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Impact of new operational dosimetric quantities on individual monitoring services

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IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING SERVICES

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Abstract. The new operational dosimetric quantities framework, proposed in the report ICRU95, has stimulated the scientific community to start investigations aiming at assessing its impact on radiation protection practices. As part of this effort, the present study describes an inter-comparison exercise among Individual Monitoring Services (IMS) on passive whole body dosimetry. The intercomparison is performed in terms of both the existing operational dose quantity $H_p(10)$ and its proposed replacement H_p , to allow an evaluation of the actions that may be necessary to adapt dosimetry systems to the proposed quantity. For two of the tested IMSs simple modifications to the detector response function, or the dose calculation algorithm, were sufficient to obtain results within acceptable limits. However, these approaches are not sufficient to give a level of performance comparable to that achieved in terms of $H_p(10)$. This may require a modification of dosimeter design.

Keywords: Operational quantities, Personal dosimetry, Dosimetry service.

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1. Introduction

In 2017 the International Commission on Radiation Units and Measurements (ICRU) and the International Commission on Radiological Protection (ICRP) issued a draft

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING SERVICES

for consultation containing a novel approach to external radiation exposure based on the introduction of new operational dosimetric quantities. These quantities include ambient dose, H^* and personal dose H_p for environmental and whole body personal dosimetry respectively. There are also new quantities for skin and eye lens dosimetry that are expressed in terms of absorbed dose instead of equivalent dose. The report based on the 2017 draft was published in late 2020 as ICRU Report 95 [1]. The main motivation was to tackle some issues with the existing operational dosimetric quantities. In some irradiation situations, for instance in high energy radiation fields, the operational quantities are not conservative with respect to the limit quantities such as effective dose etc. In other situations, such as low energy photons in the energy range of tens of keV, the operational quantities are overly conservative. A detailed description of the proposed new framework has been provided by Otto et al [2]. Unlike the current operational quantity for whole body personal dosimetry $H_p(d)$, the newly proposed quantity H_p , does not relate to a specific depth in tissue. It is instead based on effective dose and is calculated across the whole energy spectrum using an anthropomorphic computational phantom [3]. For calibration of dosimeters, the same conversion coefficients can be used on surrogates of the computational phantoms such as the ISO water slab phantoms or the ISO PMMA (polymethyl methacrylate) rod phantom [4] [5], without important variations [1]. However, the proposed change to H_p implies a variation in a dosimeters response because of the change of conversion coefficients. References [6], [7] and [8] report theoretical studies of how a change to H_p would affect the responses of existing photon dosimeters. As expected, these studies show that the responses of the dosimeters are not fitting for the new quantity below an energy of 50 keV.

The new operational quantities will have a significant impact in terms of new procedures, education of personnel, adaption of calibration facilities, re-characterization of dosimetry systems, modification of existing dosimeters. In this view, EURADOS [9] set up a task group with the aim of preparing a report on the consequence of the introduction of the new quantities on radiation protection practices. In the framework of this effort, this paper focuses on an experimental comparison between $H_p(10)$ and H_p , describing an inter-comparison exercise among Individual Monitoring Services (IMS) in terms of both quantities. In particular two participants to the standard (i.e. referring to the existing quantities) inter-comparison exercise, agreed to characterize their dose evaluation algorithm in terms of H_p , based on the conversion coefficients reported in [8]. The results in terms of existing operational quantities and in terms of H_p have been processed according to the standard ISO 14146 [10].

2. Inter-comparison organization

The whole body dosimetry inter-comparison has been organized by the laboratory of Metrology of Ionizing Radiation (LaMIR) at the Department of Energy of the Politecnico di Milano. It has been carried out as part of the process leading to the accreditation of

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING S

Table 1. Radiation qualities used for the inter-comparison exercise.

Radiation quality	Irradiation angle	Dose range (mSv)
W-60	0°	1.6 - 2.4
W-80	0°	0.8 - 1.2
W-110	0°	1.6 - 2.4
W-110	45°	5.5 - 7.0
W-300	0°	1.6 - 2.4
S-Cs	0°	0.4 - 0.6
S-Cs	0°	1.2 - 1.8
S-Cs	0°	4.0 - 6.0
S-Cs	0°	40.0 - 60.0
S-Cs+W-60 ^a	0°	0.8 - 1.2

^a The dose in the mixed field irradiation is equally distributed between the two irradiation qualities.

the LaMIR as proficiency test provider. Seven IMSs participated in the inter-comparison exercise, with a total of 9 dosimeter sets (an IMS could participate with more than one dosimeter type) and the quantities used were $H_p(10)$ and $H_p(0.07)$, both on the ISO water slab phantom. The participants used two different dosimeter types:

- Two dosimetry systems based on film-badge;
- Seven dosimetry systems based on TL (thermoluminescence) detectors;

Each dosimetry system is identified with a letter from A to L (leaving out I, J and K).

The irradiation scheme is reported in table 1. The dose ranges indicated in table 1 were given to the irradiation laboratory, but were unknown to the participants. The participants expected the irradiation in a dose range 0.4 - 60 mSv, but had no knowledge of the association between energy and dose range.

A graphical representation of the IMSs performance in terms of $H_p(10)$ is shown in Figure 1. Each tested dosimetry system is indicated by a letter. The comparison is presented as response R , i.e. the dose measured by the IMS divided by the reference dose certified by the irradiation laboratory. The continuous lines indicate the acceptance limits as proposed in the standard ISO 14146 [10]. Only two dosimetry systems, namely E and F, present underestimations lower than the minimum acceptance limit, for a number of experimental results greater than 10% of the total (maximum allowed by ISO 14146). Figure 2 reports the results in terms of $H_p(0.07)$ and confirms the underestimation of the above indicated dosimetry systems. The graph shown in Figure 3 highlights the systematic deviation by specific radiation quality. In this case the almost flat response in terms of $H_p(10)$ indicates that, on average, the response of the dosimetry systems is energy independent.

3. Data analysis in terms of H_p

When moving from the existing operational dosimetric quantities to H_p , the impact on the dosimetry systems can be identified in one of the following scenarios, sorted by

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING S

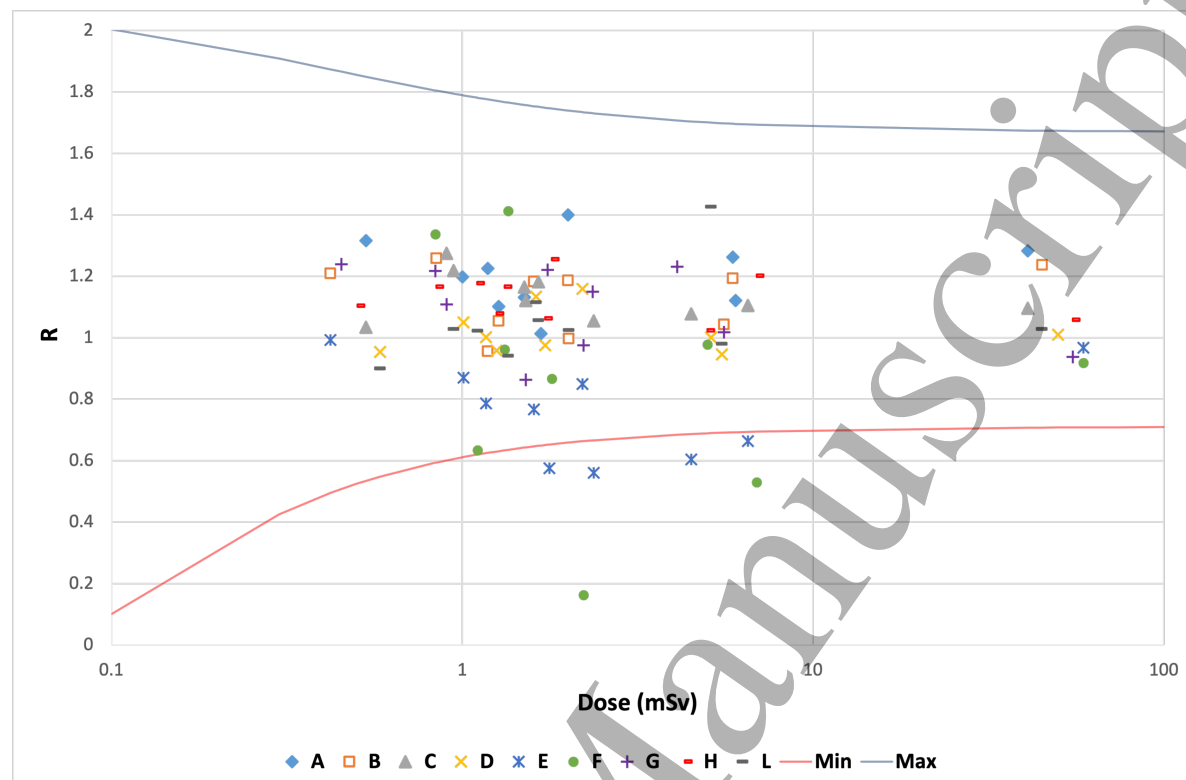


Figure 1. Results of the inter-comparison in terms of $H_p(10)$. The ordinate shows the ratio R of the dose measured by the IMS, normalized to the reference dose of the irradiation.

increasing severity:

- (i) The dosimeter responds well "as it is", or simply applying an energy independent correction coefficient.
- (ii) The dosimeter needs a modification of the response function by changing the reference value of the radiation qualities, but the dose calculation algorithm works well also with the new response function.
- (iii) The algorithm of dose calculation must be modified but the design of the badge works well also for H_p .
- (iv) None of the above give a satisfactory response, in which case the specified energy range of the dosimeter must be restricted or a new design of the dosimeter badge is needed.

The scenario (i) is of course the desirable one, but very unlikely to occur. Scenarios (ii) and (iii) are manageable without a serious impact on the cost. At the other extreme, scenario (iv) will have significant impact in terms of the time and cost involved in developing and commissioning a new dosimeter badge.

It is worth specifying that the analysis presented in this work is not exhaustive because the number of energies/irradiation and irradiation angles is limited and lower than the minimum needed for a complete type test. Also, the number of the tested

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING S

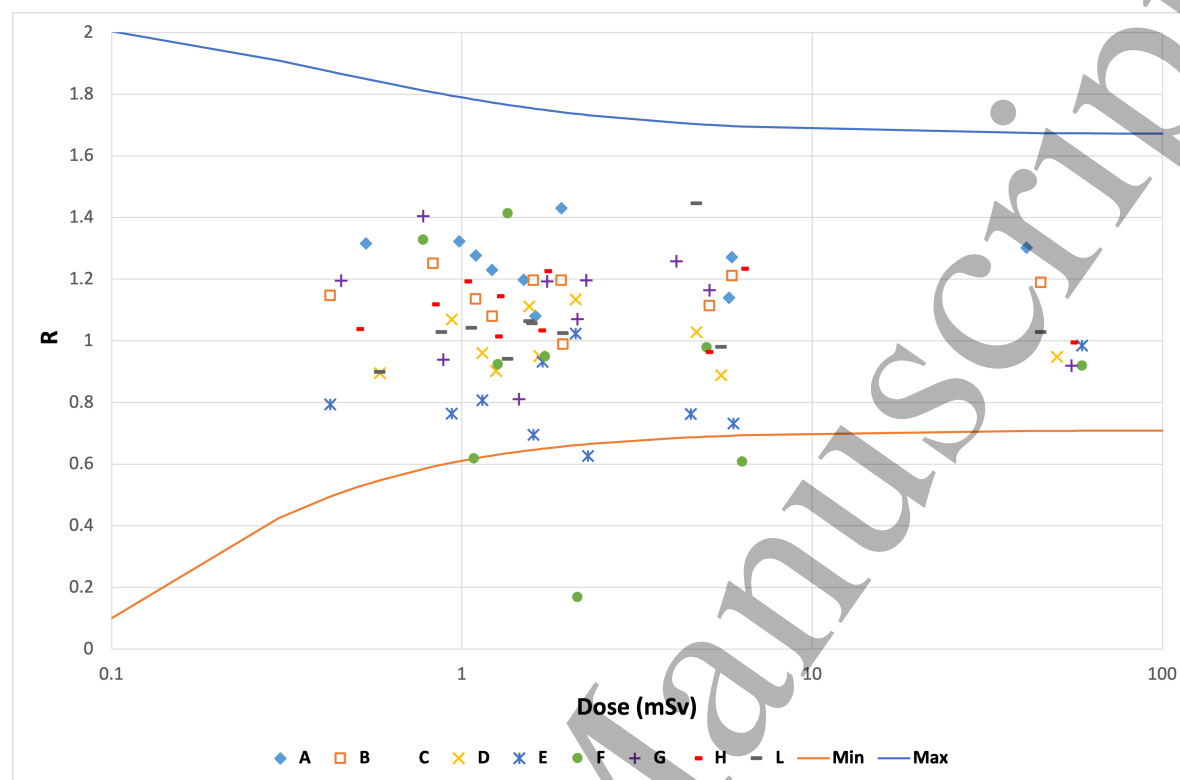


Figure 2. Results of the inter-comparison in terms of $H_p(0.07)$. The ordinate shows the ratio R of the dose measured by the IMS, normalized to the reference dose of the irradiation.

dosemeter types is only a subset of the existing ones. In this framework, the aim of our analysis is to identify which is the scenario more likely to occur. Dosimetry systems E and F were excluded from this analysis because they did not provide results within the acceptance limits in the standard inter-comparison, i.e. in terms of $H_p(10)$.

To check scenario (i), the same representation has been chosen in the figures expressing the reference dose in terms of H_p and maintaining unchanged the results given by the IMS as $H_p(10)$. The reference values for H_p were obtained applying the conversion coefficients reported in table 2 and taken from [8]. As the new conversion coefficients $h_{pK}(\alpha)$ are lower than the previous ones $h_{pK}(10; \alpha)_{\text{slab}}$, especially at low energies, the values are shifted to higher values of R , indicating an overestimation more pronounced at qualities W-60 and W-80 (Figure 4).

A first attempt to double check the validity of scenario (i), without modification of either the dosimeter badge or its algorithm, was to identify a normalization coefficient C_n , energy independent, to apply to the data referenced to $H_p(10)$. If the normalization coefficient exists it means that scenario (i) could be valid option. C_n was tuned in the range 1 - 1.5, to get the mean value of R referenced to H_p equal to one for $S - Cs$ irradiation. In principle it is possible to normalize also to different energies, and probably get better results. However in this paper the focus is more on the approach rather than a fine tuning. Figure 5 compares the R values with and without the normalization

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING S

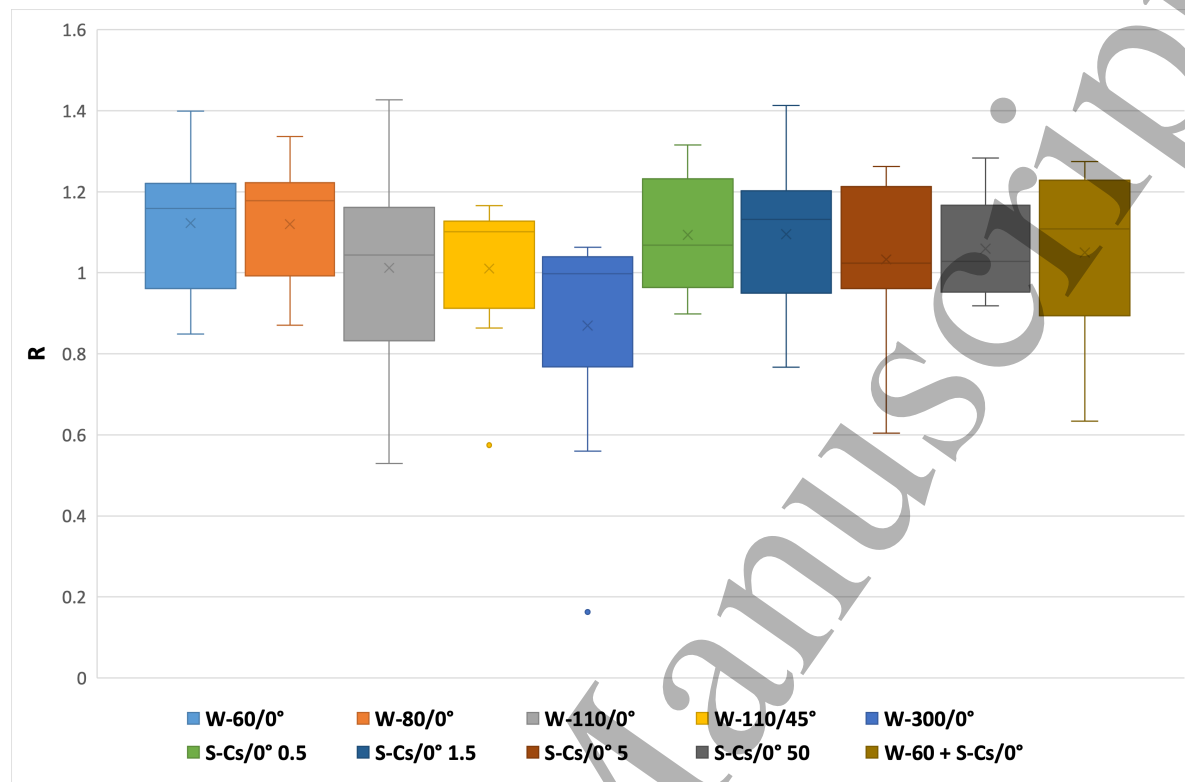


Figure 3. Box plot representation of the results of the inter-comparison in terms of $H_p(10)$. The ratio R is grouped per radiation quality, assembling the results of all the IMSs. The line inside boxes is the median, the x is the mean, the box is the interquartile range and the whiskers represent the 2nd and the 98th percentile. The points external to the whiskers indicate clearly wrong dosimetric results.

Table 2. Conversion coefficients for total air kerma to personal dose H_p and for total air kerma to dose equivalent $H_p(10)$ for radiation qualities of inter-comparison.

Radiation quality	$h_{pK}(\alpha)$	$h_{pK}(10; \alpha)_{\text{slab}}$
W-60 - 0°	0.8906 (0.8879) ^a	1.55
W-80 - 0°	1.1772	1.77
W-110 - 0°	1.4021	1.87
W-110 - 45°	1.2042	1.72
W-300 - 0°	1.1545	1.47
S-Cs - 0°	1.0158	1.21

^a The conversion coefficients are indicated for a distance of 2.5 m between the X-ray tube and the point of irradiation; for a distance of 1.0 m we apply the values in brackets.

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING S

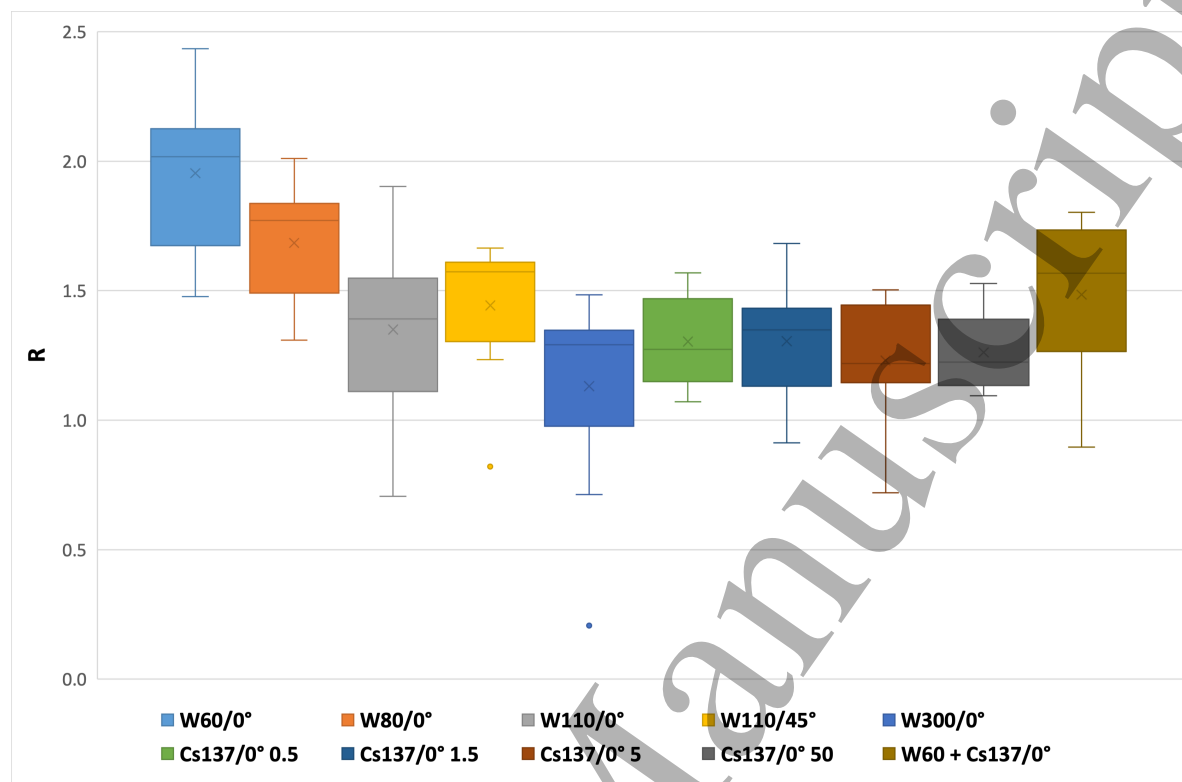


Figure 4. Box plot representation of the results of H_p without normalization coefficient. R is grouped per radiation quality, assembling the results of all the IMSs. The line inside boxes is the median, the x is the mean, the box is the interquartile range and the whiskers represent the 2nd and the 98th percentile. The points external to the whiskers indicate clearly wrong dosimetric results. The overestimation is more pronounced at low energies.

coefficient. Even though the results are within the limit of the trumpet curves, the overestimation at low energies is still evident. Thus, scenario (i) can work for this specific inter-comparison exercise, but as several points are rather near the upper limit, it doesn't seem a reliable approach.

A second, more detailed analysis involved directly the two IMSs that recalculated the response function of their dosimetry systems basing on the coefficients reported in [8] and optimize consequently the algorithm as discussed below. This kind of analysis allows one to check if the scenario (ii) and partially scenario (iii) are likely to occur. The first IMS participated in the inter-comparison with two identical sets of dosimeters (only different readers used). The dosimeter is composed of two detectors, both TLD-100 (Thermo Scientific Harshaw). One detector is covered by a thin (0.2 mm) plastic layer for protective purposes. The second detector is shielded by a 1.5 mm thick Aluminum filter. With this configuration the ratio of the two readings is a monotonic function of photon energy. The dosimeter is characterized in terms of $H_p(10)$ with reference irradiation at different beam qualities, typically N and W series and S-Cs, according to the ISO 4037. The response function is normalised to S-Cs. The new response function

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING S

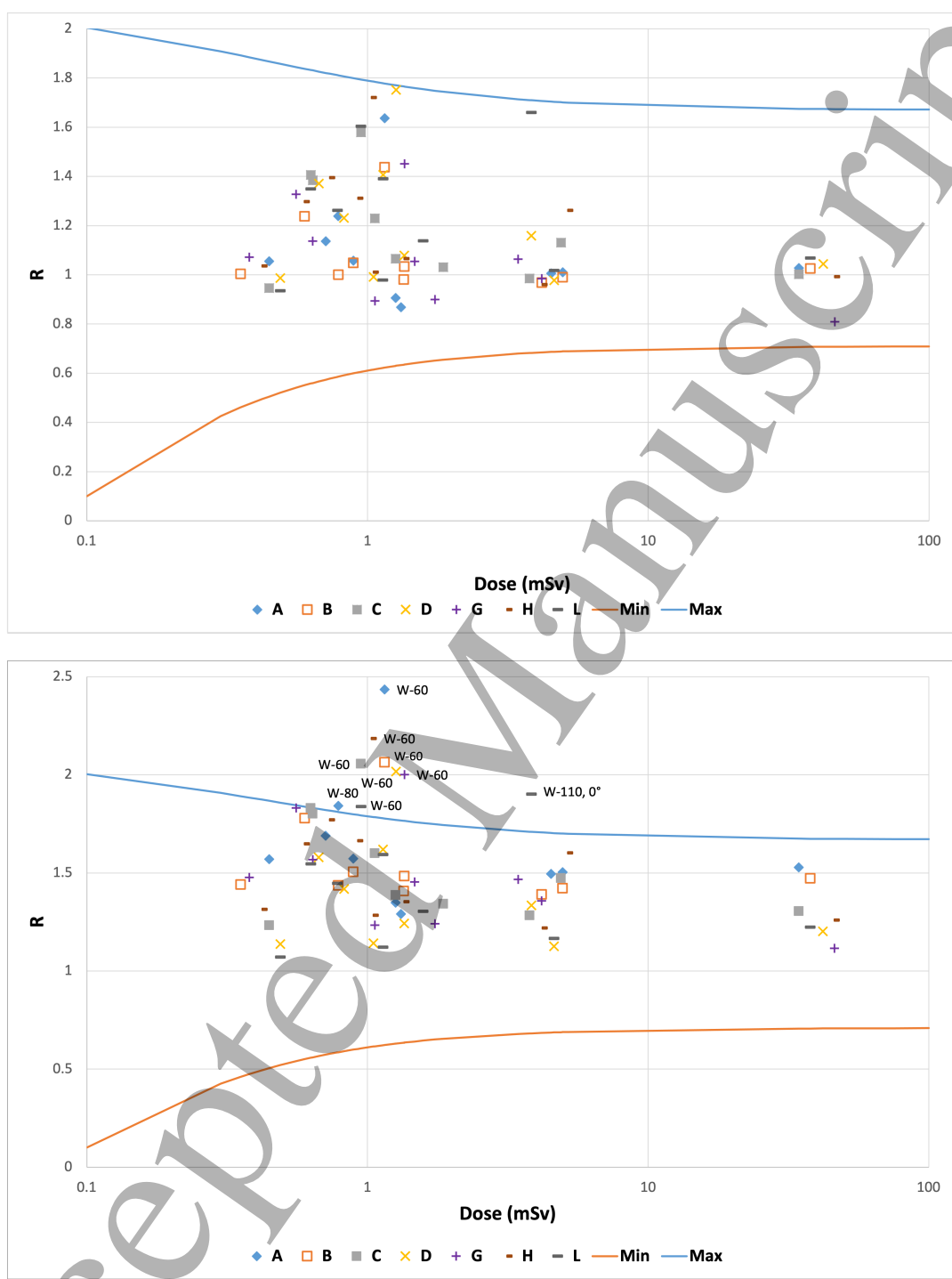


Figure 5. Results in terms of H_p with (top) and without (bottom) the energy independent normalization coefficient

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Table 3. Panasonic UD-802A badge: structure and composition

Detector	Composition	Overall front filtration (mg/cm ²)	Overall rear filtration (mg/cm ²)
1	ⁿ Li ₂ B ₄ O ₇ :Cu	plastic: 14	plastic: 28
2	ⁿ Li ₂ B ₄ O ₇ :Cu	plastic: 303	plastic: 303
3	CaSO ₄ :Tm	plastic: 303	plastic: 303
4	CaSO ₄ :Tm	plastic: 143 lead: 874	plastic: 143 lead: 874

in terms of H_p has been obtained by re-scaling the reference irradiation with the new conversion coefficients. The personal dose is calculated multiplying the response D of filtered TL detector referred to S-Cs by the response function in terms of H_p .

The second IMS uses a whole body dosimeter which is sensitive to beta, X and γ radiation. It consists of a transparent plastic outer casing (of dimensions 50x50x14 mm) with the Panasonic TLD badges UD-802A series. The badge contains four thermoluminescent detectors covered with different protective material and/or shielding. The choice of thickness and front and rear construction of the dosimeter serves the purpose of providing a more selective response to radiation of different nature and energy. Table 3 shows the composition of each thermoluminescent detector and the overall front and rear thickness of the different materials that shield each of them. The different elements and filtrations enable the discrimination of the radiation-type through the ratio between the light counts of different elements. The personal dose equivalent is calculated through equation 1 that uses only signals from the 2nd and 3rd element.

$$D = (C_2 - B_2) \cdot S_{Cs-kerma} \cdot F\left(\frac{C_3 - B_3}{C_2 - B_2}\right) \quad (1)$$

where:

- D is the personal dose equivalent $H_p(10)$
- C_2, C_3 are the signals of the 2nd and 3rd element
- B_2, B_3 are the background signals of the 2nd and 3rd element
- $S_{Cs-kerma}$ is the response function in terms of air kerma
- $F\left(\frac{C_3 - B_3}{C_2 - B_2}\right) \left[\frac{Sv}{Gy}\right]$ is a fourth order polynomial function correlating the air kerma to $H_p(10)$

To move from $H_p(10)$ to H_p , the dosimetric algorithm keeps unchanged the equation 1 but modifies the polynomial function. This approach can be regarded as a change of algorithm and so connected to the scenario (iii). According to the confidentiality rules of the inter-comparison exercise, results of these three sets will be presented anonymously, using the codes S1, S2 and S3.

To better understand the effect of the new dosimetric quantities, Figure 6 shows the result to the regular inter-comparison, Figure 7 shows the results in terms of $H_p(10)$ compared with H_p as reference, Figure 8 shows the impact of the correction with the

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING S

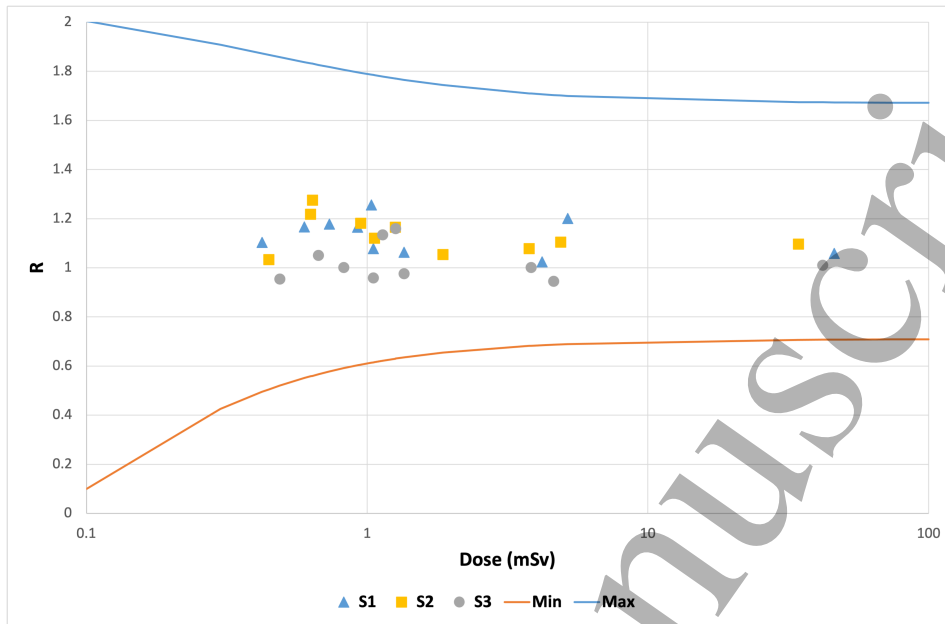
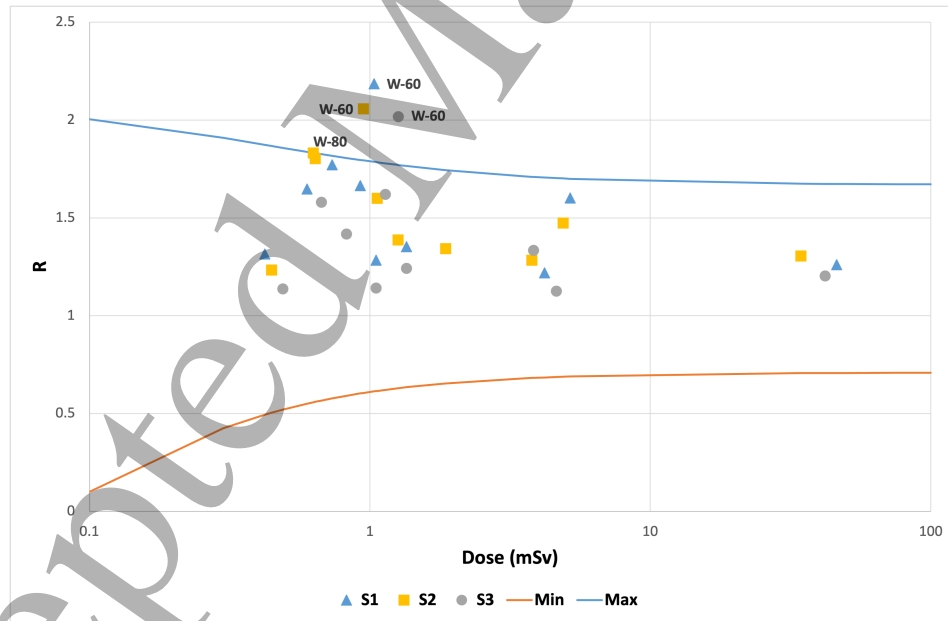


Figure 6. Inter-comparison results in terms of $H_p(10)$ of the two selected IMSs



Hp10.png

Figure 7. Inter-comparison results in terms of $H_p(10)$, referenced to H_p , of the two selected IMSs

energy independent normalisation constant, as described above, and Figure 9 shows the results with the modified algorithm.

4. Discussion and conclusion

The analysis of the whole data set and in particular the comparison of Figure 3 and Figure 4 shows that the impact of the new dosimetric quantities is mostly on the beam

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING S

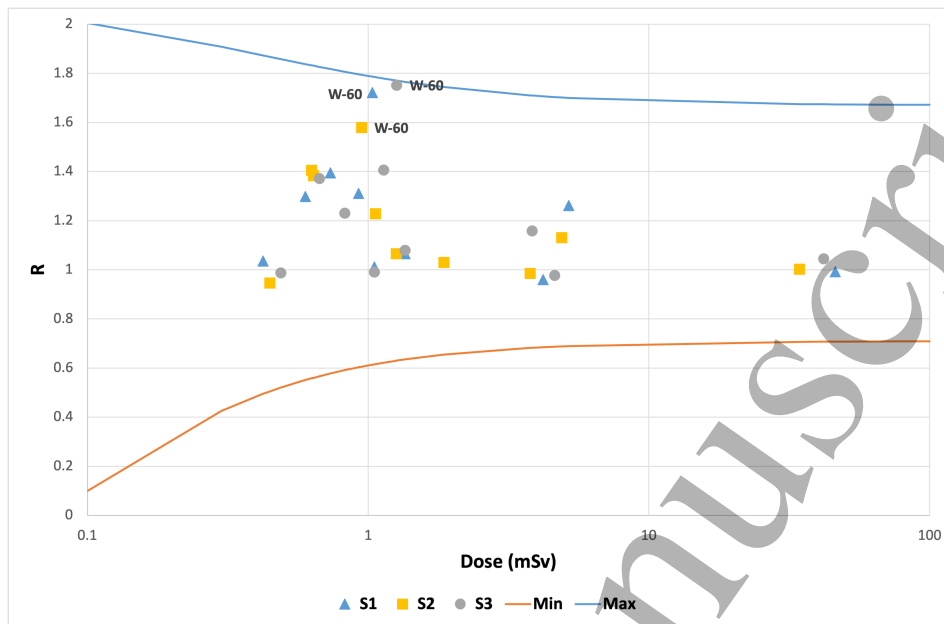


Figure 8. Inter-comparison results referenced to H_p and corrected with the energy independent normalization constant

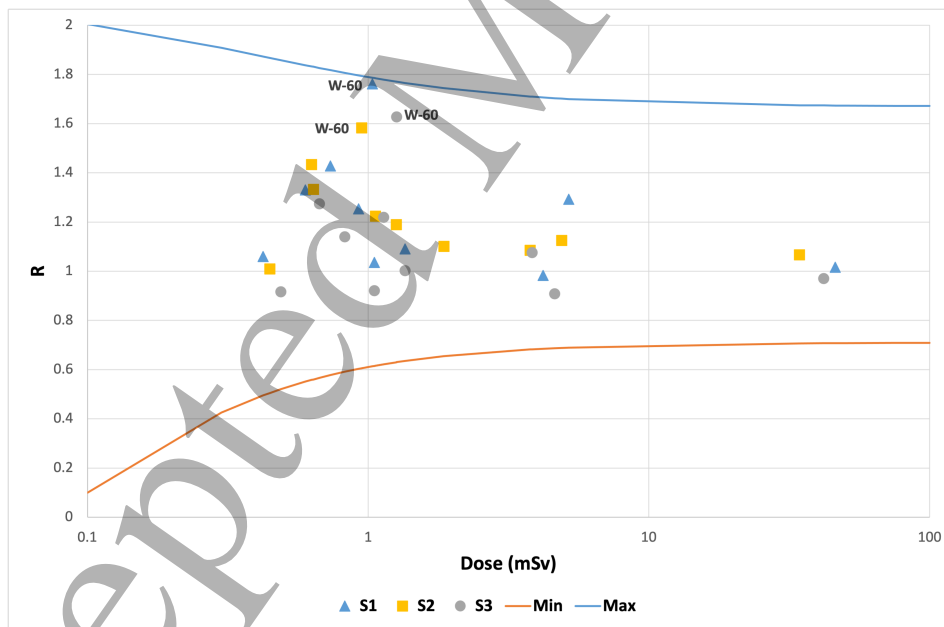


Figure 9. Inter-comparison results in terms of H_p of the two selected IMSs, after the modification of the dosimetric algorithm

qualities W-60 and W-80, with mean energy about 45 keV and 54 keV respectively. It is assumed that the effect will be more significant at lower energies. This is an expected result considering the difference of the conversion coefficients for $H_p(10)$ and H_p as reported in table 2 and agrees with [11], where a similar overestimation at low energies is reported for whole body dosimeters based on BeOSL technology. The effect of the

IMPACT OF NEW OPERATIONAL DOSIMETRIC QUANTITIES ON INDIVIDUAL MONITORING SYSTEMS

normalization coefficient C_n has a positive impact although the response values R are, on average, much larger than unity, indicating an overestimation of the dose assessed by the dosimeter. No particular difference between TLD and Film-badge based dosimeters is noted. Strictly speaking, the result of hypothetical proficiency test were positive, although the rather large number of points close to the upper limit makes this approach questionable. This means that it is difficult to think of scenario (i) as a reliable option. Scenarios (ii) and (iii) have been checked by asking two IMSs to recalculate their response function. Unfortunately, this second approach doesn't lead to significant improvement. Comparing Figure 8 and Figure 9 it is evident that the tendency to values $R > 1$ is still dominant. Thus, for the two specific dosimetry system analysed in this work neither scenario (ii) nor scenario (iii) seem to be a valid option. Probably there is room for a finer tuning of the algorithms, but it seems unlikely to get a performance in H_p comparable to the one in $H_p(10)$, without a physical modification of the badge. This means that scenario (iv) cannot be excluded a priori. As mentioned above, the authors are aware that this analysis is limited and does not represent a type test. However, scenario (iv) may have a financial impact on IMSs and consequently on the end users.

If the new operational quantities will be accepted by the scientific community, their introduction into national legislation will take 15 - 20 years. In this long period, there is time for the scientific community to react, adapting progressively to the new framework. For instance, primary and secondary standard calibration laboratories could provide irradiation certificates reporting both existing and new operational quantities. This can be done without significant additional cost as the irradiation setup is the same. In this way, IMSs can characterize their system in both existing and new quantities. Proficiency test providers can consider exercises similar to the one presented in this work, involving a wider number of dosimetry systems and a wider number of radiation qualities. Such an approach would allow IMSs to gain confidence in the new operational quantities and determine to what extent existing dosimeter badges can be used as they are without reducing the quality of dosimetric results. Alternatively IMSs can identify the best way to modify the different methods or badges design to optimize the response to the new operational quantities.

5. Acknowledgements

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