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Implications of the ICRU 95 quantities for various personal dosimetry techniques

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ABSTRACT

The objective of this work is to assess the photon energy and angular response of various dosimetry systems in terms of the operational quantities for external radiation exposure personal dose, H_p, and personal absorbed dose in local skin, $D_{local\ skin}$, defined in Report 95 of the International Commission on Radiation Units and Measurements (ICRU). The dosimetry systems in Switzerland offer an opportunity to evaluate the status quo in personal dosimetry, due to variety of techniques employed and the possibility of accessing commissioning data from the various services.

The photon energy and angular responses in terms of the ICRU Report 51 personal dose equivalents $H_p(10)$ and $H_p(0.07)$ were compiled for the dosimetry systems used by the Paul Scherrer Institute (radiophotoluminescence and direct ion storage), the Lausanne University Hospital (optically stimulated luminescence), the CERN (direct ion storage), Dosilab (thermoluminescence), and the SUVA (thermoluminescence). From this data, the response of the systems to the ICRU Report 95 quantities for whole body dosimetry (H_p) and skin dosimetry ($D_{local\ skin}$) was calculated using conversion coefficients from air kerma to the respective operational quantities. Regardless of the detector material, whole-body dosimeter design, or technique, each system over-estimated the personal dose, H_p, in the low-energy range (< 70 keV) up to a factor of 3 or 4. The indicated values for the personal absorbed dose in local skin, $D_{local\ skin}$, remains within the limits $(0.71 - 1.67)$. These estimates highlight the impact of the ICRU 95 Report at a country's scale and prompts discussion regarding potential solutions and challenges.

1. Introduction

The operational quantity currently used to estimate whole body doses, $H_p(10)$, defined in the Report 51 of the International Commission on Radiation Units and Measurements (ICRU, 1993), over-estimates the effective dose for photon energies <70 keV in an antero-posterior (AP) irradiation. This is due to the fact that such low energy photons are not penetrating, contributing to the dose at a depth of 10 mm depth, therefore to $H_p(10)$, but not contributing significantly to the average absorbed dose over the entire body, that is, to the effective dose E.

In 2020, the ICRU released the Report 95 "*Operational Quantities for External Radiation Exposure*" (ICRU, 2020), jointly prepared with the International Commission on Radiological Protection (ICRP). The ICRU Report 95 recommends the replacement of the personal dose equivalent $H_p(10, \Omega, \epsilon)$, where 10 is the depth in tissue in mm, Ω the angle of incidence, and ϵ the energy, by the personal dose $H_p(\Omega, \epsilon)$. $H_p(\Omega, \epsilon)$ is defined in the ICRU Report 95 as the product between the particle fluence at a point of the body, ϕ, and a conversion coefficient h_p. The conversion coefficient h_p itself directly relates the particle fluence to the value of effective dose, E, and is calculated such as $h_p = E/\phi$. Therefore, by definition, H_p is numerically identical to the effective dose, E, for the given angle. This new definition eliminates the over-estimation by $H_p(10)$, but, as we will see, introduces other challenges.

Similarly, the personal absorbed dose in local skin, $D_{local\ skin}$, is also defined in the ICRU Report 95 as the product of the particle fluence incident on the body or extremity, ϕ, and a conversion coefficient $d'_{local\ skin}$. $d'_{local\ skin}$ relates the particle fluence to the value of the personal absorbed dose in local skin, such as $d'_{local\ skin} = D_{local\ skin}/\phi$.

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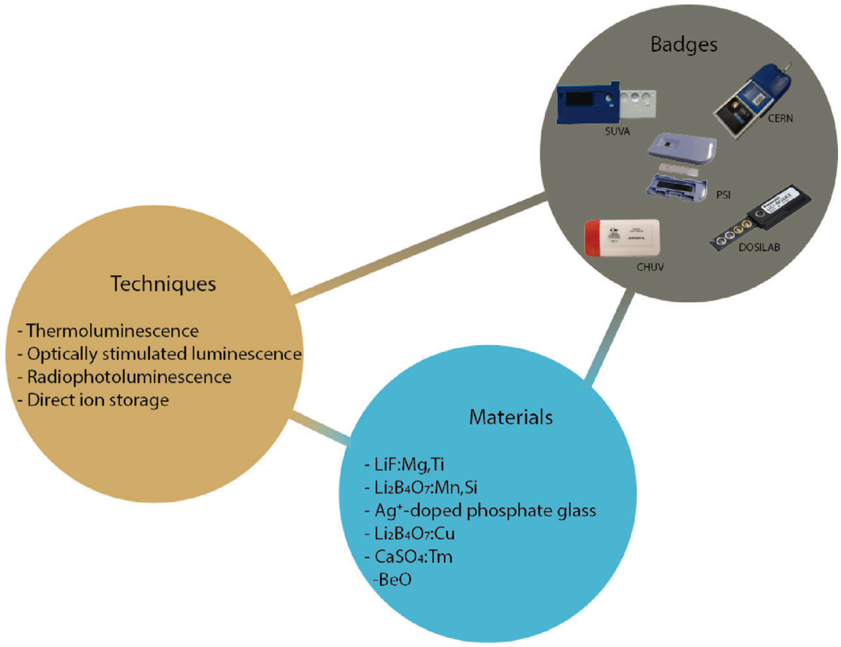

Fig. 1. Techniques, materials and badges employed by Swiss dosimetry services.

This quantity is expressed in grays (Gy), instead of, as is the case for $H_p(0.07)$ in the ICRU report 51, sieverts (Sv).

The dosimetry systems currently used are optimised to measure $H_p(10)$ and $H_p(0.07)$, and, ideally, to have a flat photon energy response for these quantities. In the photon low-energy range (<70 keV), where $H_p(10)$ over-estimates E, it is likely that all current dosimetry systems will over-estimate H_p, as $H_p(10) > E \sim H_p$. This has been demonstrated for BeO Optically Stimulated Luminescence (OSL) dosimeters (Hoedlmoser et al., 2020; Otto, 2019), ^{7}LiF:Mg,Cu,P Thermoluminescence dosimeters (TLDs) (Eakins and Tanner, 2019; Ekendahl et al., 2020; Otto, 2019), $CaSO_4$:Dy TLDs (Polo et al., 2022), electronic dosimeters (Ekendahl et al., 2020; Otto, 2019), and Ag^+-doped phosphate glass RPL dosimeters (Bossin et al., 2022).

Nevertheless, these studies still do not include some widely used techniques, such as direct-ion-storage (DIS) dosimeters, or other types of TLD materials, such as $Li_2B_4O_7$:Mn,Si, $Li_2B_4O_7$:Cu, and $CaSO_4$:Tm. In particular, it would be interesting to see if there are major differences between the techniques or materials and understand how they can be adapted in the future to accurately estimate the new operational quantities. Furthermore, it is important to evaluate specific dosimetry systems, because the final energy and angle responses are not only a function of the technique or material, but also depend on the badge design, materials combined and algorithm used to combine the signal from the different detectors or detector materials.

The objective of the present work is to assess the photon energy and angular response of various dosimetry systems used commercially in terms of the operation quantities personal dose, H_p, and personal absorbed dose in local skin, $D_{\text{local skin}}$ defined in the ICRU Report 95. The energy and angular response of H_p and $D_{\text{local skin}}$ of five dosimetry systems used in Switzerland at the Paul Scherrer Institute (PSI), the Lausanne University Hospital (CHUV), the CERN, Dosilab, and the SUVA, were derived from their respective $H_p(10)$ and $H_p(0.07)$ responses using conversion coefficients from air kerma to respective quantities provided either in the ICRU Report 95 or ISO 4037-3:2019. This provides an overview of the status-quo for different measurement techniques — thermoluminescence (TL), optically stimulated luminescence (OSL), radiophotoluminescence (RPL), and direct ion storage (DIS-1) — as well as for different materials (BeO, Ag^+-phosphate glass, LiF:Mg,Ti, $Li_2B_4O_7$:Mn,Si, $Li_2B_4O_7$:Cu, and $CaSO_4$:Tm), badges (see Fig. 1), and algorithms. This work will serve to evaluate the challenges ahead, if those quantities are to be implemented.

2. Materials and methods

2.1. Dosimetry systems and measurement procedures

The systems and their descriptions used are listed and described in Table 1. It should be noted that DIS-1 dosimeters posses several chambers. The ones of interests provide dose estimates for either $H_p(10)$ in the low dose range (<4 mSv), $H_p(10)$ in the high dose range (>4 mSv), or $H_p(0.07)$. Here, the energy and angular response of the two latter chambers is presented. The energy and angle response of the $H_p(10)$ low dose range chamber is presented in the Supplementary Materials, Sections 1 and 2 respectively.

All of those systems are approved by the Swiss authorities to perform personal dosimetry. They have thus been previously characterised for their photon energy and angular response. This commissioning data is used as the basis of this study.

2.2. Calculation of responses for H_p and $D_{\text{local skin}}$

The responses in terms of the new ICRU Report 95 quantities H_p and $D_{\text{local skin}}$ were calculated from the response in terms of the ICRU 51 quantities $H_p(10)$ and $H_p(0.07)$ using:

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

where R_{new} and R_{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_{new} and h_{old}, the respective kerma to operational quantity conversion coefficients. The values for h_{new} were taken from the ICRU Report 95 Table A.5.2b for H_p and Table 5.4.1b for $D_{\text{local skin}}$. The values for h_{old} were extracted from the ISO 4037-3 (ISO, 2019). As the ICRU Report 95 does not provide conversion coefficient for the narrow series used to characterise the systems, these were taken from Behrens and Otto (2022).

Table 1
Description of the systems characterised within this study.

	Technique	Dosimetry service	Manufacturer	Material	Badge	Filters	Reader	Dose calculation software
a	RPL	Paul Scherrer Institute (PSI)	Chiyoda	Ag^{+}-doped phosphate glass type FD-7	GBFJ-0	ABS (0.05 mm); ABS (0.5 mm); Al (0.4 mm); Cu (0.3 mm); Tn (1.4 mm)	FDG-660	CDEC-Easy, Chiyoda Technol Corp.
b	OSL	University Hospital Lausanne (CHUV)	RadPro International GmbH	BeO	myOSL 4.0	PTFE (1.35 mm); Sn (1.20 mm); Cu (0.5 mm); ABS (0.45 mm)	myOSLraser 4.0	OSLDosimetry, RadPro Int.
c	TL	Dosilab	Panasonic	$Li_2B_4O_7$:Cu and $CaSO_4$:Tm	UD-802AT	PE (14 mg/cm^2); 2 × ABS (160 mg/cm^2); Pb (0.7 mm)	UD-7900	Panasonic TL algorithm with Dosilab linear optimisation
d	Direct ion storage	Paul Scherrer Institute (PSI), CERN	Mirion	–	DIS-1	–	DBR1	–
e	TL	SUVA	Rados	$Li_2B_4O_7$:Mn,Si	Rados TLD badge	Al (1 mm); PE (3 mm)	Rados RE 2000	WinTLD software

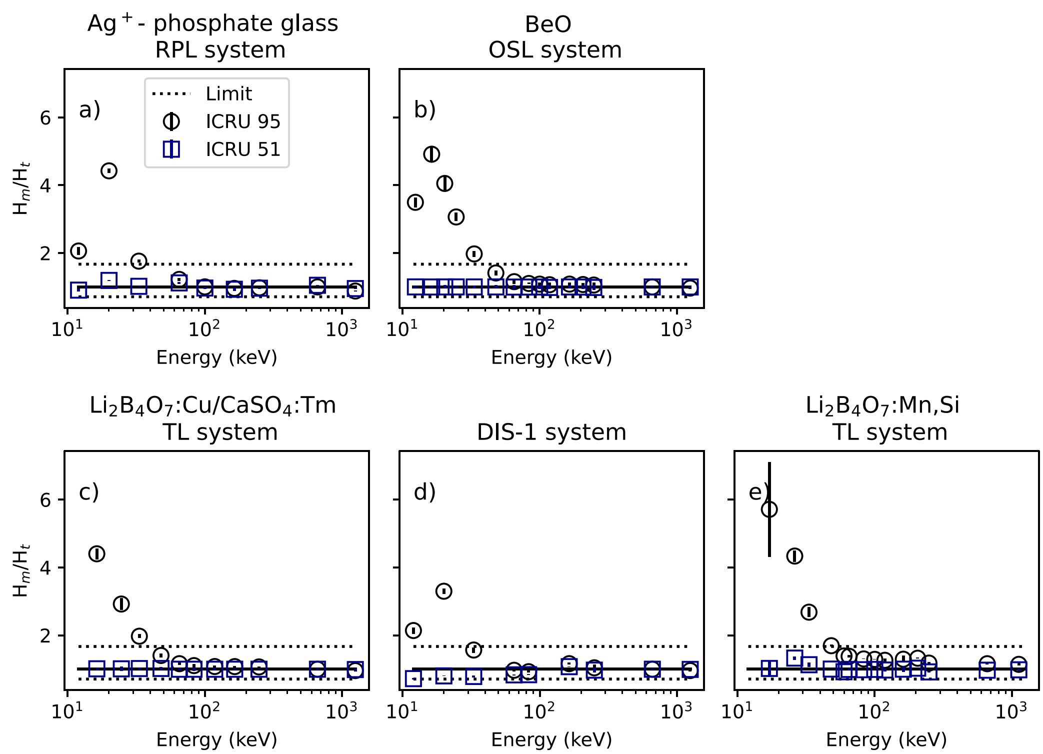

Fig. 2. Photon energy response in terms of the personal dose H_p (ICRU 95, open circles) or $H_p(10)$ (ICRU 51, blue squares) of (a) the RPL system used at PSI, (b) the BeO OSL system used at the CHUV, (c) the $Li_2B_4O_7$:Cu/$CaSO_4$:Tm TL system used by Dosilab, (d), the DIS-1 system used by PSI and the CERN, and (e) the $Li_2B_4O_7$:Mn,Si TL system used at the SUVA. The solid black line indicates the unity, the dotted black lines the IEC 62387:2020 limits for $H_p(10)$. The vertical lines represent the error bars, but are not discernible on most datapoints.

All the results are presented in terms of H_m/H_t, where H_m is the indicated value of the dosimetry system and H_t the conventional true value for the operational quantity in question.

2.3. Performance assessment

The requirements used here to assess the performances of the system are those of the IEC 62387:2020 (IEC, 2020) for $H_p(10)$ and $H_p(0.07)$, as performance requirements for the ICRU Report 95 quantities have not yet been established.

3. Results and discussion

3.1. Response in terms of the ICRU Report 95 definitions

3.1.1. Whole body monitoring

Fig. 2 shows the photon energy response of the systems presently used in terms of the personal dose H_p, and $H_p(10)$. Whereas all the systems were compliant with the IEC 62387:2020 in terms of $H_p(10)$, they show an over-response at energies <70 keV in terms of H_p. The over-response is of the order of four in this energy range. It is lesser for the DIS-1 systems, as they exhibited an under-response in terms of $H_p(10)$, both in the high-dose chamber and the low-dose chamber (see Supplementary Materials, Section 1). Dosimeters currently used have been optimised for a flat energy response to $H_p(10)$, whether it is by choice of appropriate detector and filter material or dose calculation algorithms combining different measured signals.

Fig. 3 shows the angular response in terms of H_p, and $H_p(10)$ for a N-40 radiation quality (33 keV mean energy) for angles up to ±60°. The data is normalised to the response for N-40 at 0°. Differences in angular response between the old and new quantity are negligible.

3.1.2. Skin monitoring

The dosimetry systems correctly estimate the personal absorbed dose in local skin, $D_{local\ skin}$ (Fig. 4). $D_{local\ skin}$ underestimates $H_p(0.07)$

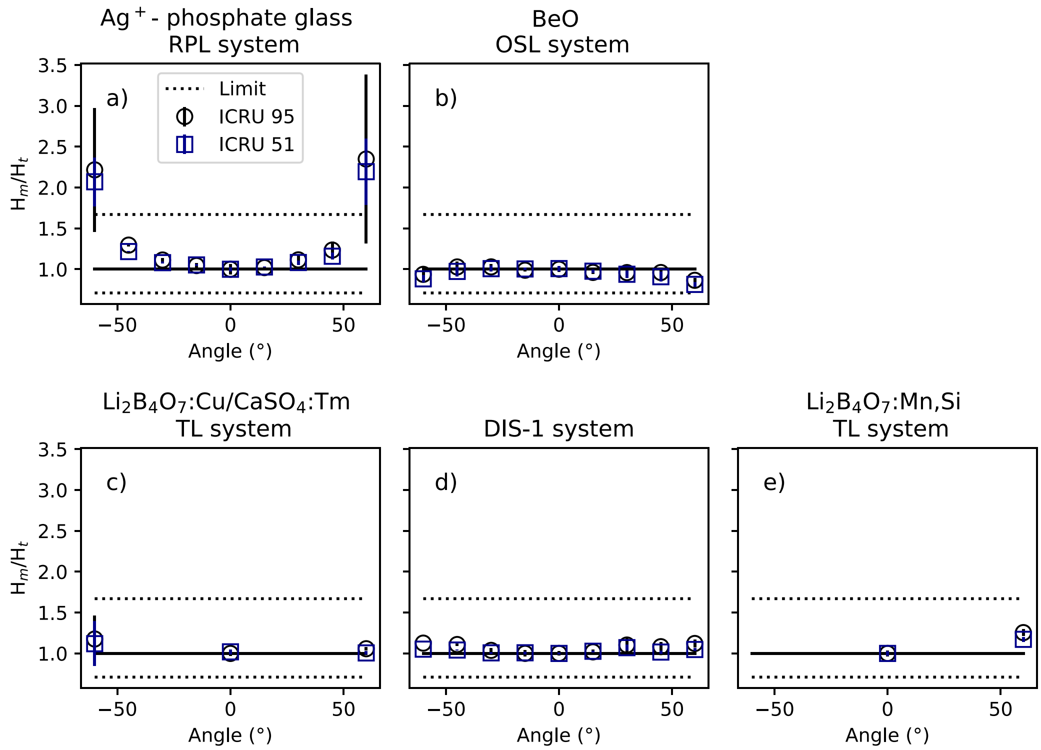

Fig. 3. Angular response in terms of the personal dose H_p (ICRU 95, open circles) or $H_p(10)$ (ICRU 51, blue squares) to a N-40 irradiation of (a) the RPL system used at PSI, (b) the BeO OSL system used at the CHUV, (c) the $Li_2B_4O_7$:Cu/$CaSO_4$:Tm TL system used by Dosilab, (d), the DIS-1 system used by PSI and the CERN, and (e) the $Li_2B_4O_7$:Mn,Si TL system used at the SUVA. The solid black line indicates the unity, the dotted black lines the IEC 62387:2020 limits for $H_p(10)$. The vertical lines represent the error bars, but are not discernible on most datapoints.

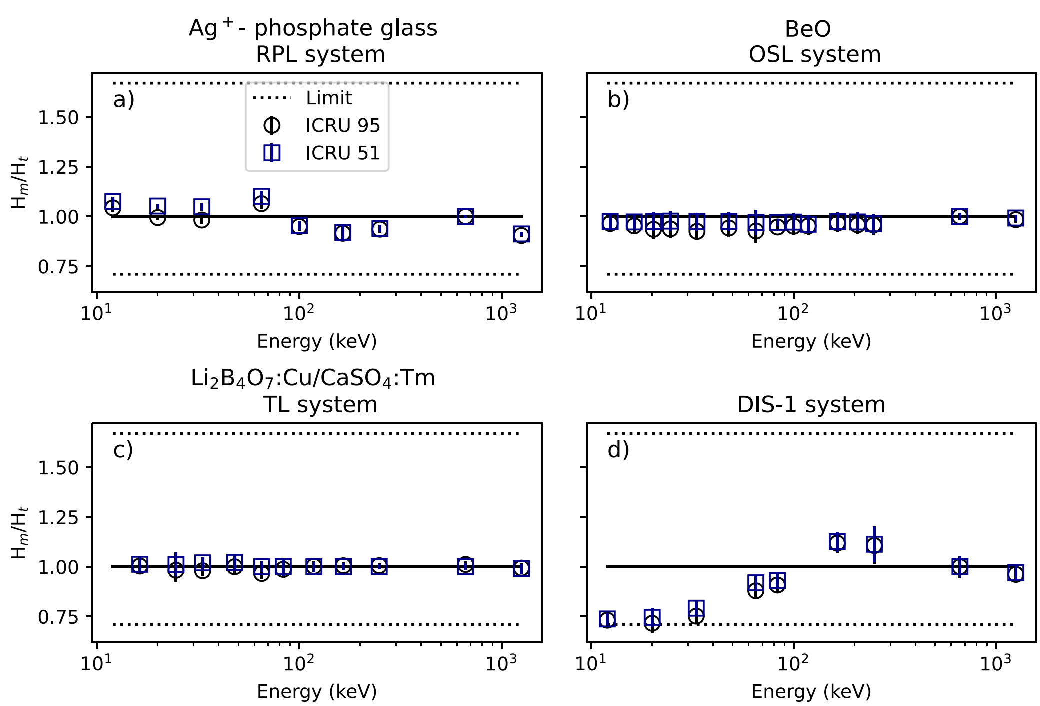

Fig. 4. Photon energy response in terms of the personal dose $D_{\text{local skin}}$ (ICRU 95, open circles) or $H_p(0.07)$ (ICRU 51, blue squares) of (a) the RPL system used at PSI, (b) the BeO OSL system used at the CHUV, (c) the $Li_2B_4O_7$:Cu/$CaSO_4$:Tm TL system used by Dosilab, and (d), the DIS-1 system used by PSI and the CERN. The solid black line indicates the unity, the dotted black lines the IEC 62387:2020 limits for $H_p(0.07)$. The vertical lines represent the error bars, but are not discernible on most datapoints.

by about 6% around 30 keV, which leaves the photon energy response for skin monitoring unaffected in the range of 12–1250 keV. Similarly, the angle dependence for the estimation of the personal absorbed dose in local skin $D_{\text{local skin}}$ differs little from that of $H_p(0.07)$ for the N-40 radiation quality tested (Fig. 5). This was expected, as the conversion coefficients from air kerma to $H_p(0.07)$ or $D_{\text{local skin}}$ are comparable.

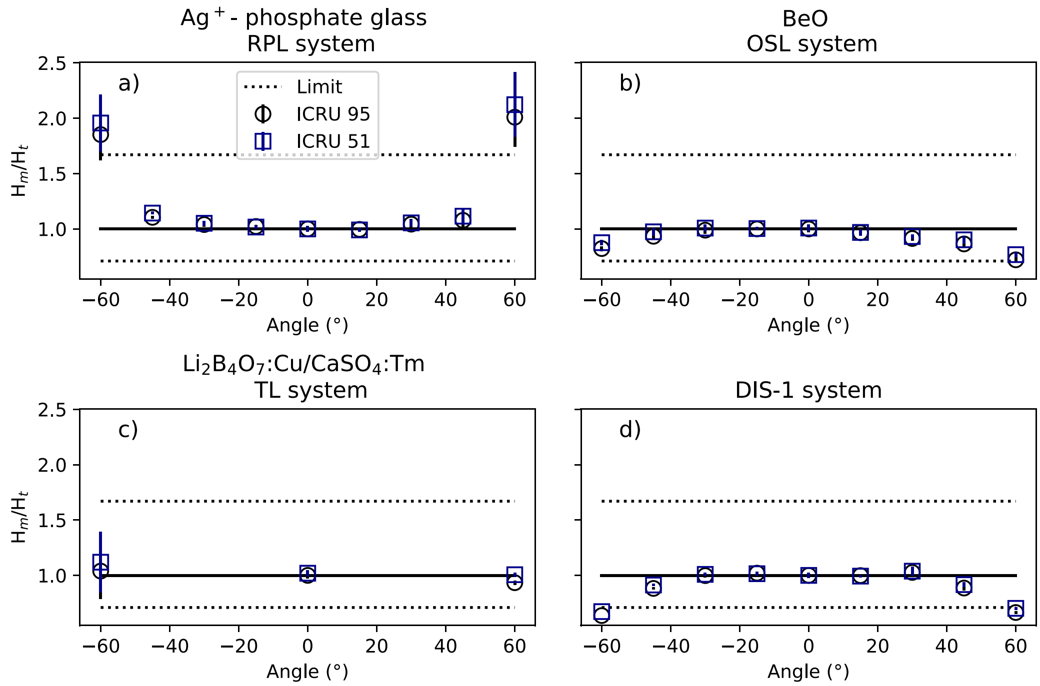

Fig. 5. Angular response in terms of the personal dose $D_{\text{local skin}}$ (ICRU 95, open circles) or $H_p(0.07)$ (ICRU 51, blue squares) to a N-40 irradiation of (a) the RPL system used at PSI, (b) the BeO OSL system used at the CHUV, (c) the $Li_2B_4O_7$:Cu/$CaSO_4$:Tm TL system used by Dosilab, and (d), the DIS-1 system used by PSI and the CERN. The solid black line indicates the unity, the dotted black lines the IEC 62387:2020 limits for $H_p(0.07)$. The vertical lines represent the error bars, but are not discernible on most datapoints.

3.2. Discussion

Most of the dosimeters used in Switzerland use multiple elements or multiple filters, thus giving multiple signals with varying photon energy responses. Typically, this difference in photon energy response can be used by an algorithm to assess the energy of the incident photons and correct the response accordingly. This has been investigated in greater details for the RPL dosimeter used at the Paul Scherrer Institute, and an algorithm capable of fulfilling the IEC 62387:2020's criteria for photons for H_p was developed (Bossin et al., 2022). It is outside the scope of this work to propose an algorithm for each of the available systems, but some of the challenges are already clear from this study.

Systems designed such that they can purely rely on the properties of detector and filter materials to obtain a correct response in $H_p(10)$ and $H_p(0.07)$, e.g. the two-element TLD system based on $Li_2B_4O_7$:Mn,Si and the DIS-1 dosimeters, will require an additional dose calculation algorithm. The $Li_2B_4O_7$:Mn,Si detectors are mostly energy independent in terms of $H_p(10)$ and $H_p(0.07)$ (Wall et al., 1982), as seen in Figs. 2 and 4. In the worst case, the dosimeter design could not allow an algorithm to properly discriminate photon energies, which is likely to yield erroneous estimates of H_p and $D_{\text{local skin}}$. Furthermore, since this algorithm relies on the ratio of different detector signals, the estimation of the photon energy may be biased when irradiating the dosimeter under angles larger than 0°.

Addressing mixed beta/photon fields is yet another challenge to be met. The data presented here is restricted to photon fields only. Any algorithm re-design must also take into account the variations in the response of the different detectors in a mixed beta/photon field. As an example, the presence of mixed beta/photon field does not affect the response of the two-element system based on $Li_2B_4O_7$:Mn,Si, since the detector elements are simply providing an indication of the absorbed dose at the respective depths of 0.07 mm and 10 mm. No photon energy determination is required. This is not the case anymore for the quantities H_p and $D_{\text{local skin}}$ of the ICRU Report 95.

In summary, whereas four or five element detectors coupled with a robust algorithm are likely to be able to assess the quantities H_p and $D_{\text{local skin}}$ in such variety of situations (Bossin et al., 2022), there is no such guarantee for simpler designs (e.g., two-element systems). In previous work done on two-elements systems based on tissue-equivalent materials (TLD-700), the choice was made to investigate a change in filter rather than algorithm (Eakins and Tanner, 2019). Furthermore, one of the systems used by two dosimetry services in Switzerland, the DIS-1 system (PSI/CERN) does not make use of an algorithm that could be adapted for the ICRU Report 95 personal dose quantity. It is possible that, by introducing multiple elements and filters, combined with a suitable algorithm, we can obtain a better photon energy response for direct (zero angle) irradiation. Nevertheless, it is also likely that this will result in a worse angle dependence and worse performance in mixed fields.

It is crucial to evaluate at an early stage what can be achieved in regards of the challenges listed above, and to weigh in the benefits versus drawbacks of introducing the new quantities proposed in the ICRU Report 95.

4. Conclusion

The results presented here confirm the fact that, without changes in dosimeter design and dosimetry algorithm, current dosimetry systems in use in Switzerland will over-estimate the quantity H_p, defined by the ICRU Report 95, by a factor of approximately four at photon energies <70 keV. On the other hand, the systems will continue to provide reasonable estimates for the quantity $D_{\text{local skin}}$ for all photon energies.

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 and this may be possible when using dosimeter containing multiple elements. Nevertheless, the investigation presented here is restricted to a few conditions and to photon irradiation only. The study needs to be extended to include the angular dependence for a wider range of photon energies, as well as mixed beta/photon fields. Such investigations will require a significant effort, particularly with respect to the algorithm development and testing.

The option of simply changing an algorithm does not seem to apply to simpler dosimeter designs containing only two elements.

Whereas previous work has proposed an algorithm to estimate H_p for photon fields using a five-elements system (Bossin et al., 2022), this work is yet to be extended to mixed fields, or simpler designs. Until research has shown the wider capability of an algorithm change, it is not clear if the benefits of adopting the recommendations of the ICRU Report 95 out-weight the costs.

CRediT authorship contribution statement

Lily Bossin: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Pierre Carbonez:** Writing – review & editing, Methodology, Data curation. **Jeppe Brage Christensen:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Miha Furlan:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Franziska Fürholz:** Writing – review & editing, Formal analysis, Data curation. **Sabine Mayer:** Writing – review & editing, Formal analysis, Data curation. **Andreas Pitzschke:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Eduardo Gardenali Yukihara:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.radmeas.2024.107207.

References

Behrens, R., Otto, T., 2022. Conversion coefficients from total air kerma to the newly proposed ICRU/ICRP operational quantities for radiation protection for photon reference radiation qualities. J. Radiol. Prot. 42 (1), 011519.

Bossin, L., Christensen, J.B., Pakari, O.V., Mayer, S., Yukihara, E.G., 2022. Performance of radiophotoluminescence personal dosimeters in terms of the ICRU Report 95's operational quantities. Radiat. Meas. 156.

Eakins, J., Tanner, R., 2019. The effects of revised operational dose quantities on the response characteristics of a beta/gamma personal dosemeter. J. Radiol. Prot. 39 (2), 399.

Ekendahl, D., Čemusová, Z., Kurková, D., Kapuciánová, M., 2020. Response of current photon personal dosemeters to new operational quantities. Radiat. Prot. Dosim. 190 (1), 45–57.

Hoedlmoser, H., Bandalo, V., Figel, M., 2020. BeOSL dosemeters and new ICRU operational quantities: Response of existing dosemeters and modification options. Radiat. Meas. 139, 106482.

ICRU, 1993. ICRU Publication 51. Quantities and Units in Radiation Protection Dosimetry. ICRU.

ICRU, 2020. ICRU Report 95. Operational Quantities for External Radiation Exposure. ICRU.

IEC, 2020. International Standard IEC 62387:2020. Radiation Protection Instrumentation - Passive Integrating Dosimetry Systems for Personal and Environmental Monitoring of Photon and Beta Radiation. International Electrotechnical Commission.

ISO, 2019. International Standard ISO 4037-3. Radiological Protection — X and Gamma Reference Radiation for Calibrating Dosemeters and Doserate Meters and for Determining Their Response as a Function of Photon Energy — Part 3: Calibration of Area and Personal Dosemeters and the Measurement of Their Response as a Function of Energy and Angle of Incidence. International Organisation for Standardization.

Otto, T., 2019. Response of photon dosimeters and survey instruments to new operational quantities proposed by ICRU RC26. J. Instrum. 14 (01), P01010.

Polo, I.O., Santos, W.S., de Moraes, C.V., Nicolucci, P., 2022. Response of a TLD badge to the new operational quantity $H_p(\theta)$: Monte Carlo approach. Radiat. Phys. Chem. 191, 109869.

Wall, B., Driscoll, C., Strong, J., Fisher, E., 1982. The suitability of different preparations of thermoluminescent lithium borate for medical dosimetry. Phys. Med. Biol. 27 (8), 1023.