ and $h_{\text{old}}$ the respective kerma to operational quantity conversion coefficients. The values for $h$ were taken from the ICRU Report 95 Table A.5.1b for $H_p$ and Table 5.4.1b for $D_{\text{local skin}}$. The values for $h_{\text{old}}$ were extracted from the ISO 4037-3 (ISO, 2019b).

All the results are presented in terms of $H_m/H_i$, where $H_m$ is the indicated value of the dosimetry system and $H_i$ the conventional true value for the operational quantity in question. For each datapoint, the uncertainties were calculated as the standard deviation of all the measurements—which comprises a set of ten detectors measured ten times on two different readers, i.e., 200 measurements in total. The relative uncertainties were small, and consequently are frequently hidden by the symbols used in the graphs.

### 2.3. Algorithm development

The indicated value $H_m$ is calculated via a weighted sum of signals $S_i$ as

$$H_m = \sum_{i=1}^{N} c_i S_i,$$

(2)

where $S_i$ may represent the signal for a single channel or the difference between signals from different channels. In total, the signals of the five dosimeter channels were combined into $N$ unique variables $S_i$, where $c_i$ are the corresponding weights determined from a least-squares minimisation using the Nelder-Mead method as implemented in scipy for Python v. 3.8.

The commissioning data from Assenmacher et al. (2017) were used to compute these coefficients.

### 2.4. Performance assessment

Since performance requirements for personal and area dosimeters are not yet established for the operational quantities defined in the ICRU Report 95, we assume here that the same criteria as those listed in the IEC 62387:2020 (IEC, 2020) for $H_{p}(10)$ and $H_{p}(0.07)$ would apply to the dosimeter performance in terms of the new quantities.
3. Results

3.1. RPL response in terms of the ICRU report 95 definitions

The RPL photon energy responses in terms of the personal dose, \(H_p\), and the personal absorbed dose in local skin, \(D_{\text{local skin}}\), for the current RPL system and algorithm are shown in Fig. 2. The RPL system over-estimates the personal doses \(H_p\) in the energy range <50 keV, by up to a factor 4.5 at 20 keV (Fig. 2a). In comparison, the RPL photon energy response in terms of \(H_p(10)\) was within \(\pm 14\%\), within the IEC 62387:2020 requirements.

The RPL system estimation of the personal absorbed dose in local skin, \(D_{\text{local skin}}\), only exhibited minor changes in terms of the energy response (Fig. 2b). For both \(H_p(0.07)\) and \(D_{\text{local skin}}\) the deviation is less than \(\pm 10\%\) across the energy range considered (12 – 1250) keV.

The available RPL commissioning data includes data on the angle dependence on the RPL signal for angles up to \(\pm 60^\circ\) for either a S-Cs (662 keV) or an N-80 radiation qualities (65 keV mean energy)–here only the asymmetric rotation is considered; see Assenmacher et al. (2017). The angle dependence in terms of the old and new operational quantities is shown for S-Cs energy in Figs. 3a and for the N-80 radiation quality in Fig. 3b. Whilst the angle dependence for a S-Cs irradiation in terms of the personal dose \(H_p\) would still comply with the IEC 62387:2020 limits, its maximum deviation increases from less than \(2\%\) under the former quantities to \(15\%\) for the ICRU Report 95 operational quantities (Fig. 3a). Likewise, the maximum angle response deviation increases from 19\% for \(H_p(10)\) to 29\% for \(H_p\) (Fig. 3b).

The angle dependence for the estimation of the personal absorbed dose in local skin \(D_{\text{local skin}}\) differs little from that of \(H_p(0.07)\), at least for the S-Cs or N-80 radiation qualities (Figs. 3c and 3d).

3.2. Improving the RPL dose calculation algorithm

The results above show that, whilst the present RPL system performs well when estimating the personal absorbed dose in local skin, \(D_{\text{local skin}}\), it requires improvements when estimating the personal dose \(H_p\), at least if the requirements of the IEC 62387:2020 are assumed to be applicable to the new quantities. Therefore, we developed a new dose algorithm and tested it in terms of the ICRU Report 95 operational quantities.

The following sections detail the performances of this algorithm in terms of energy response and angle response, for a range of doses (linearity and reproducibility tests), and for mixed energy fields.

3.2.1. Energy response

The indicated values of the old and new algorithms as an estimation of \(H_p\) in the energy range (12 – 1250) keV are compared in Fig. 4. Although an under-response of \(\sim 30\%\) was still observed at 20 keV, the deviation was within \(\pm 20\%\) for the remaining energies. Overall, the entire energy range’s response is within the IEC 62387:2020 limits (IEC, 2020).

3.2.2. Angle dependence

The RPL angle dependence in terms of \(H_p\) calculated with the new algorithm shows less deviation (<12\% for S-Cs, <23\% for N-80) in comparison with the original algorithm, and are within the IEC 62387:2020 limits (Fig. 5). For the S-Cs radiation quality, however, the new algorithm leads to an under-estimation of the personal dose \(H_p\) at oblique irradiations, instead of the over-estimation observed using the current algorithm (Fig. 5a).

3.2.3. Linearity and reproducibility

The relative response to different dose levels was tested for the S-Cs radiation quality in the 60\(\mu\)Sv – 6.1 Sv dose range, to assess the algorithm’s performances in terms of linearity and reproducibility. Apart from a 8\% deviation at the lowest dose (60\(\mu\)Sv), the deviation from linearity was better than 3\% across the dose range considered (Fig. 6).

Additionally, the reproducibility was tested by calculating the coefficient of variation at various dose levels in the 60\(\mu\)Sv – 6.1 Sv range. The coefficient of variation was calculated as the standard deviation of the group of 10 dosimeters measured each 10 times on two different readers, divided the mean of the aforementioned group. The results are shown in Fig. 7. A maximal coefficient of variation of 14\% at 60\(\mu\)Sv was observed, better than the 15\% allowed by the IEC 62387:2020 in this dose range.

3.2.4. Mixed energy fields

The response of the system using the new algorithm was tested for the mixed energy irradiations carried out within the scope of the commissioning of the RPL system, where a S-Cs radiation quality was combined with different X-ray fields, one of them being at an angle (Assenmacher et al., 2017). The irradiation conditions, as well as the doses for the six irradiated detectors are listed in Table 1.

The relative responses of the six detectors irradiated in these mixed-fields are shown in Fig. 8, plotted against the reference dose. The results indicate that all configurations are within the IEC 62387:2020 limits.

4. Conclusion

The calculated RPL responses in terms of the new operational quantities defined in the ICRU Report 95 show that the current RPL system and dose calculation algorithm overestimates the quantity \(H_p\), up to a factor 4.5 at 20 keV. This result agrees with those obtained for other dosimetry systems (Eakins and Tanner, 2019; Otto, 2019;
Ekendahl et al., 2020) and is a results of the redefinition of the operational quantities. Although less impacted, the angle response of the $H_{p,\theta}$ estimation under the current RPL system is also worse than that of $H_{\phi(10)}$, with up to a 15% deviation for a S-Cs source, where a maximum of 2% was measured for $H_{\phi(10)}$. With regard to the personal absorbed dose in local skin, $D_{\text{local skin}}$, no changes to the present system are needed. The criteria defined in the (IEC, 2020) were used to assess the performance of our algorithm, since criteria for the new operational quantities do not exist yet.

The results also demonstrated the feasibility of designing an algorithm which improves the RPL response for estimating the personal dose $H_p$. These initial evaluations show that, at least for photons and for a dosimeter containing five different detector elements with differing energy response, such as the RPL system used at PSI, a physical redesign of the badge may not be necessary to achieve suitable estimations of $H_p$ and $D_{\text{local skin}}$ for energies in the (12–1250) keV range. Instead, a change in the algorithm may be sufficient, as predicted by Otto (2019).

Avoiding a complete dosimeter redesign would represent a great simplification in the transition from the ICRU Report 51 to the ICRU Report 95 operational quantities. Nevertheless, the investigation presented here needs to be expanded to include the angle dependence for a wider range of photon energies, and the algorithm needs also to include mixed beta-photon fields. Such investigations will require a significant effort, particularly with respect to the algorithm development and testing.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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