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Performance assessment of commonly used active radiation protection dosimeters for individual and area workplace monitoring

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ABSTRACT

Background: Improvement in radiation protection practice may be achieved by acquisition of reliable and accurate dosimetry data. Use of dosimeters with known properties provides insight into their performance in real radiation fields encountered in radiation monitoring practice.
Aim: Performance evaluation in a wide range of radiation conditions provides insight into dosimeter behaviour, providing input for revision, update and harmonization of IEC type testing standards.
Methods: A total of 32 active dosimeters were investigated, of which 26 are used for area workplace, and 6 for individual monitoring. Dosimeter performance was evaluated against the IEC 60846–1:2009 standard for portable workplace and environmental meters and monitors and the IEC 61526:2024 standard for active personal dosimeters in a wide range of photon energies, angles of incidence and dose equivalent rates. Performance was examined beyond the minimum rated range: 33.3 keV–1.25 MeV photon energy; (0°; ±75°) angle of incidence for personal dosimeters and (0°; ±120° with 180°) for area dosimeters; 3 μSv h^{-1} – 7 Sv h^{-1} dose rate range. In addition, dosimeter short-term stability and overload properties were investigated.
Results: State-of-the-art and commonly used dosimeters complied with the standard defined limits of variation with respect to the manufacturer stated specifications. Some dosimeters had significantly lower variations in terms of relative response than the current standard stated requirements.
Conclusion: Potential update of the relevant IEC type testing standards was considered, with the possibility of introducing two distinct dosimeter classes, one of which would comply with reduced limits of variation.

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1. Introduction

Radiation protection of exposed workers and the general public is regulated by various national acts, decrees and additional regulations with respect to the established exposure limits which are internationally recognized. In practice, this is achieved through individual and area monitoring programs (IAEA, 2018; Vanhavere & Van Hoey, 2022). Accurate and reliable dosimetry data can be acquired by using dosimeters which comply with relevant international standards (Calvacante et al., 2025; Yasar et al., 2017).

According to European regulations (Euratom, 2013), individual monitoring is mandatory for category A radiation workers, whereas individual monitoring is optional in the case of category B radiation workers. However, sufficient measurements need to be performed to adequately classify exposed workers. Monitoring is realized either through individual monitoring of exposed workers or through workplace area monitoring. In most countries, legal dosimetry data is obtained by passive dosimetry systems for both area and individual monitoring applications, which are commonly based on thermoluminescent dosimeters (TLDs) or optically stimulated luminescence dosimeters (OSLDs) (Stanković Petrović et al., 2021; Vanhavere & Van Hoey, 2022). Some countries require the use of active personal dosimeters (abbreviated as PDs) in addition to passive ones, in certain exposure scenarios, where the dose rate is sufficiently high, surpassing the established national threshold (Abuelhia & Alghamdi, 2020; Ciraj-Bjelac et al., 2018; O'Connor et al., 2021; Ramadhan et al., 2024).

PDs are usually based on semiconductor Si-diode detectors or Geiger-Müller (G-M) detectors. Their main advantage is the possibility of real-time dose indication, accompanied with audio and/or visual signal if a certain threshold is surpassed, as well as the measurement of doses below the detection limit of most passive dosimeters (Pavelić et al., 2019). Existing research has highlighted that PDs exhibit unreliable performance in low-energy and/or pulsed radiation fields (Ankerhold et al., 2009; Cui et al., 2024; Hupe et al., 2019; Kržanović et al., 2017; Li et al., 2025; Yasar et al., 2017). These irradiation conditions are encountered in medical applications of X-rays, particularly in interventional radiology procedures. Taking these findings into consideration, further testing under such conditions would provide more insight into the state-of-the-art dosimeter performance, optimizing the radiation protection of exposed workers.

Area monitoring can be categorized into workplace monitoring, which is used for evaluation of the effective doses to exposed workers, and environmental monitoring, essential for monitoring of background radiation and possible variations due to the release of artificial man-made radiation sources in the environment. Active area dosimeters (abbreviated as ADs) commonly utilize detectors based on G-M tubes. Additionally, semiconductor detectors, pressurized ionization chambers and scintillation detectors are often encountered in workplace monitoring practice (Alomairy, 2023; Pavelić et al., 2019). Workplace monitoring covers a wide range of applications and photon energies, spanning from low-energy medical applications to high-energy nuclear technology applications. Besides focusing on different workplace monitoring exposure scenarios, the relevant type testing standards also pertain to installed/mounted equipment and portable monitoring devices. Previously conducted research evaluated the performance of several commonly used ADs for workplace monitoring, showcasing strong energy dependence at low photon energies for some of the G-M tube-based devices, highlighting their inadequate energy compensation (Ćeklić et al., 2014). In the case of environmental area monitoring G-M tubes are commonly used in non-governmental radiation monitoring networks, including detectors with different geometries and volumes, measurement ranges, sensitivity, and different radiation-based characteristics. Even though these devices may comply with the relevant standard in the minimum rated range, they displayed significant over-response when exposed to low-energy radiation fields (Morosh et al., 2021).

There are several IEC standards which provide requirements for different types or uses of radiation protection dosimeters, such as IEC 60846–1:2009 (IEC, 2009) for workplace area dosimeters and IEC 61526:2024 (IEC, 2024) for personal dosimeters. This research is part of a larger effort to propose updates and harmonization of IEC standards for type testing of radiation protection dosimeters, initiated already in the 17RPT01 DOSEtrace project (Kržanović et al., 2022). The effort of IEC standard update and harmonization is pursued by 22NRM07 GuideRadPROS project (GuideRadPROS, 2025) and European Metrology Network for radiation protection (Alves et al., 2024). Data necessary for the update of standards include overview of the existing standards, collection of existing calibration and type testing data, data on dosimeter use, overview of the current state-of-the-art and upcoming technologies.

In order to test the dosimeter performance against the IEC requirements, 32 active dosimeters have been examined in this work. A measurement protocol was derived and implemented in the Secondary Standard Dosimetry Laboratories (SSDL) participating in the project. The protocol was drafted to collect missing data on dosimeter performance, following the survey of existing papers on dosimeter testing (Kržanović et al., 2019; Morosh et al., 2021; Ćeklić et al., 2014; Đaletić et al., 2025) and the historical calibration data of the 22NRM07 GuideRadPROS participants. Performance of ADs and PDs was evaluated against the requirements defined in IEC 60846–1:2009 (IEC, 2009) and IEC 61526:2024 (IEC, 2024) standards, respectively.

Following the IEC type testing methodology, the influence quantity minimum rated ranges, as well as the performance requirements in terms of variation in dosimeter response, this research aimed to investigate the performance of selected active radiation protection dosimeters in an expanded test range covering various ionizing radiation practices. Testing beyond manufacturer stated ranges would provide the knowledge on their usability in specific scenarios (such as low-energy radiation fields characteristic for diagnostic and interventional radiology applications, or the use of area workplace dosimeters for environmental monitoring applications). Additionally, performance characteristics could provide input in future revisions of the IEC standards by re-evaluation of the current performance requirements, the influence quantity test ranges and/or by exploring the prospect of introducing two distinct dosimeter classes.

2. Materials and Methods

2.1. Secondary Standard Dosimetry Laboratories

Several SSDLs participated in the data collection using the developed measurement protocol presented below in section 2.4. The SSDLs which took part in this study include the Vinča Institute of Nuclear Sciences (*VINS*), the Turkish Energy, Nuclear and Mineral Research Agency (*TENMAK*), Czech Metrology Institute (*CMI*), Institute Ruđer Bošković (*IRB*), Greek Atomic Energy Commission (*EEAE*), National Institute of Metrology (*INM*) and the Belgian Nuclear Research Centre (*SCK CEN*). All SSDLs have established Quality Management Systems according to ISO/IEC 17025:2017 (ISO/IEC, 2017) and have their calibration and measurement capabilities published in the key comparison database of BIPM (BIPM, 2025).

All of the SSDLs have established traceability to the primary standards in terms of air kerma, while the secondary standard reference values are determined either in terms of the operational dosimetry quantity directly (i.e., by employing the secondary standard for $H_p(10)$ or $H^*(10)$), or in terms of air kerma, where conversion coefficients from air kerma to the operational dosimetry quantity are used to determine the reference value of the operational quantity. These conversion coefficients depend on the photon energy and angle of incidence (ISO, 2019c).

All the SSDLs employ reference radiation fields which are established according to the requirements of ISO 4037–1:2019, including radionuclide-based radiation fields (Cs-137 and Co-60, abbreviated as S-Cs and S-Co) and N-series radiation qualities (narrow-spectrum X-ray radiation fields) (ISO, 2019a). Dosimeter testing was performed using either the substitution method, the known radiation field method or the substitution method with the use of the monitoring ionization chamber (IAEA, 2000). A schematic of the setup is presented in Fig. 1.

2.2. *Active radiation protection dosimeters*

The investigated dosimeters were selected to collect additional data needed for the update of the relevant IEC standards (IEC, 2009; IEC, 2024). The dosimeters are commercially available models, including both new models, which reflect the current state-of-the-art, as well as older models which are still in use. In this research the performance of 26 ADs and 6 PDs was evaluated. The manufacturer specifications of ADs and PDs are listed in Tables 1 and 2, respectively.

Most ADs utilize detectors based on G-M tubes, whereas a small portion uses a high-pressure ionization chamber, organic/plastic scintillator or a semiconductor detector. Additionally, most dosimeters, as stated by the manufacturers, are suitable for measurement of low-dose rates starting from the background radiation level (e.g., 10 nSv h^{-1}), and cover a broad energy range (Table 1).

Evaluated PDs utilize G-M tube-based detectors, except for one semiconductor-based dosimeter. They operate in a wide range of dose rates, up to 3 Sv h^{-1}, in a broad energy range, with mean photon energies going from 10 keV to 20 MeV (Table 2).

2.3. *Dosimeter response and influence quantities*

Influence quantities are defined as quantities which are not the subject of the measurement, but can affect the measurement result. The effects of these quantities are evaluated during specialized performance tests within the rated ranges of the influence quantities for which the dosimeter is designed to be used. The influence quantities can have a multiplicative or additive effect on the measurand, and they are categorized as type F and type S, respectively. The IEC standards define the minimum rated ranges for the influence quantities for which the dosimeter performance should be in line with the standard requirements, usually defined as limits of variation in terms of relative response (type F) or deviation (type S). The most important radiation-based influence quantities (photon energy, angle of incidence and non-linearity) are classified as type F influence quantities (IEC, 2009; IEC, 2024).

The response of an active dosimeter, R, is defined as the quotient of the measured value and the reference (conventional true) value of the operational dosimetry quantity, obtained with a reference class standard instrument:

$$R = \frac{M}{H_r} \tag{1}$$

where M is the mean measured value, and H_r is the reference value under specific irradiation conditions.

Relative response, r, is defined as the dosimeter response normalized to the dosimeter (reference) response, which is determined under reference conditions:

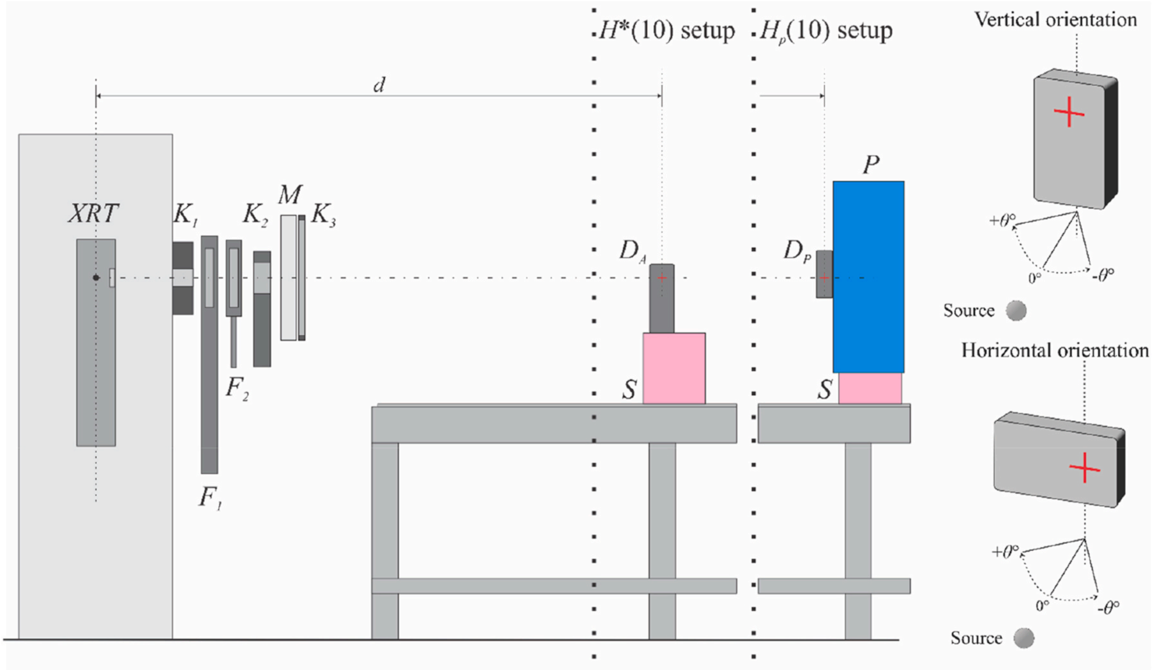

Fig. 1. Schematic representation of the experimental setup. (left): XRT - X-ray tube; K1, K2 and K3 - apertures; F1 and F2 - additional filtration; M - monitor ionization chamber; d - source-to-detector distance; P – ISO slab phantom (used with PDs); S – positioning support (low Z material); D_A – AD; D_P – PD. (right): Dosimeter orientation and rotation for the angular dependence test.

Table 1
Manufacturer specifications of tested ADs in terms of detector type, dose rate and photon energy measurement range.

Manufacturer and Model	Detector type	Dose rate measurement range		Photon energy range		AD No. (DL)	Symbol
		Min [μSv h^{-1}]	Max [mSv h^{-1}]	Min [keV]	Max [MeV]		
Atomtex AT6130	G-M tube	0.1	10	20	3	AD1	●
Atomtex AT1123	Plastic scintillator	0.05	10 000	15	10	AD2	●
						AD3	●
Automess 6150 AD3	G-M tube	1	1000	45	3	AD4	▲
						AD5	▲
Automess 6150 AD6/H	G-M tube	0.1	10	60	1.3	AD6	▲
Canberra Radiagem 2000	G-M tube	0.3	100	40	1.5	AD7	★
						AD8	★
						AD9	★
						AD10	★
						AD11	★
Fluke 451P	High Pressure Ionization chamber	0	50	25	1.25	AD12	■
Ludlum 9DP	High Pressure Ionization chamber	0	50	60	1.25	AD13	▼
Polimaster PM1401K-3P	CsI(Tl), G-M tube	0.1	100	15	15	AD14	▶
Raysafe 452	G-M tube	0	0.02	20	1	AD15	◀
	Si – diode	20	1000	20	5	AD16	◀
						AD17	◀
Mirion RDS-30	G-M tube	0.01	100	48	3	AD18	◆
Mirion RDS-200	G-M tube	0.01	10 000	50	3	AD19	◆
Thermo Fisher RadEye B20 ER	G-M tube	0.2	100	17	3	AD20	⬟
						AD21	⬟
Thermo Fisher FH40G-L10	Proportional counter	0.01	100	30	4.4	AD22	⬢
						AD23	⬢
						AD24	⬢

(continued on next page)

Table 1 (*continued*)

Manufacturer and Model	Detector type	Dose rate measurement range		Photon energy range		AD No. (DL)	Symbol
		Min [μSv h^{-1}]	Max [mSv h^{-1}]	Min [keV]	Max [MeV]		
VINS DMRZ-M15	G-M tube	0.1	1	59	1.3	AD25 AD26	◧ ◧

$$r = \frac{R}{R_0} \tag{2}$$

Reference conditions are defined by the type testing standards for each of the influence quantities (IEC, 2009; IEC, 2024). During the performance tests all the influence quantities which are not the subject of a certain test should be within their respective reference conditions.

The multiplicative correction factors, which are derived from the beforementioned radiation-based influence quantity tests, can be directly used to correct the indicated value and obtain the measured value with reduced measurement uncertainty. The measured value can be represented with the following model equation:

$$M = N_H \cdot \frac{I - \sum_{i=1}^{n} D_i}{\prod_{j=1}^{m} r_j} \tag{3}$$

where M represents the corrected measured value, I the indicated value, N_H the calibration coefficient (derived under reference or standard test conditions), while D_i and r_j represent the additive (type S) and multiplicative (type F) corrections, respectively (IEC, 2009; IEC, 2024).

2.4. Measurement protocol

Based on dosimeter manufacturer specifications, analysis of historical calibration data and the previous research on radiation protection dosimeter performance and applications, the measurement protocol was developed to test the effects of radiation-based influence quantities. The focus of the protocol was on dosimeter response energy dependence, angular dependence and non-linearity, as well as overload and stability. The protocol was designed in a way to collect data in a wide range of influence quantity values, in order to assess dosimeter performance even outside their respective manufacturer-stated specifications. Data collection in standardized reference conditions can provide insight into their performance in real workplace poly-energetic and multidirectional radiation fields. The dosimeter performance was evaluated against the limits of variation defined in the respective IEC standards for testing of ADs and PDs (IEC, 2009; IEC, 2024).

2.4.1. Variation in dosimeter response due to photon energy

Photon energy is one of the most important radiation-based influence quantities, and variation in dosimeter response due to its effect could produce unreliable and erroneous data. The performance of ADs and PDs was investigated in a wider energy range than the minimum rated range stated in relevant standards (IEC, 2009; IEC, 2024), as well as the manufacturer stated measurement range. The minimum rated range stated by the standards (IEC, 2009; IEC, 2024), for both operational quantities ($H^*(10)$ and $H_p(10)$), covers mean photon energies from 80 keV to 1.25 MeV, which corresponds to general industrial applications of ionizing radiation. The expanded photon energy range used in this test covered mean photon energies from 33.3 keV to 1.25 MeV, including low-energy applications such as diagnostic radiology modalities and Am-241 photon radiation field. X-ray Narrow spectrum radiation qualities (N-series), from N-40 up to N-200, and radionuclide radiation fields Cs-137 and Co-60, termed as S-Cs and S-Co, respectively, were used (ISO, 2019a). The dose rate was kept constant during all irradiations in the energy dependence test. Both AD and PD type testing standards state the limits of variation from −29 % to +67 %, defined for the minimum rated range. The dosimeter relative energy response curve was determined by normalizing the response value at a specific photon energy to the response value obtained for S-Cs (IEC, 2009; IEC, 2024).

2.4.2. Variation in dosimeter response due to angle of incidence

High angles of incidence accompanied with low photon energies can have a great effect on the dosimeter response (Kržanović et al., 2017;

Table 2
Manufacturer specifications of tested PDs in terms of detector type, dose rate and photon energy measurement range.

Manufacturer and Model	Detector type	Dose rate measurement range		Photon energy range		PD No. (DL)	Symbol
		Min [μSv h^{-1}]	Max [Sv h^{-1}]	Min [keV]	Max [MeV]		
Graetz GPD150G	G-M tube	0.1	1	55	1.3	PD1 PD2	● ●
Mirion Rad-60S	Si – diode	5	3	60	6	PD3 PD4	▲ ▲
Polimaster RadFlash	G-M tube	0.1	1	15	1.5	PD5	★
Polimaster PM1621A	G-M tube	0.1	1	10	20	PD6	■

Čeklić et al., 2014). Dosimeter angular dependence was evaluated for the three lowest energy radiation qualities for which the energy dependence of the response was in line with the IEC standards (IEC, 2009; IEC, 2024) and for the S-Cs radiation quality. The dose rate was kept constant within the standard test conditions defined by the respective standards. This test was done in both vertical and horizontal dosimeter orientations. The angular dependence test was conducted in a broader range of angles, than the minimum rated range stated by the standards (IEC, 2009; IEC, 2024). In the case of ADs, the minimum rated range stated by the standard covers angles of incidence from 0° to ±45° from the reference direction. This range is defined with respect to the area workplace monitors. For area dosimeters, the following angles were used, 0°, ±45°, ±60°, ±90°, ±120°, and 180°. In this way, the potential of area dosimeters to be used in conditions specific for environmental monitoring was explored. In the case of PDs, the minimum rated range covers angles of incidence from 0° to ±60°. For personal dosimeters the angular dependence test was performed in both directions of rotation for the angles 0°, ±30°, ±45°, ±60°, and ±75°. Relative response for a specific energy and angle of incidence was determined by normalizing the specific response value to the response obtained at S-Cs and 0°. Limits of variation for the energy and angular dependence test are set from −29 % to +67 % in both standards (IEC, 2009; IEC, 2024).

2.4.3. *Variation in dosimeter response due to dose rate – non-linearity*

Based on the ionizing radiation practice, the range of encountered dose (rate) values can significantly differ. Due to dead-time effects which can occur at high dose rate rates (respective to the tested dosimeter measurement range), and the low-dose rate effects related to dosimeter resolution and detection limits, it is important to test the non-linearity of the dosimeter response. This test was performed over the dosimeter measurement range based on the manufacturer specifications at least at two dose rate values per order of magnitude. The test was conducted in S-Cs and S-Co reference radiation fields. In the cases when S-Co was used for the non-linearity test, type F correction factor was introduced to account for the energy dependence of dosimeters, relative to S-Cs. In the case of ADs, dosimeter performance was evaluated in the dose rate range from 3 μSv h $^{-1}$ to 7 Sv h $^{-1}$, whereas in the case of PDs the dose rate range spanned from 3 μSv h $^{-1}$ to 2 Sv h $^{-1}$. The IEC 60846–1:2009 (IEC, 2009) sets the limits of variation for this test from −15 % to +22 %, whereas the IEC 61526:2024 (IEC, 2024) sets the limits of variation from −13 % to +18 %.

2.4.4. *Stability and overload*

The stability test was performed for five consecutive days in order to evaluate the reproducibility and consistency of measurements under constant irradiation conditions. All measurements were performed utilizing the same radiation source (S-Cs), dose-rate of.

100 μSv h^{-1}, source to detector distance and dosimeter positioning. Cs-137 decay during this period was negligible. The stability test was performed for 20 ADs and 2 PDs, due to time constraints and the availability of tested units. Dosimeter behaviour in the overload conditions was investigated by irradiating the dosimeter with a dose rate which is at least ten times above the upper limit of the measurement range, if such a dose rate was attainable in the SSDL. Following this exposure, measurements under reference conditions (100 μSv h^{-1} at S-Cs) were performed, and the post-overload dosimeter response was recorded. The dosimeter overload test was performed for 12 ADs.

2.4.5. *Interpretation of the results and decision rules*

Both standards (IEC, 2009; IEC, 2024) state that the limits of variation for each test should be enlarged by the measurement uncertainty of the conventional quantity value. Due to different measurement uncertainties reported by different laboratories and for different quantity values, graphic representations of the limits of variation in the figures all use the limits with zero uncertainty. Measurement uncertainties for the calibration of radiation protection dosimeters in terms of operational dosimetry quantities are similar for all SSDLs (e.g., 4.5–4.8 %, $k = 2$). The largest contributions to the overall measurement uncertainty are attributed to the calibration coefficient of the secondary standard, the secondary standard stability, and the conversion coefficient from air kerma to the operational dosimetry quantity. According to the ISO 4037–3:2019 (ISO, 2019c) standard, the conversion coefficient measurement uncertainty for matched reference fields is estimated as 2.0 % ($k = 1$). In the case of characterized reference fields, the conversion coefficient measurement uncertainties are estimated either by using dosimetry or spectrometry methods defined in the ISO 4037–2:2019 (ISO, 2019b). Detailed uncertainty budgets can be found in Živanović et al. (2023).

Results on dosimeter performance for each test were obtained through multiple measurements. Measurement uncertainty (with $k = 2$) is added to the data points, and, for data points outside the limits, a result is considered acceptable if any part of the uncertainty bar crosses the limit. Correlations in measurement uncertainty are not considered in this work, because of the quantity of measured data and many different laboratories using different equipment and procedures, causing slightly larger limits of variation in some cases. However, this is not considered important for the purpose of this paper, because fail/pass status of single dosimeters is not of special interest, but instead the general state-of-the-art and the possibility to update the standards. Also, differences in practices between laboratories may point toward further needs to improve the type testing protocols.

3. Results and Discussion

The results of AD and PD relative response to the radiation-based influence quantities are presented in Figs. 2–9 and Figs. A1-A7. In Figs. 2 and 3 the energy dependence of ADs and PDs is displayed, respectively. Figs. 4 and 5 show the angular dependence of ADs in N-40 and N-100 radiation qualities, respectively. Figs. 6 and 7 display the angular dependence of PDs in radiation qualities N-40 and N-60, and N-100 and N-120, respectively. Figs. 8 and 9 present the non-linearity response of ADs and PDs, respectively. Figs. A1 – A7 are provided in Appendix A, with additional information on performance of tested dosimeters. Data points outside the dosimeter manufacturer specified range are represented as hollowed out symbols.

3.1. *Variation in dosimeter response due to photon energy*

For the most part, the performance of ADs is in line with the standard defined limits of variation for this test (−29 %, +67 %), for the minimum rated range from 80 keV to 1.5 MeV mean photon energies (IEC, 2009). As previously mentioned, the dosimeters were tested in a broader range of photon energies, going down to N-40 (mean photon energy 33.3 keV). In case of some dosimeters, such as AD18, AD19, AD25 and AD26, a more pronounced energy dependence in the range of lower photon energies was observed. This under response was observed for the N-40 and N-60 radiation qualities, which are outside of the manufacturer-stated photon energy range. On the other hand, dosimeters AD4 and AD5 showcased a steady under response throughout the entire tested energy range in X-ray fields. This could possibly be attributed to the fact that Automess 6150 AD3 was designed to measure the predecessor of $H^{*}(10)$, and is a discontinued model replaced with newer ones, such as Automess

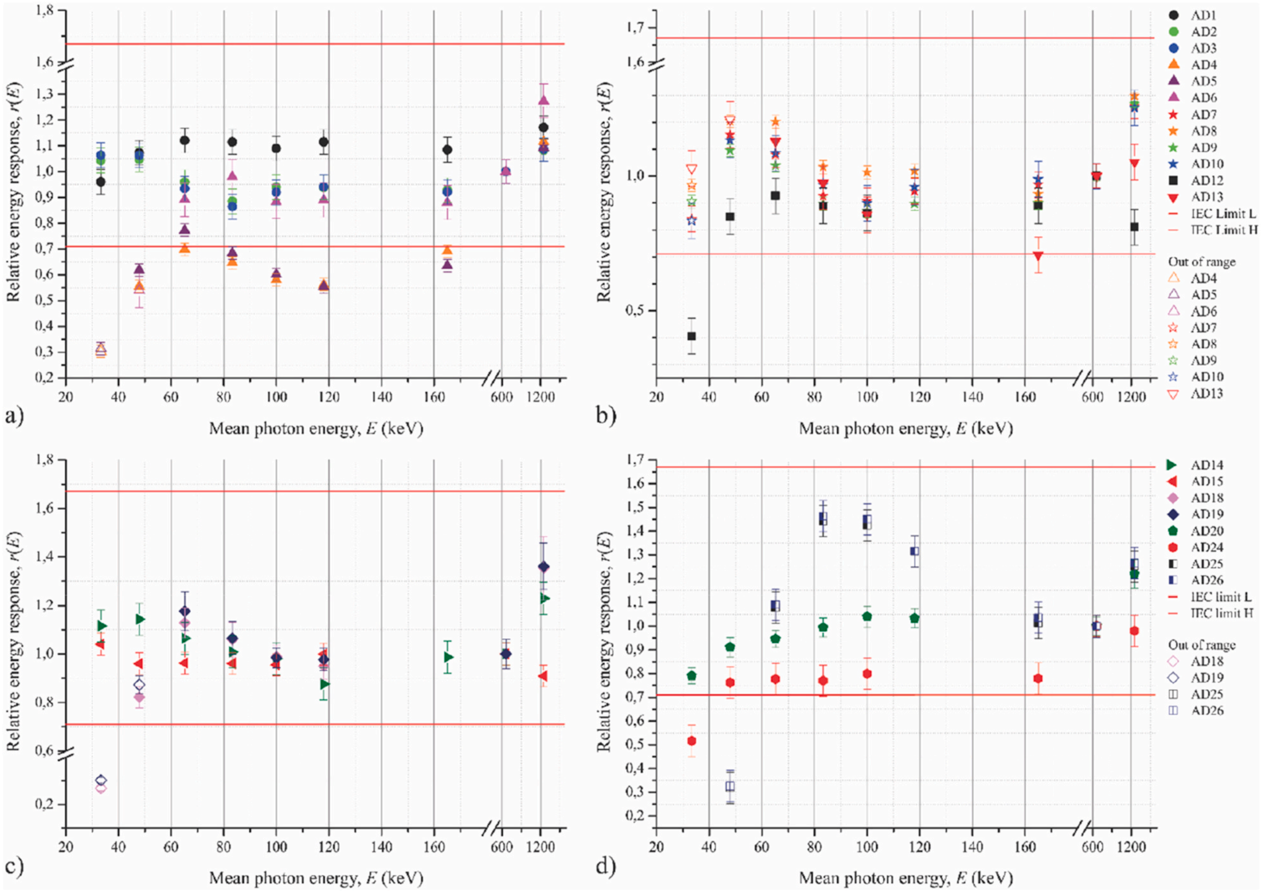

Fig. 2. Energy dependence of active area dosimeter (AD) response in the range from 33 keV (N-40) to 1.25 MeV (S-Co): a) AD1-AD6; b) AD7-AD13; c) AD14-AD19; d) AD20-AD26. The limits of variation (−29 %; +67 %) in terms of relative energy response are displayed (IEC, 2009).

6150 AD6. Some end-users still request calibration for this dosimeter model, which is why dosimeter verification, in addition to regular calibration is important. Additionally, AD12 and AD24 showed a large deviation from the reference response of −59.4 % and −48.4 %, respectively, for the radiation quality N-40, even though that radiation quality is within their manufacturer stated measurement range. The noted under response could be associated with the age of the specific device unit under test and could indicate degradation of its electronic components or possible gas leakage, when it comes to Fluke 451P (AD12), which is not uncommon for pressurized ionization chambers. Most of the devices do not have a significant energy dependence at high photon energies, e.g., making them suitable for environmental monitoring at nuclear facilities. The summarized response energy dependence of ADs is presented in Fig. 2.

Based on the tested ADs it can be concluded that the dosimeters exhibit performance in line with the area workplace type testing standard (IEC, 2009). The tested AD sample included mostly area workplace monitors. It should be noted that in the case of environmental area monitoring many ADs fail to comply with relevant IEC standards. This is especially present in environmental monitoring activities done by laymen and in non-governmental networks, where low-cost devices are utilized (Morosh et al., 2021). To adequately assess the performance of ADs for environmental monitoring, the IEC standard related to area workplace monitoring could additionally include specific tests and requirements for area environmental monitoring. In terms of energy dependence, the IEC test methods could include the standard L-series radiation qualities (ISO, 2019a), as an alternative to the N-series radiation qualities, suitable for low-dose rate applications (Kržanović et al., 2022).

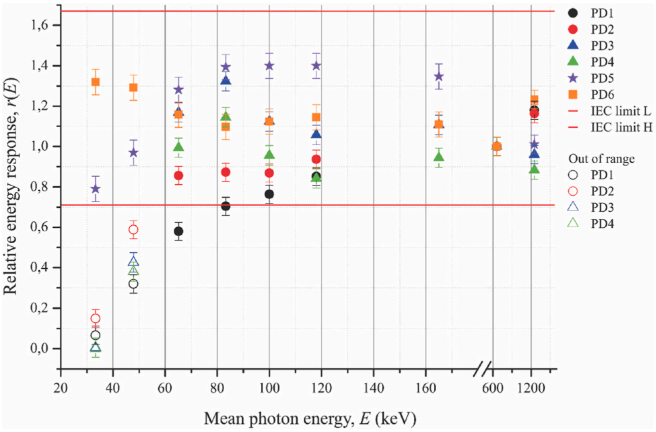

Fig. 3. Energy dependence of active personal dosimeter (PD) response in the range from 33 keV (N-40) to 1.25 MeV (S-Co). The limits of variation (−29 %; +67 %) in terms of relative energy response are displayed (IEC, 2024).

When observing the tested PDs, it can be noted that exhibited performance is mostly in line with the standard defined limits of variation in the minimum rated range (IEC, 2024). PD1 showcased a significant under response up until N-120, which is not in line with the manufacturer stated photon energy range. On the contrary, PD2 exhibited a satisfactory energy dependence, in line with the manufacturer specifications. Considering that PD1 and PD2 are different units of the same dosimeter model, they exhibit similar energy dependence trend at low-photon energies. Therefore, dosimeter recalibration and/or adjustment could be required. This observation can be used to emphasize the importance of individual dosimeter unit verification in addition to the type testing of the dosimeter model (which may be based on the manufacturer selected sample from a given production series). In some countries the legal requirements on radiation protection dosimeters are fulfilled if singular dosimeter units used in practice are regularly calibrated, and/or if the dosimeter model is IEC type tested by designated laboratories, while verification is not a very common requirement. For PD2, PD3 and PD4, an under response can be observed for the radiation qualities N-40 and N-60. These radiation qualities are outside the scope of their respective photon energy ranges, which should be considered if these dosimeters are to be used in certain exposure scenarios (such as interventional radiology or similar medical applications where high doses to exposed workers can be recorded), to prevent the acquisition of unreliable dosimetry data. PD5 and PD6 exhibited good performance across the entire tested energy range, with the maximum deviation from the reference response being +39.9 % for the radiation qualities N-120 and N-150, and +31.9 % for the radiation quality N-40, respectively. Response energy dependence of PDs is presented in Fig. 3.

The observed PD performance in this work is in line with the findings of previous research, where the applications of active personal dosimeters in low-energy continuous radiation fields were considered (Kržanović et al., 2017; Lee et al., 2016). Further examination of the dosimeter performance in low-energy radiation fields, regarding the effects of photon energy, could be done by utilizing real poly-energetic radiation fields encountered in diagnostic radiology (such as the standardized RQR radiation quality series). Such performance tests, focused on fluoroscopy modalities were previously done, where dosimeters, which had their energy response in line with the IEC standard in the medical energy range, were identified. Even though the energy dependence criteria were fulfilled, the non-linearity effect at very high (pulsed field) dose rates caused performance issues (Clairand et al., 2011; Struelens et al., 2011).

Considering the current developments in individual monitoring, hybrid dosimeters which incorporate properties of both active and passive dosimeters are being proposed as an alternative to the existing technologies. Performance tests of novel dosimeter models have also been done, and their characteristics are on par with the commercially available PDs and TLDs/OSLDs (Garzon et al., 2019; Haag et al., 2021; Vlahović et al., 2025).

3.2. Variation in dosimeter response due to angle of incidence

Angular dependence of AD response is in line with the IEC 60846–1:2009 (IEC, 2009) standard requirements in the minimum rated range. Therefore, these dosimeters are suitable for general area workplace applications where the encountered angles of incidence are less than ±45°. The angular response test for ADs included a wider range of angles, to consider irradiation conditions which are encountered when the dosimeters are used for area environmental monitoring. The angular response of ADs in N-40 and N-100 radiation qualities, in both dosimeter orientations is presented in Figs. 4 and 5, respectively. N-40 was highlighted as low photon energies and high angles of incidence present unfavourable irradiation conditions (often encountered in medical applications of ionizing radiation). N-100 represents the lowest energy radiation quality within the IEC stated minimum rated range of photon energy (IEC, 2009; IEC, 2024). Additional information on angular dependence of ADs in other investigated radiation fields is presented in the Appendix (Figs. A1 – A5).

As the geometry of the dosimeter (the position of its active volume relative to the associated electronics, any additional filtration, the structure of the dosimeter casing etc.) has an important role in its angular dependence, sufficient information regarding the dosimeter reference point, orientation and positioning should be clearly stated by the manufacturers. In the S-Cs radiation field it was observed that some of the AD models had their angular response within the standard limits even for the whole test range (0°, ±45°, ±60°, ±90°, ±120°, and 180°), exhibiting potential for applications in environmental monitoring. In the low-energy radiation fields (N-40 and N-60) for the angles of incidence larger than ±45° the angular dependence is more pronounced. It should also be noted that in the manufacturer specifications there is no sufficient information on the angular rated range.

As the minimum rated range in (IEC, 2009) is defined for a narrow angle range, specific to area workplace monitors, the current standard test criteria could be updated by introducing the dosimeter requirements

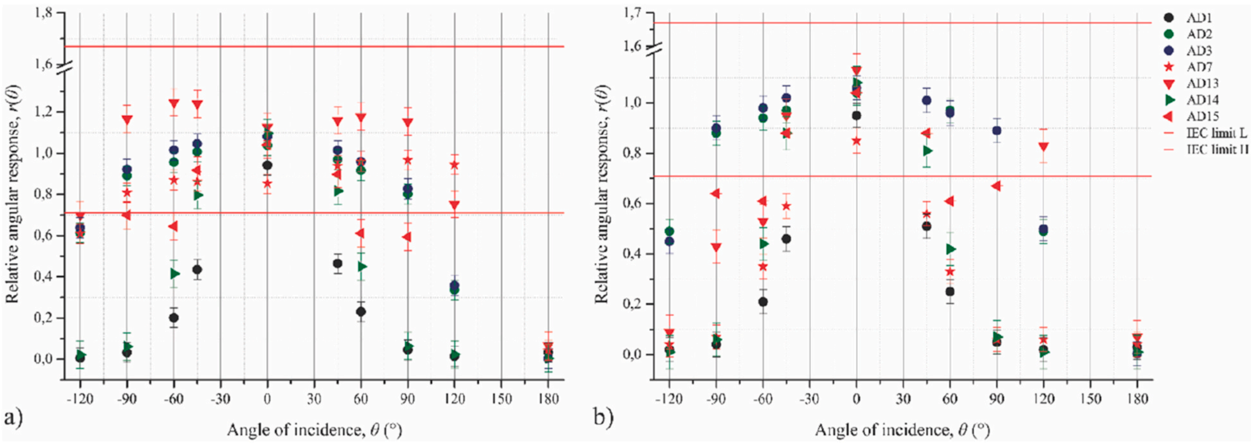

Fig. 4. Angular dependence of active area dosimeter (AD) response in the N-40 (mean photon energy 33.3 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2009).

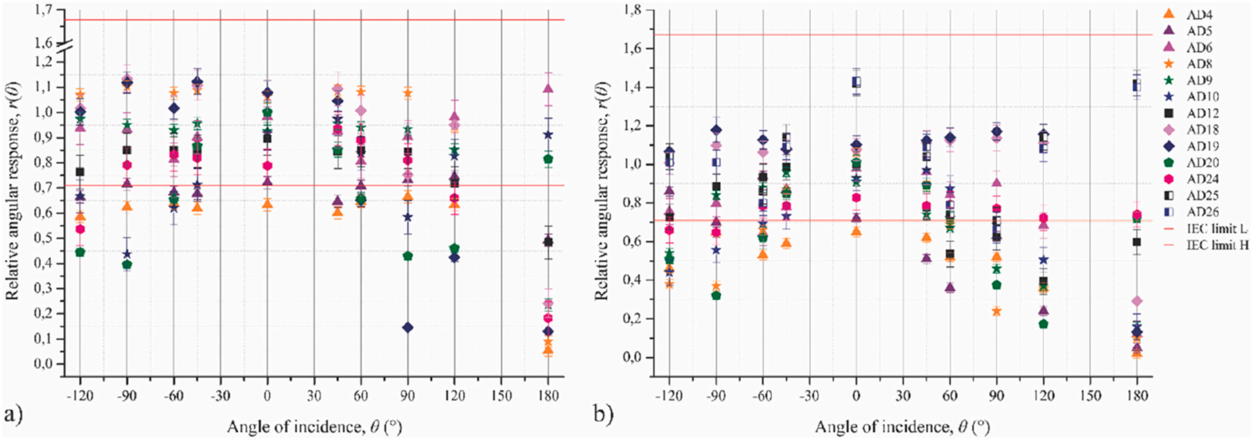

Fig. 5. Angular dependence of active area dosimeter (AD) response in the N-100 (mean photon energy 83.3 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2009).

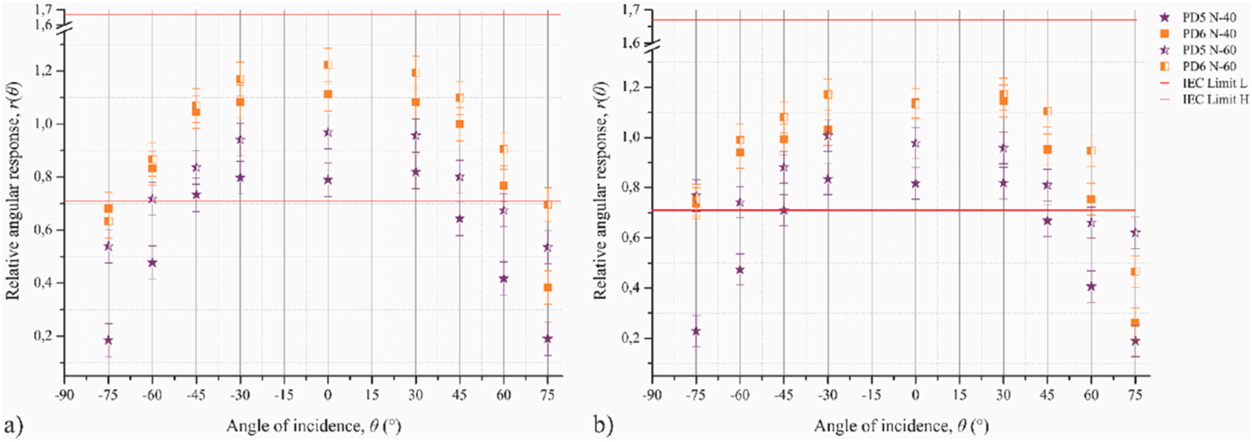

Fig. 6. Angular dependence of active personal dosimeter (PD) response in the N-40 and N-60 (mean photon energies 33.3 keV and 47.9 keV) radiation qualities. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2024).

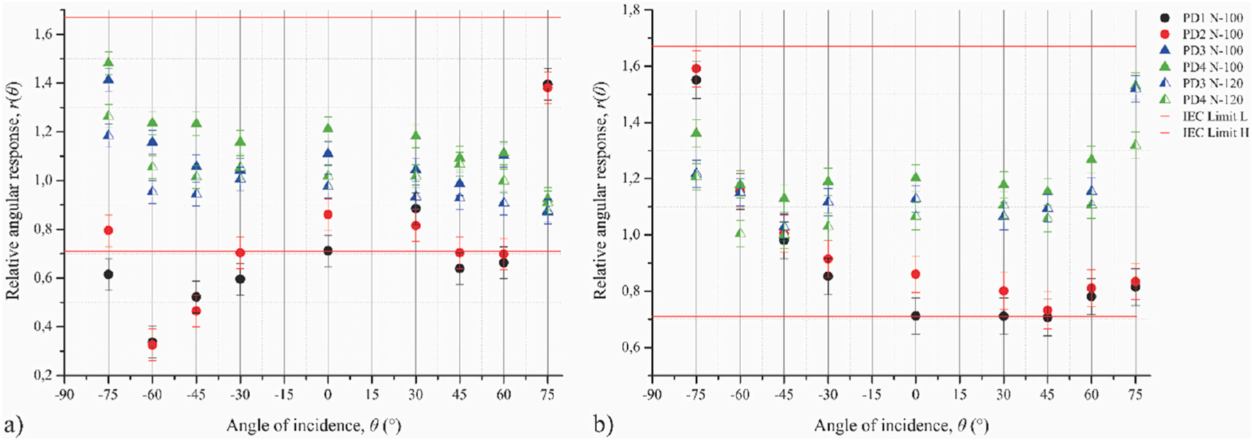

Fig. 7. Angular dependence of active personal dosimeter (PD) response in the N-100 and N-120 (mean photon energies 83.3 keV and 100 keV) radiation qualities. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2024).

in a broader angular range, specific to environmental monitoring, with adapted limits of variation for larger angles.

In the case of PDs, it was observed that the angular dependence criteria are fulfilled for the S-Cs radiation quality. Considering the manufacturer specifications of the tested dosimeters (Table 2), only two dosimeter models (PD5 and PD6) are designed for low-energy applications. As the photon energy decreases the angular dependence becomes more prominent, with significant under response at higher angles of incidence. In the N-40 and N-60 radiation fields they have displayed alignment with the standard criteria up to approximately ±45°. It

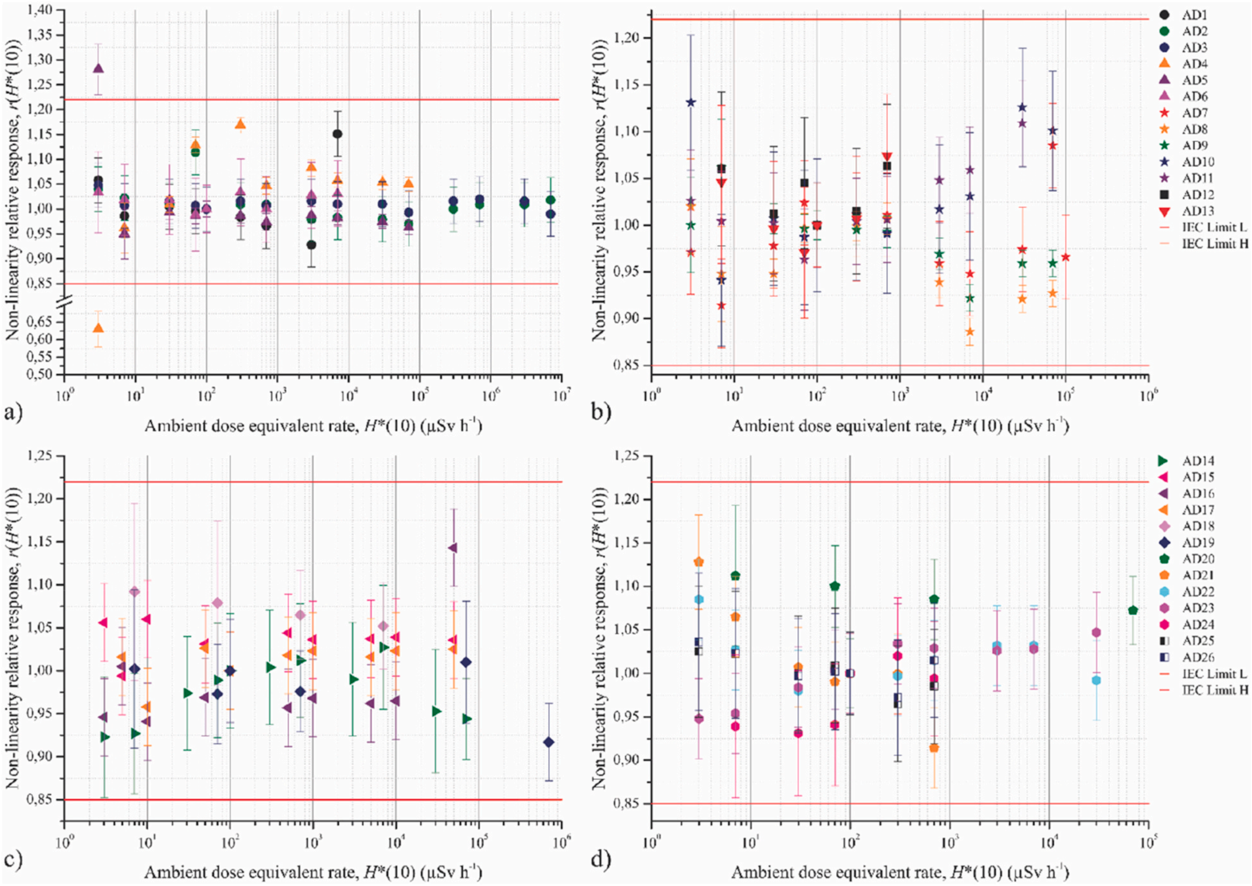

Fig. 8. Non-linearity of active area dosimeter (AD) response in the dose rate range from 3 µSv h $^{-1}$ to 7 Sv h $^{-1}$: a) AD1-AD6; b) AD7-AD13; c) AD14-AD19; d) AD20-AD26. The limits of variation (−15 %; +22 %) in terms of relative response are displayed (IEC, 2009).

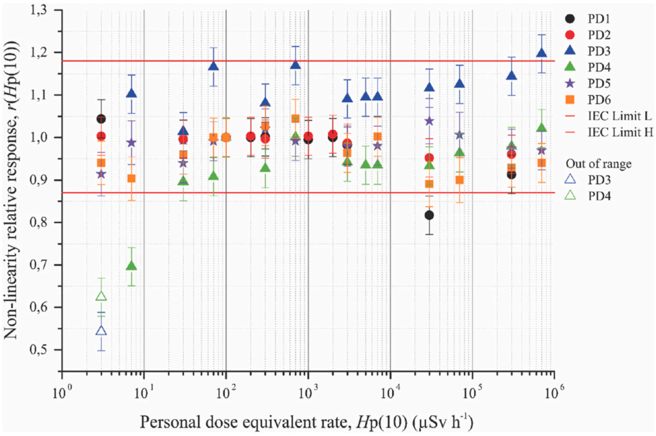

Fig. 9. Non-linearity of active personal dosimeter (PD) response in the dose rate range from 3 µSv h $^{-1}$ to 2 Sv h $^{-1}$. The limits of variation (−13 %; +18 %) in terms of relative response are displayed (IEC, 2024).

should be noted that very low photon energies and high angles of incidence represent unfavourable irradiation conditions. Also, the PD sample sizes are not well representative of the dosimeter type. PD1 and PD2 have displayed a pronounced angular dependence, which could possibly be attributed to their geometry and instrument design. PD3 and PD4 have performed within the standard requirements in line with the manufacturer's specifications. The angular response of PDs in N-40 and N-60, and N-100 and N-120 radiation qualities, in both dosimeter orientations is presented in Figs. 6 and 7 respectively. Additional information on angular dependence of PDs in S-Cs and N-80 radiation qualities is presented in the Appendix (Figs. A6 – A7). Angular dependence tests on current state-of-the-art hybrid dosimeters for individual monitoring proves that some of the new dosimeter models have commendable angular dependence even at very low energies (Garzon et al., 2019; Haag et al., 2021; Vlahović et al., 2025).

Table 3
Dosimeter stability in terms of Coefficient of Variation (CoV).

AD/PD	CoV (%)	AD/PD	CoV (%)
AD1	0.8	AD13	0.7
AD2	0.8	AD14	1.1
AD3	0.9	AD21	0.4
AD4	9.0	AD22	0.6
AD5	4.1	AD23	0.4
AD6	0.9	AD24	3.0
AD7	0.4	AD25	0.2
AD8	2.5	AD26	0.3
AD9	1.8	PD3	4.4
AD10	1.2	PD4	4.7
AD11	2.8		
AD12	0.9		

3.3. *Variation in dosimeter response due to dose rate (non-linearity)*

All the tested ADs have complied with the standard requirements on non-linearity of the response. Over the whole tested dose rate range, relative responses within ±10 % were observed for most dosimeters, making them suitable for various exposure scenarios in both industrial and medical applications. AD4 and AD5 had displayed pronounced non-linearity at the lowest dose rate included in the test (3 µSv h^{-1}), which

Table 4
Overload message indication and post-overload response.

AD	Message	Response
AD4	999 mSv h^{-1}, screen blink	0.868
AD5	999 mSv h^{-1}, screen blink	0.987
AD6	999 mSv h^{-1}, screen blink	1.001
AD8	9999 Sv h^{-1}, screen blink	1.015
AD9	9999 Sv h^{-1}, screen blink	0.964
AD10	9999 Sv h^{-1}, screen blink	1.001
AD14	OVL mSv h^{-1} (overload)	1.001
AD18	OFL (overflow)	0.963
AD19	OFL (overflow)	0.968
AD20	Overload	0.945
AD25	Overload	0.995
AD26	Overload	0.997

may be attributed to the resolution of the instrument reading. Non-linearity of ADs is presented in Fig. 8.

Similar behaviour is observed with PDs where most of the devices fulfil the criteria over the whole tested dose rate range. For the lowest dose rates of 3 μSv h^{-1} and 7 μSv h^{-1}, PD3 and PD4, which represent the same dosimeter model, have exhibited pronounced non-linearity. As with the AD4 and AD5, this behaviour might be attributed to the instrument resolution. This dose rate value is outside of the manufacturer stated measurement range. Non-linearity of PDs is presented in Fig. 9.

Most of the dosimeters included in the study have behaved in accordance with the standards in the tested dose rate ranges, with respect to the manufacturer specifications. In previous studies focused on dosimeter performance the effects of dose rate were investigated in the radiation fields where very high dose rates are encountered, specifically in the pulsed radiation fields. Under these extreme irradiation conditions many of the devices fail to provide any indication. It was observed that in general the non-linearity effect becomes very significant at dose rates approximately above 1 Sv h^{-1} (Clairand et al., 2011; Hupe et al., 2019).

3.4. Stability and overload

Out of the 20 ADs, for which the stability test was conducted, more than half of them exhibited excellent stability, with the Coefficient of Variation (CoV) below 1 %. For the remaining ADs, the CoV was below 5 %, except for AD4, which showed a CoV of 9 % (Table 3). Overall, the dosimeters showcased good stability, indicating that they provide reliable and precise measurements, which is essential when performing dosimetry measurements.

In the case of PDs, only two dosimeters were evaluated in this test, both exhibiting CoV values below 5 % (Table 3), making them suitable for the acquisition of reliable and precise dosimetry data.

For the dosimeter overload test all of the 12 tested ADs either displayed an overload indication message or a numerical value indicating over range (Table 4). The maximum deviation from the reference value of −13.2 % was reported for AD4, which could be attributed to the age of the device. For the rest of the ADs the deviation was less 6 %, which demonstrates that even after being exposed to dose rates beyond the manufacturer stated measurement range, the devices functionality is not compromised and they still provide accurate measurements.

3.5. Possibilities for the update of IEC standards

State-of-the-art radiation protection dosimeters are designed in such a way that they are able to measure within a wide range of photon energies and doses (dose rates). The performance indicators presented in previous sections showcase overall good dosimeter performance, in line both with the standard stated minimum rated ranges, as well as the manufacturer specifications. Additionally, some dosimeters exhibited good performance even beyond their respective manufacturer-stated measurement ranges.

The current standard defined minimum rated ranges and limits of variation are defined to accommodate various ionizing radiation applications. Literature review, everyday practice and state-of-the-art technology overview have shown that the current limits of variation are achievable by various dosimeter manufacturers for different detector technologies. In this way, a variety of dosimeters are available on the market, at different price points, in order to accommodate different end-user needs.

The limits are derived based on the allowed variation of the calibration coefficient of ±40 % (IEC, 2009; IEC, 2024). Current limits of variation lead to higher measurement uncertainties in real poly-energetic and multi-directional radiation fields. These uncertainties are sufficient for most common dosimeter applications and most routine measurements. Measurements of operational quantities are usually performed to estimate effective dose, which is only an approximation of the risk for stochastic effect (ICRP, 2021). However, when high precision measurements are required, with a lower measurement uncertainty (e.g., when comparing different methods, equipment or procedures, transfer instruments for dosimeter comparisons), it could be beneficial to introduce another class of instruments, with lower limits of variation.

Currently, there is no distinction between dosimeters which have small variations in relative response and those which have more pronounced dependence on radiation based influence quantities. Based on the performance test results two dosimeter classes are proposed (Table 5). In the case of the energy and angular dependence test, limits

Table 5
Overview of the minimum rated ranges for radiation-based influence quantities, and their proposed limits of variation in terms of relative response for class A and class B dosimeters.

IEC standard	Influence quantity	Minimum rated range	Limits of variation	
			Class A	Class B
IEC 60846–1:2009	Photon energy	80 keV–1.25 MeV 20 keV–150 keV	0.83–1.25	0.71–1.67
	Angle of incidence	80 keV–1.25 MeV 20 keV–150 keV 0 - ±45°	0.83–1.25	0.71–1.67
	Non-linearity	three orders of magnitude including 10 μSv h^{-1}	0.91–1.11	0.85–1.22
IEC 61526:2024	Photon energy	80 keV–1.25 MeV 20 keV–150 keV	0.83–1.25	0.71–1.67
	Angle of incidence	80 keV–1.25 MeV 20 keV–150 keV 0 - ±60°	0.83–1.25	0.71–1.67
	Non-linearity	0.5 μSv h^{-1} – 1 Sv h^{-1}	0.91–1.11	0.83–1.25

of variation, which would pertain to class B dosimeters, should remain unchanged (0.71–1.67). Such limits are valid for two application based minimum rated ranges, medical, which covers mean photon energies from 20 keV to 150 keV, and industrial, with mean photon energies from 80 keV to 1.25 MeV, with the respective angle of incidence minimum rated ranges for PDs (0°; ±60°) (IEC, 2024), and for ADs (0°; ±45°) (IEC, 2009). Proposed class A dosimeters would comply with more strict limits of variation, 0.83–1.25, which correspond to the ±20 % variation in the calibration coefficient. Observed performance test results indicate that some current and novel dosimeters exhibit small response variations relative to reference conditions, being <±10 %, even outside the minimum rated range. It should be noted that the number of tested personal dosimeters in this study is not sufficiently large, however novel dosimeters exhibit good performance across the entire tested range (Garzon et al., 2019; Haag et al., 2021; Vlahović et al., 2025). Observed dosimeter response variation due to dose rate was within ±10 % for most of the tested dosimeters, which suggests that the limits of variation could be stricter than currently stated in the standard. For class A dosimeters limits of variation could be set to 0.91–1.11, whereas the limits set for proposed class B dosimeters would remain unchanged (IEC, 2009; IEC, 2024).

Considering the proposed distinct dosimeter classes, evaluation of dosimeter performance against stricter criteria was performed to assess the number of ADs and PDs which could be considered class A dosimeters.

Based on the energy dependence test results 12 out of 20 ADs fulfil the newly proposed criteria in the minimum rated range (Fig. 2) (IEC, 2009). If the performance is assessed within the respective manufacturer-stated energy ranges 10 out of 12 ADs fulfil the class A criteria. In the case of PDs, it was observed that 3 out of 6 dosimeters can be considered class A dosimeters within the minimum rated range (Fig. 3).

The angular dependence of the response was evaluated for the three lowest photon energy radiation qualities for which the energy dependence complies with the standard. For the minimum rated range (N-100 radiation quality, mean photon energy 83.3 keV) 8 out of 11 and 6 out of 13 ADs in vertical and horizontal orientation, respectively, satisfy class A requirements (Fig. 5). For the N-80 radiation quality (65.2 keV mean photon energy) 10 out of 17 and 13 out of 19 ADs in vertical and horizontal orientation, respectively, met the newly proposed criteria (Fig. A4) (IEC, 2009). In the case of PDs 2 out of 4 dosimeters comply with the class A requirements in the minimum rated range (N-100) (Fig. 7), whereas 4 out of 6 PDs met the requirements in the N-80 radiation quality (Fig. A7), for both orientations (IEC, 2024).

In the case of non-linearity test nearly all (24 out of 26) ADs can be categorized as class A dosimeters (Fig. 8), while 3 out of 6 PDs fulfil the newly proposed criterion (Fig. 9) (IEC, 2009; IEC, 2024).

4. Conclusion

In this work a measurement protocol was developed based on the IEC type testing standards (IEC, 2009; IEC, 2024) to evaluate the performance of commonly used radiation protection dosimeters, in terms of variation in response caused by radiation-based influence quantities. The test ranges used in this study were extended beyond the minimum rated ranges and manufacturer-stated ranges. ADs and PDs exhibited overall good performance in terms of relative response within the standard defined limits of variation and manufacturer specifications for all the conducted tests (IEC, 2009; IEC, 2024). Some of the dosimeters showcased small variations in response even beyond these ranges, while others exhibited more pronounced variations under these irradiation conditions: low-energy photons (such as N-40 and N-60 radiation fields), high angles of incidence (such as ±75° for PDs, or ±90°/±180° for ADs depending of geometry) and very low dose rates (where device resolution is the limiting factor) or very high dose rates (where devices can be in overload or can be affected by detector dead time). The presented results emphasize the possibility for introducing two dosimeter classes. Class A dosimeters would have to comply with more strict limits of variation than the current standard stated ones, whereas the limits of variation for Class B dosimeters would remain as they are. The aim of these proposed updates is to enhance the quality and reliability of dosimetry data and to reinforce radiation protection of both the exposed workers and the general public. Due to the insufficient number of PDs included in this study, it is necessary to extend the sample size in future work, to provide supporting evidence for the proposed classification. Complementary to this study, future research is needed towards performance tests in pulsed-radiation fields.

CRediT authorship contribution statement

Jelena Vlahović: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nikola Kržanović:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Miloš Živanović:** Writing – review & editing, Validation, Formal analysis. **Ivana Stojanović:** Validation, Investigation, Data curation. **Luka Bakrač:** Writing – review & editing, Validation, Investigation, Data curation. **Argiro Boziari:** Writing – review & editing, Validation, Investigation, Data curation. **Miloš Đaletić:** Writing – review & editing, Validation, Investigation, Data curation. **Ana Fernandes:** Writing – review & editing, Formal analysis. **Liviu-Cristian Mihailescu:** Writing – review & editing, Validation, Investigation, Data curation. **Erinc Reyhanoglu:** Writing – review & editing, Validation, Investigation, Formal analysis, Data curation. **Siarhei Saroka:** Writing – review & editing, Validation, Formal analysis, Data curation. **Teemu Siiskonen:** Writing – review & editing, Project administration, Formal analysis, Data curation, Conceptualization. **Jana Šmoldasová:** Validation, Investigation, Formal analysis, Data curation. **Vladimir Sochor:** Writing – review & editing, Validation, Investigation, Formal analysis, Data curation. **Maria do Ceu Ferreira:** Writing – review & editing, Investigation. **Nataša Todorović:** Writing – review & editing, Supervision.

Declarations of interest

None.

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Appendix A. Results on the performance of Active Area Dosimeter (AD) and Active Personal Dosimeter (PD) in terms of response to radiation-based influence quantities

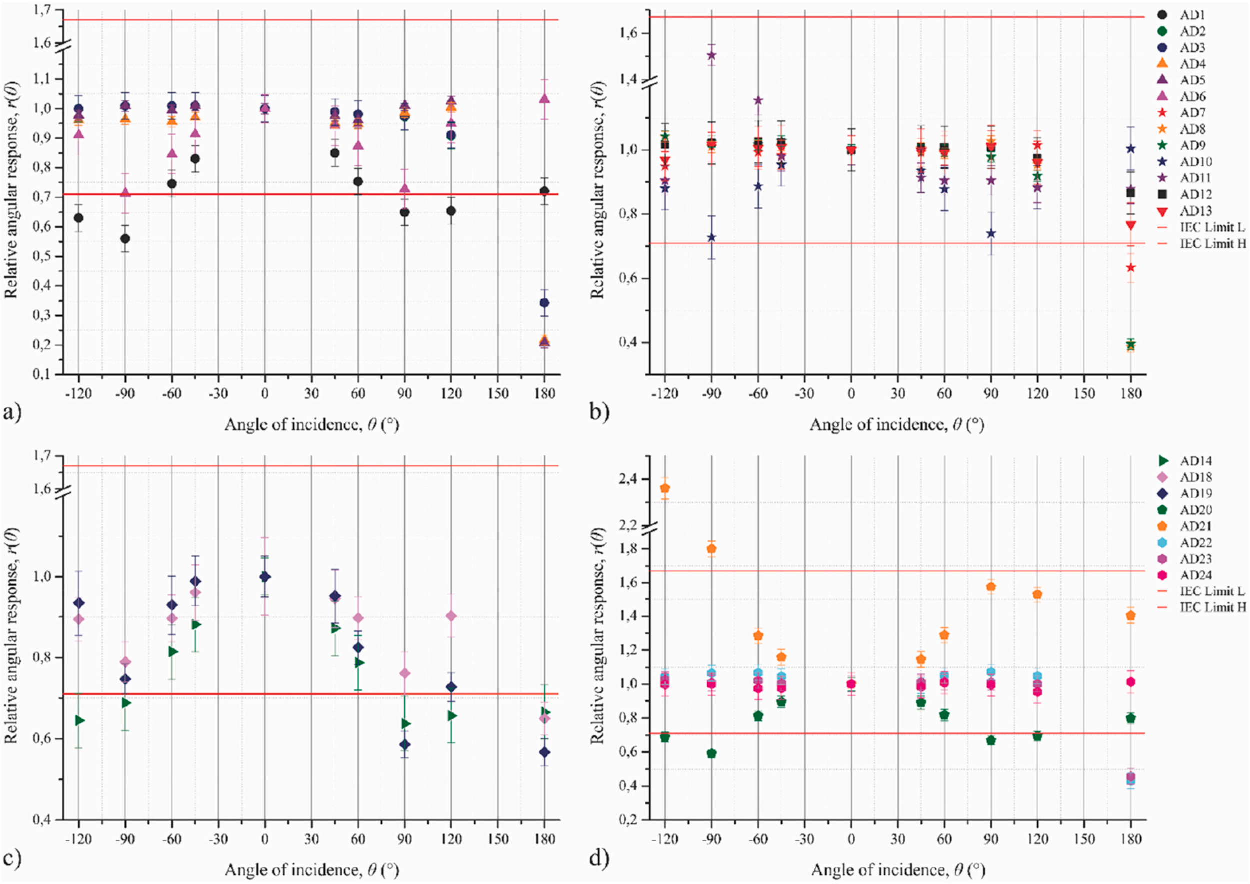

Fig. A1. Angular dependence of active area dosimeter (AD) response in the S-Cs (mean photon energy 662 keV) radiation quality in vertical dosimeter orientation. a) AD1-AD6; b) AD7-AD13; c) AD14-AD19; d) AD20-AD26. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2009).

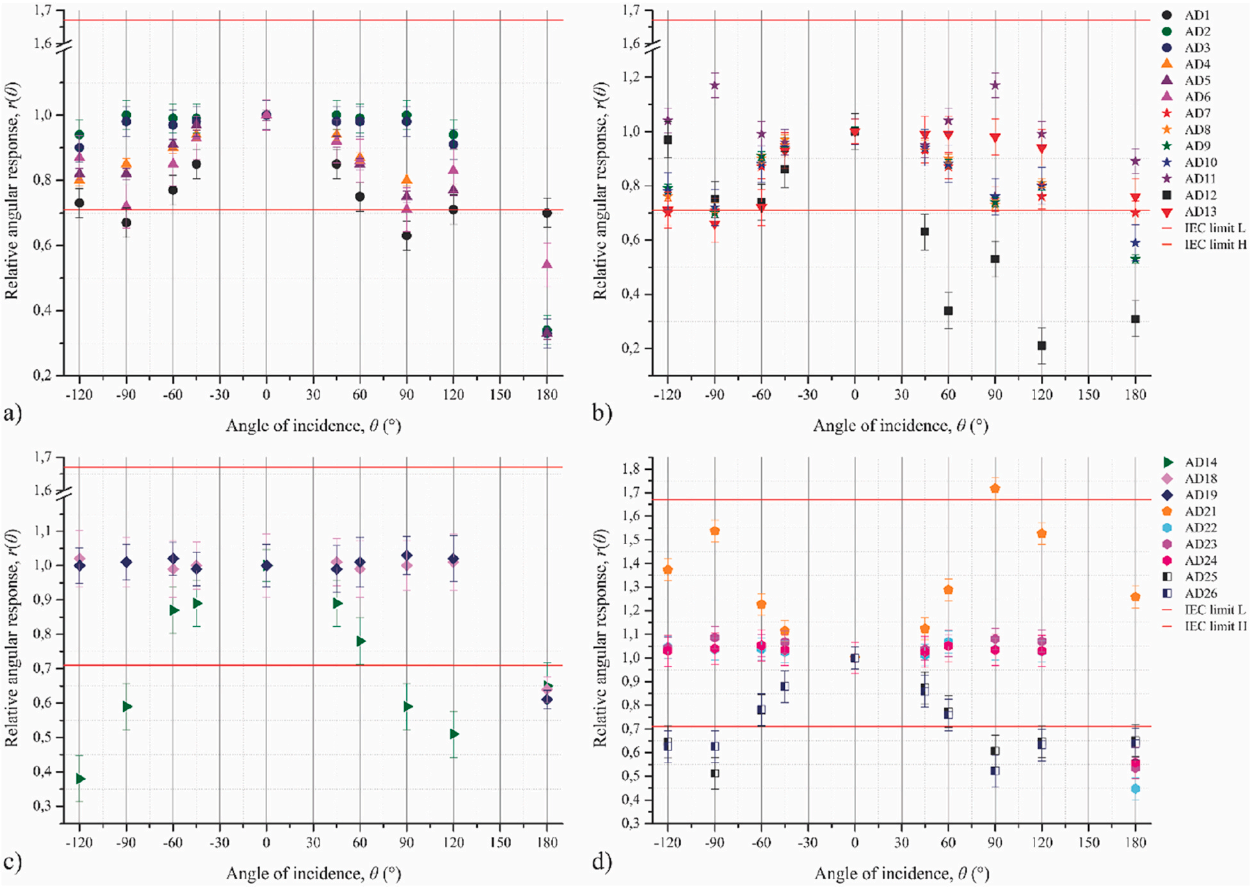

Fig. A2. Angular dependence of active area dosimeter (AD) response in the S-Cs (mean photon energy 662 keV) radiation quality in horizontal dosimeter orientation. a) AD1-AD6; b) AD7-AD13; c) AD14-AD19; d) AD20-AD26. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2009).

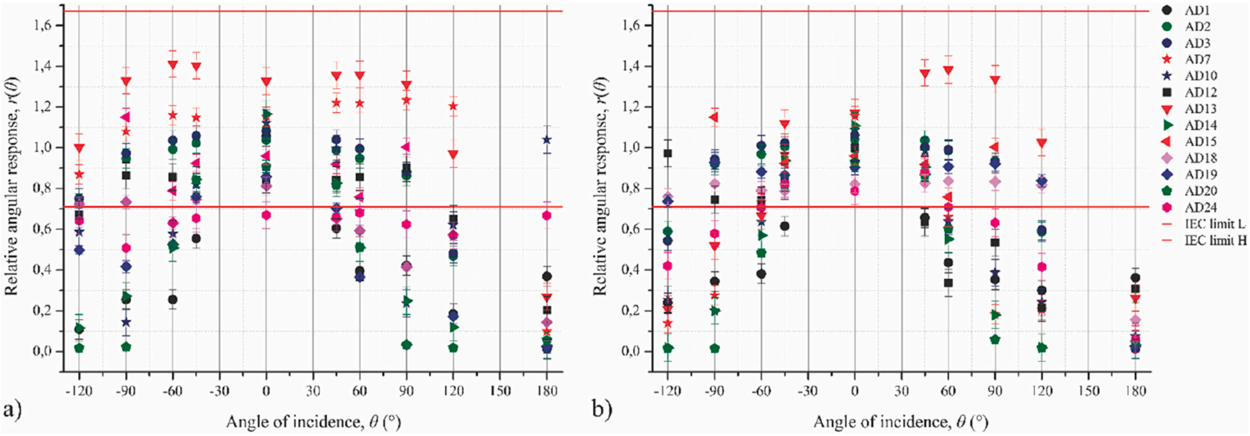

Fig. A3. Angular dependence of active area dosimeter (AD) response in the N-60 (mean photon energy 47.9 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2009).

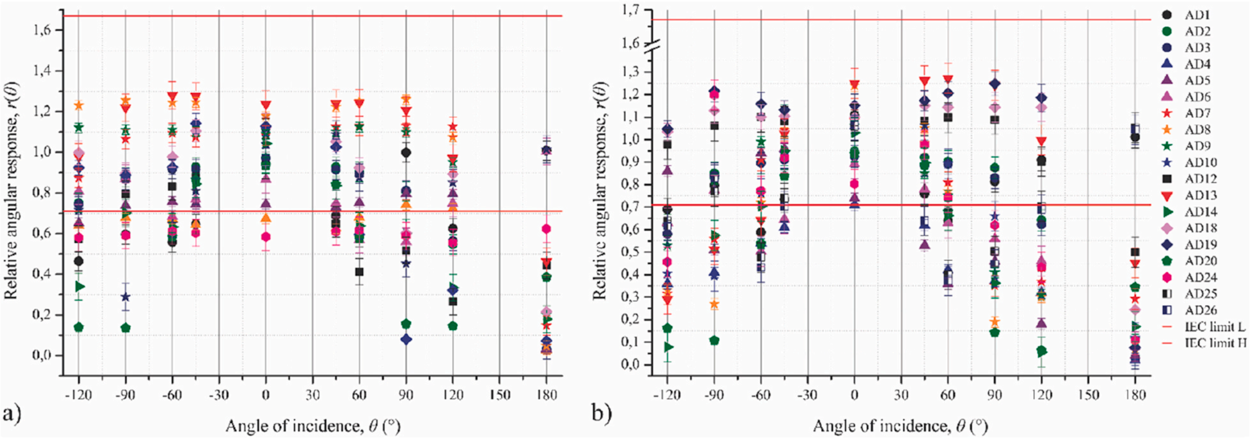

Fig. A4. Angular dependence of active area dosimeter (AD) response in the N-80 (mean photon energy 65.2 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2009).

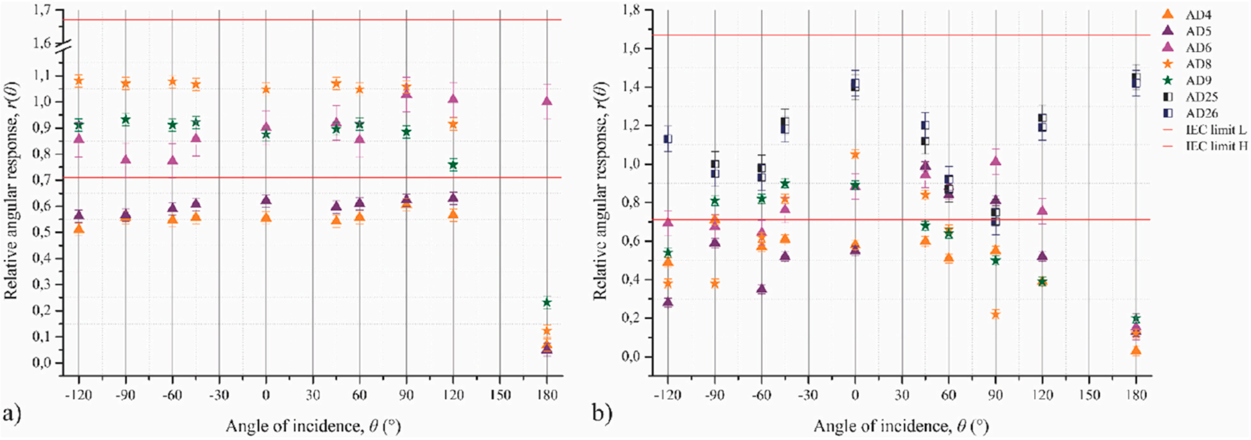

Fig. A5. Angular dependence of active area dosimeter (AD) response in the N-120 (mean photon energy 100 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2009).

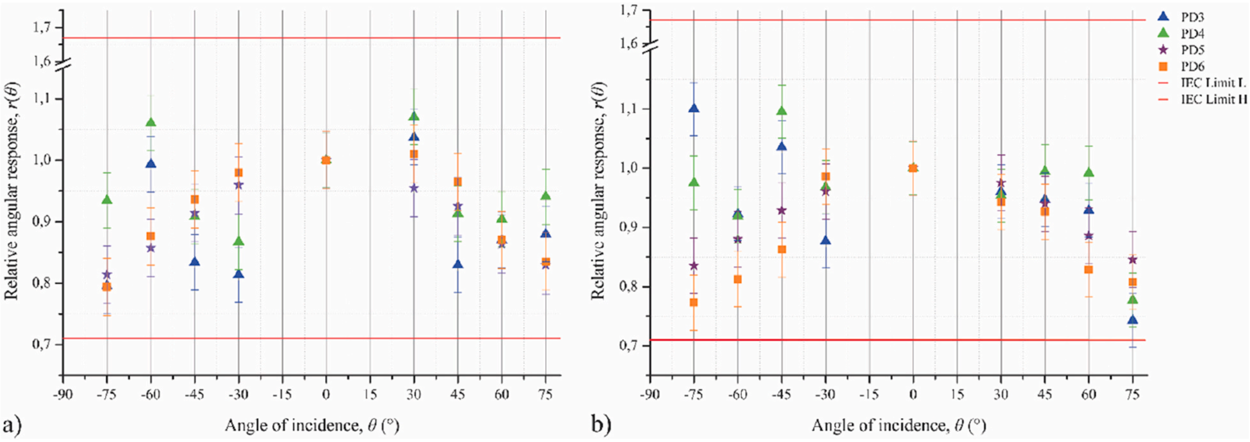

Fig. A6. Angular dependence of active personal dosimeter (PD) response in the S-Cs (mean photon energy 662 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2024).

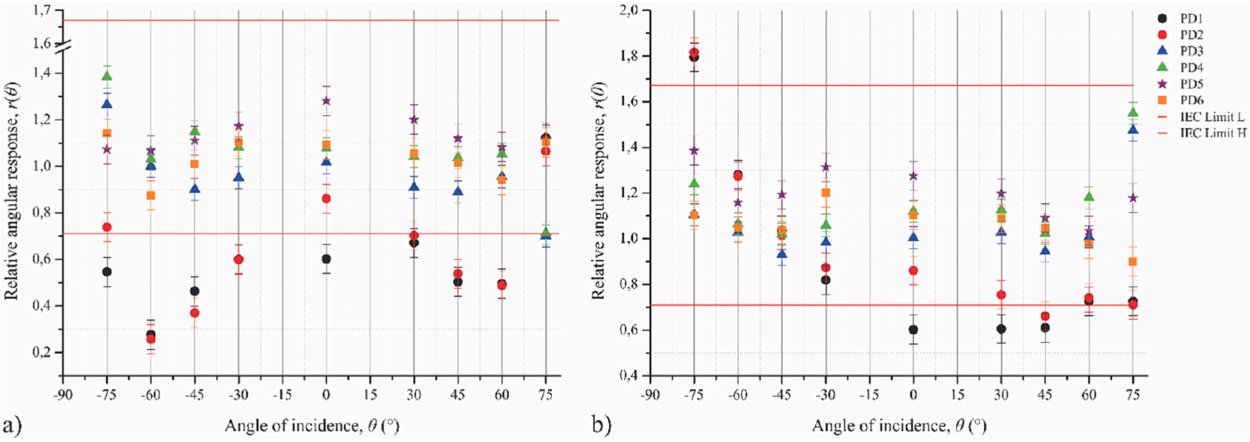

Fig. A7. Angular dependence of active personal dosimeter (PD) response in the N-80 (mean photon energy 65.2 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (−29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2024).

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