

## 22NRM07 GuideRadPROS

**D6** Guidelines on validated procedures for harmonised type testing based on existing IEC standards (e.g., IEC 61526, IEC 60846-1, IEC 60846-2, IEC 61017, IEC 60532 and IEC 62387) including a report on where requirements in existing standards deviate and standardisation gaps exist for radiation protection dosimeters for photon radiation

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**Deliverable Cover Sheet**

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## 1 Comparison of the current and existing IEC standards

Identified IEC standards for individual monitoring are related to passive dosimetry systems (IEC 62387:2020) and active (electronic) dosimeters (IEC 61526:2024). Hybrid dosimeters are briefly mentioned in the standard for passive dosimeters, while they are covered in the scope of the new (and current) version of the standard relative to active dosimeters. Both standards cover distinct photon energy ranges specific to different personal dose equivalent quantities ( $H_p(10)$ ;  $H_p(0.07)$ ;  $H_p(3)$ ). The covered dose and dose rate ranges are also defined. The standard for passive dosimeters covers general applications where individual monitoring is performed and required, while the standard for active dosimeters distinguishes between industrial and medical applications specifically. A summary of the scope is presented in Table 1.1.

Table 1.1. Scope of IEC type testing standards of dosimeters used for individual monitoring.

International standard	Photon energy range, $E$	Dose (rate) range	Dosimeter	Application
IEC 61526:2024	80 keV – 1.25 MeV, $H_p(10)$ 20 keV – 150 keV, $H_p(10)$ 30 keV – 250 keV, $H_p(3)$ 30 keV – 1.25 MeV, $H_p(0.07)$ 20 keV – 150 keV, $H_p(0.07)$	1 $\mu$ Sv – 1 Sv, $H_p(10)$ 300 $\mu$ Sv – 1 Sv, $H_p(3)$ 1 mSv – 3 Sv, $H_p(0.07)$  (0.5 $\mu$ Sv $\cdot$ h $^{-1}$ - 1 Sv $\cdot$ h $^{-1}$ ), $H_p(10)$ (0.1 $\mu$ Sv $\cdot$ h $^{-1}$ - 1 Sv $\cdot$ h $^{-1}$ ), $H_p(3)$ (5 $\mu$ Sv $\cdot$ h $^{-1}$ - 1 Sv $\cdot$ h $^{-1}$ ), $H_p(0.07)$	active hybrid	industrial medical
IEC 62387:2020	12 keV – 7 MeV, $H_p(10)$ 8 keV – 1.25 MeV, $H_p(0.07)$ 8 keV – 7 MeV, $H_p(3)$	0.01 mSv – 10 Sv	passive hybrid	individual monitoring

The summary of the minimum rated ranges and limits of variation for selected radiation-based influence quantities (photon energy, angle of incidence and dose equivalent (rate)) is provided in Tables 1.2 – 1.4. As with the release of the new version of IEC 61526:2024 Ed. 4.0, the requirements on these influence quantities are nearly completely harmonized, having equivalent limits of variation for all influence quantities. Still, minimum rated ranges differ for some of the quantities due to the properties of the dosimeters which are covered by the relevant standard. In the case of whole-body personal dose equivalent  $H_p(10)$  the allowed variation in dosimeter response caused by the change in photon energy relative to the reference radiation condition is set from -29 % to +67 %. The most common reference radiation condition is the S-Cs (ISO 4037:2019) radiation quality. The standard for active electronic dosimeters allows testing in two different rated ranges which are related to industrial applications or medical applications. Extension of the rated ranges from 10 keV up to 10 MeV is possible if required. The criteria set for angular dependence of the response as well as the minimum rated range are equivalent in both standards. The minimum rated range for dose values in the non-linearity test differs for the  $H_p(10)$  quantity, possibly due to the detection limits of passive dosimetry systems. The limits of variation for non-linearity have been harmonized with Ed. 4.0 of IEC 61526. Since the beginning of the 22NRM07 GuideRadPROS project, the hybrid dosimeters were included in the IEC 61526:2024 standard, covering the novel state-of-the-art technology developments in individual monitoring. Definition of two different minimum rated ranges of photon energy, covering industrial applications and low-energy medical applications, addresses well the distinct ranges of radiation conditions encountered in practice. This is defined in the standard for active dosimeters (IEC 61526) but not in the standard for passive dosimetry systems (IEC 62387) where only one minimum rated range is considered. Even though, IEC 61526 recognizes both industrial and medical minimum rated range, no reference radiation quality for the medical range is explicitly specified in the standard. Minimum rated range up to  $\pm 60^\circ$  covers most of radiation conditions in real radiation fields, and non-linearity is tested for a wide range of dose and dose rates, covering each order of magnitude. Dosimeter performance is evaluated by determining the variation in response relative to the reference conditions in both standards, for all three influence quantities analysed.

Table 1.2. Minimum rated ranges and limits of variation for photon energy influence quantity test for individual monitoring dosimeters.<sup>1</sup>

International standard	Dosimeter type, Application	Specific conditions	Minimum rated range	Influence quantity reference value	Response limits
IEC 61526:2024	Active personal dosimeters, Individual monitoring	Industrial Medical $H_p(10)$	(80 keV; 1.5 MeV) (20 keV; 150 keV) Extended to (10 keV; 10 MeV)	S-Cs / otherwise stated by the manufacturer	$r(E)$ , 0.71 – 1.67
		$H_p(0.07)$	(20 keV; 150 keV)	S-Cs / otherwise stated by the manufacturer	$r(E)$ , 0.67 – 1.67
IEC 62387:2020	Passive dosimetry systems, Hybrid dosimeters, Individual monitoring	$H_p(10)$ , $H^*(10)$	(80 keV; 1.25 MeV)	S-Cs	$r(E)$ , 0.71 – 1.67
		$H_p(0.07)$ , $H'(0.07)$	(30 keV; 250 keV)		
		$H_p(3)$	(30 keV; 1.25 MeV)		

Table 1.3. Minimum rated ranges and limits of variation for the angle of incidence influence quantity test for individual monitoring dosimeters.

International standard	Minimum rated range	Influence quantity reference value	Response limits	Specific conditions
IEC 61526:2024	(0°, ± 60°)	0°, Cs-137	$r(E, \Omega)$ , 0.71 – 1.67	individual
IEC 62387:2020	(0°, ± 60°)	0°, Cs-137	$r(E, \Omega)$ , 0.71 – 1.67	individual

Table 1.4. Minimum rated ranges and limits of variation for the non-linearity influence quantity test for individual monitoring dosimeters.

International standard	Included dose (rate) range or values	Orders of magnitude/ Testing points	Response limits
IEC 61526:2024	1 $\mu\text{Sv} - 1 \text{ Sv}$ , $H_p(10)$ 1 mSv – 3 Sv, $H_p(0.07)$ 300 $\mu\text{Sv} - 1 \text{ Sv}$ , $H_p(3)$	ALL / limits+{30%}	$r(H)$ , 0.87 – 1.18
	(0.5 $\mu\text{Sv}\cdot\text{h}^{-1} - 1 \text{ Sv}\cdot\text{h}^{-1}$ ), $H_p(10)$ (0.1 $\mu\text{Sv}\cdot\text{h}^{-1} - 1 \text{ Sv}\cdot\text{h}^{-1}$ ), $H_p(3)$ (5 $\mu\text{Sv}\cdot\text{h}^{-1} - 1 \text{ Sv}\cdot\text{h}^{-1}$ ), $H_p(0.07)$		
IEC 62387:2020	$H_p(10)$ , 100 $\mu\text{Sv} - 1 \text{ Sv}$ $H_p(0.07)$ , 1 mSv – 3 Sv $H_p(3)$ , 0.3 mSv – 1 Sv	ALL / limits+{30%}	$r(H)$ , 0.87 – 1.18

In the case of area monitoring a greater number of standards are available covering different applications and exposure scenarios. As with individual monitoring, area monitoring by using passive dosimetry systems is covered with the IEC 62387:2020 standard. This standard provides requirements for area monitoring in the workplace, as well as in the environment. On the other hand, other identified IEC standards provide test methods and requirements for active electronic dosimeters. Currently, the requirements and test methods in these standards are not harmonized. Different standards for active dosimeters pertain to different applications including regular workplace, accident and post-accident exposure scenarios, specific applications related to nuclear powerplants and nuclear waste disposal facilities, and environment. Some of the identified standards are related to active portable dosimeters, other for installed devices used

<sup>1</sup> The symbol  $r$  denotes relative response, while  $R$  denotes absolute response, as defined in the respective IEC standards.

for area monitoring and one specific standard which also covers radionuclide identifying devices. Summary of the IEC standards' scope used for area monitoring is given in Table 1.5.

Table 1.5. Scope of IEC type testing standards of dosimeters used for area monitoring.

International standard	Photon energy range, $E$	Dose (rate) range	Dosimeter	Application
IEC 60846-1:2009	12 keV – 10 MeV, $H^*(10)$ 8 keV – 250 keV $H'(0.07)$	0.01 $\mu$ Sv - 10 Sv 0.01 $\mu$ Sv/h – 10 Sv/h	active (portable)	workplace environment
IEC 60846-2:2015	up to 10 MeV	1 mSv/h – 10 Sv/h up to 10 Sv	active (portable)	workplace (accident, post-accident)
IEC 62387:2020	12 keV – 7 MeV, $H^*(10)$ 8 keV – 1.25 MeV, $H'(0.07)$ 8 keV – 7 MeV, $H'(3)$	0.01 mSv – 10 Sv	passive hybrid	workplace environment
IEC 60532:2010	50 keV – 7 MeV	N/A	active (installed)	workplace (NPP, NF safety)
IEC 61017:2016	50 keV – 7 MeV	30 nSv/h – 30 $\mu$ Sv/h 10 nSv – 10 mSv	active (portable/installed)	environment
IEC 62327:2017			active (portable) + identifiers	workplace

Minimum rated ranges and limits of variation (defined in terms of relative or absolute response, depending on the standard) are provided in Tables 1.6 – 1.8 for radiation-based influence quantities. Since the standard for passive dosimeters already recognizes categories for workplace and environmental monitoring, proposed criteria could be applied to active dosimeters as well. This is especially evident in the criteria set for the angular dependence test, where for the minimum rated range of  $0^\circ; \pm 60^\circ$  (and  $180^\circ; 180^\circ \pm 60^\circ$  due to the symmetry of passive dosimeter holder design) the criteria for workplace monitoring are set to (-29 %; +67 %). These limits of variation are equivalent to the individual monitoring one defined in Table 1.3. If the angular dependence test is done in the remaining range of angles ( $\pm 60^\circ, \pm 120^\circ$ ), which represents very unfavourable irradiation conditions, less strict criteria are defined (-33 %; +100 %). This additional angle of incidence range is specified for environmental monitoring, since testing in both angular rated ranges covers the  $2\pi$  geometry. Since angular dependence test includes testing in two dosimeter orientations (horizontal and vertical), testing in  $2\pi$  angle range for both orientations provides insight into the isotropy of the dosimeter response. Ideally, active electronic dosimeters which would be used for environmental monitoring should be also tested in a wider range of angles (extending the currently defined  $0^\circ; \pm 45^\circ$  range for regular workplace) and by defining more relaxed criteria under larger angles of incidence. Different minimum rated ranges and requirements could be defined for dosimeters whose design includes symmetry with respect to a certain axis (e.g., cylindrical external probes). In the IEC 60846-2:2015 specialized for external probes in accidental situations, specific rated ranges and limits of variation are already established, covering both non-telescopic probes (covered by the 1<sup>st</sup> part, IEC 60846-1:2009) and telescopic probes. Compared to the -29 %; +67 % criterion, the limits are expanded for extreme conditions. These conditions consider very large angles of incidence in the regular energy range, or the regular angle of incidence range at very high photon energies (above 1.5 MeV). Based on the observed performance, recommended test ranges and limits of variation could be proposed in a harmonized way with respect to the IEC 62387:2020 requirements and IEC 60846-2:2015 for special exposure scenarios. In the IEC 62387:2020, IEC 60846-1:2009 and IEC 60846-2:2015, the performance of dosimeters in terms of radiation-based influence quantities is expressed as variation in response relative to the reference conditions, which is aligned with the standard for individual monitoring.

The IEC 60846-1:2009 describes two different minimum rated ranges for photon energy, with their respective reference radiation qualities: 80 keV – 1.5 MeV minimum rated range with S-Cs for industrial applications, and 20 keV – 150 keV minimum rated range with N-100 for medical applications. Clearly defined application-based minimum rated ranges and reference radiation conditions should be applied to both the standard for individual monitoring with active dosimeters (IEC 61526:2024), as well as the standard for passive dosimetry systems for individual and area monitoring (IEC 62387:2020).

On the other hand, standards IEC 60532:2010 and IEC 61017:2016 which are related to specific applications, being area workplace monitoring in nuclear facilities and environmental area monitoring, respectively, have acceptability criteria which are significantly different. The limits of variation are defined in terms of absolute response as opposed to relative response criteria which are defined for IEC 62387 and IEC 60846 standard series (and the individual monitoring standard IEC 61526). Also in these standards, an important difference is that the angular dependence and energy dependence tests are evaluated and performed separately. This is identified as a standardization gap, since these

two influence quantities are usually not independent, and their effect on the response should be considered simultaneously. Testing of energy and angular dependence of response at the same time reflects the real radiation conditions. Therefore, in contrast, testing for these two influence quantities is recommended to be done jointly in IEC 62387:2020, IEC 60846-1:2009 and IEC 60846-2:2015. Therefore, addressing the identified gap would require changes in the criteria for IEC 60532:2010 and IEC 61017:2016 to be expressed in terms of relative response (to the reference conditions), instead of absolute response at certain radiation conditions, leading to harmonization with the three before mentioned standards.

If energy dependence in environmental monitoring applications would be done with active ambient dosimeters, a proposal to also include L-series (ISO 4037:2019) radiation qualities into the performance tests, besides regularly used N-series should be considered. Since L-series are the low-air kerma rate radiation qualities defined in ISO 4037:2019, these radiation qualities could be used for performance testing of active dosimeters at low dose rates. Dose rates which can be achieved with L-series radiation qualities are specific for devices used for environmental monitoring. If the devices are designed for environmental applications, the intent is to register any significant variations in the background radiation level, therefore the upper limit of the measurement ranges of these devices may be limited to the order of magnitude of  $1 \text{ mSv}\cdot\text{h}^{-1}$  (or similar). The L-series radiation qualities still have a very high homogeneity coefficient in terms of incident spectrum beam hardening (above 0.9) (similarly to the N-series which are already used for energy dependence tests at regular dose rates), which makes them suitable for energy dependence testing, specifically for very low dose rates. Such low dose rates cannot be achieved in the N-series under regular conditions, often due to limitations of the irradiation facility (e.g., the lower limit of the X-ray tube that can be used).

Table 1.6. Minimum rated ranges and limits of variation for photon energy influence quantity test for area monitoring dosimeters.

International standard	Dosimeter type, Application	Specific conditions	Minimum rated range	Influence quantity reference value	Response limits
IEC 62387:2020	Passive dosimetry systems, Hybrid dosimeters, Area monitoring (workplace, environment)	$H^*(10)$	(80 keV; 1.25 MeV)	S-Cs	$r(E)$ , 0.71 – 1.67
		$H'(0.07)$	(30 keV; 250 keV)		
		$H'(3)$	(30 keV; 1.25 MeV)		
IEC 60846-1:2009	Area workplace monitoring	Industrial Medical $H^*(10)$	(80 keV; 1.5 MeV) (20 keV; 150 keV) *Extended to 10 MeV for nuclear facilities	S-Cs N-100	$r(E)$ , 0.71 – 1.67
		$H'(0.07)$	(10 keV; 250 keV)	N-80 S-Am	
IEC 60846-2:2015	Area workplace monitoring	Non telescopic probes $H^*(10)$ $H'(0.07)$	(80 keV; 1.5 MeV) (20 keV; 150 keV) (0° to 45°)	S-Cs N-100 N-80 S-Am	IEC 60846-1 range: $r(E)$ , 0.71 – 1.67 1.5 MeV – 7 MeV: $r(E)$ , 0.625 – 2.50
		Telescopic probes $H^*(10)$ $H'(0.07)$	A. (80 keV; 1.5 MeV) a) $(0^\circ/180^\circ) \pm 60^\circ$ b) $\pm 60^\circ$ to $\pm 120^\circ$ c) $90^\circ \pm 10^\circ$ B. (1.5 MeV; 7 MeV)	S-Cs	A. a) $r(E)$ , 0.71 – 1.67 b) $r(E)$ , 0.625 – 2.5 c) $r(E)$ , 0.5 – 2.5 B. $r(E)$ , 0.625 – 2.5
IEC 60532:2010	Area workplace monitoring	Installed assemblies, Nuclear facilities and nuclear power plants $H^*(10)$	(80 keV; 1.5 MeV) *Extended to (50 keV; 7 MeV)	S-Cs	$R(E)$ , 0.75 – 1.40
IEC 61017:2016	Area environment monitoring	$H^*(10)$	(80 keV; 1.5 MeV) *Extended to (50 keV; 7 MeV)	S-Cs S-Co	$R(E)$ , 0.70 – 1.30
IEC 62327:2017	Area monitoring	Radionuclide Identifying Devices		S-Cs S-Co S-Am	$R(E)$ , 0.70 – 1.30

Table 1.7. Minimum rated ranges and limits of variation for the angle of incidence influence quantity test for area monitoring dosimeters.

International standard	Minimum rated range	Influence quantity reference value	Response limits	Specific conditions
IEC 62387:2020	$\S \in (0^\circ; \pm 60^\circ), (180^\circ; 180^\circ \pm 60^\circ)$ $\S \cup (\pm 60^\circ; \pm 120^\circ) \rightarrow 2\pi$	$0^\circ$ , Cs-137	$r(E, \Omega), 0.71 - 1.67$ $r(E, \Omega), 0.67 - 2.00$	workplace environment
IEC 60846-1:2009	$(0^\circ; \pm 45^\circ)$ $*(0^\circ; \pm 90^\circ)$ *wide angle	$0^\circ$ , Cs-137 $0^\circ$ , N-100	$r(E, \Omega), 0.71 - 1.67$	industrial medical
IEC 60846-2:2015	$(0^\circ; \pm 60^\circ), (180^\circ; 180^\circ \pm 60^\circ)$ $(\pm 60^\circ; \pm 120^\circ)$ $(90^\circ; 90^\circ \pm 10^\circ)$	$0^\circ$ , Cs-137	$r(E, \Omega), 0.625 - 2.50$ $r(E, \Omega), 0.625 - 2.50$ $r(E, \Omega), 0.50 - 2.50$	emergency
IEC 60532:2010	$(0^\circ; \pm 60^\circ)$	$0^\circ$ , Cs-137 $0^\circ$ , Am-241	$R(\Omega), 0.80 - 1.20$ $R(\Omega), 0.70 - 1.30$	nuclear safety
IEC 61017:2016	$(0^\circ; \pm 120^\circ)$	$0^\circ$ , Cs-137	$R(\Omega), 0.80 - 1.20$	environment
IEC 62327:2017	IEC 60846 series (Part 1 or Part 2) apply if RID is to be used as a dosimeter			

Table 1.8. Minimum rated ranges and limits of variation for the non-linearity influence quantity test for area monitoring dosimeters.

International standard	Included dose (rate) range or values	Orders of magnitude/ Testing points	Response limits
IEC 62387:2020	$H^*(10), 100 \mu\text{Sv} - 1 \text{ Sv}$ $H'(0.07), 1 \text{ mSv} - 3 \text{ Sv}$ $H'(3), 0.3 \text{ mSv} - 1 \text{ Sv}$	ALL / limits+{30%}	$r(H), 0.87 - 1.18$
IEC 60846-1:2009	$10 \mu\text{Sv/h} / 100 \mu\text{Sv}$	3 / {20%, 40%, 80%}	$r(H), 0.85 - 1.22$
IEC 60846-2:2015	$1 \text{ mSv/h} - 10 \text{ Sv/h}$	4 / {20%, 40%, 80%}	$r(H), 0.83 - 1.25$
IEC 60532:2010	N/A	ALL / {30%, 70%} or {25%, 50%, 75%}	$R(H), 0.70 - 1.30$
IEC 61017:2016	N/A	3 / {20%, 80%}	$r(H), 0.85 - 1.22$ $*r(H), 0.70 - 1.30$ (dose rates < 100 nSv/h)
IEC 62327:2017	IEC 60846 series (Part 1/Part 2) if RID is to be used as a dosimeter		$R(H), 0.70 - 1.30$

One of the results of the research conducted under the scope of the 17RPT01 DOSEtrace joint research project explored the possibility of designing two different rated ranges covering most relevant radiation-based influence quantities, covering both area workplace and area environmental monitoring with active electronic dosimeters (<https://doi.org/10.1016/j.radphyschem.2022.110291>). The test methods and limits of variation for this situation were defined with respect to the requirements defined in IEC 62387:2020, especially considering the angular dependence, as well as special considerations for external probes defined in IEC 60846-2:2015. The proposed measurement programme and test limits which cover energy dependence, angular dependence and non-linearity of the response are presented in Table 1.9.

Table 1.9. Summarized measurement programme for area monitoring dosimeter performance testing – radiation-based influence quantities, their rated ranges and limits of relative response variation.

Influence quantity $X$	Reference value $X_0$	Workplace monitoring		Environmental monitoring	
		$X$	$r(X)$	$X$	$r(X)$
Energy	662 keV (S-Cs)	(80 keV to 1.5 MeV) N-100, N-120, N-150, N-200, N-250, N-300, S-Cs, S-Co *N-40, N-60, N-80, R-C	0.71 to 1.67	(80 keV to 1.5 MeV) N-100, N-120, N-150, N-200, N-250, N-300, S-Cs, S-Co *N-40, N-60, N-80, R-C **L-55, L-70, L-100, L-125, L-170, L-210, L-240	0.71 to 1.67
Angle of incidence	0° at S-Cs	(0°; ±45°)	0.71 to 1.67	(0°;±60°),(180°;180°±60°) (±60°;±120°)	0.71 to 1.67 0.62 to 2.50
Linearity (dose rate)	10 µSv/h	At least 3 orders of magnitude measurement range (30 %,70 %) of each order of magnitude	0.85 to 1.22	At least 4 orders of magnitude including 100 nSv/h measurement range (30 %,70 %) of each order of magnitude	0.85 to 1.22

If the photon energy minimum rated range remains unchanged, from 80 keV to 1.5 MeV, N-series radiation qualities from N-100 (83.3 keV mean photon energy) to S-Co (1.25 MeV mean photon energy) could still cover area workplace monitoring. In the case of environmental monitoring, when the dosimeter measurement range is limited to lower dose rates X-ray L-series radiation qualities from L-55 up to L-240, in addition to low-dose rate radionuclide radiation condition (S-Cs and S-Co) could be used as an alternative to N-series. It should be noted that the presented L-series radiation qualities cover an extended energy range, while the minimum rated range would include energies down to the L-100 radiation quality. The proposed limits of variation in terms of relative response would be harmonized and set to -29 %; +67 %, being equivalent to the currently defined limits of regular area workplace in IEC 60846-1:2009 as well as IEC 61526:2024 for active and hybrid personal dosimeters.

The angular dependence of the response test range should be expanded from the current (0°; ±45°) one, defined for workplace area monitoring. For environmental dosimeters, similarly as in IEC 62387:2020 the test range would include symmetry of the response (covering angular ranges with (0°;±60°) and (180°;180°±60°), with the same limits of variation. To account for more difficult radiation conditions (±60°;±120°) less strict limits were proposed with respect to IEC 60846-2:2015 criteria, accounting for the limitations tied to the design of the instruments (geometry, position of the associated electronics, or other).

While non-linearity limits of variation would remain unchanged for both workplace and environmental monitoring purposes, the minimum rated range should include lowest dose rates as well (below 1 µSv·h<sup>-1</sup>). Special consideration should be given to the determination of the conventional true value as well as the assessment of the measurement uncertainties at very low dose rates, as the dose rates below 1 µSv·h<sup>-1</sup> are not within the scope of ISO 4037:2019.

## 2 Performance evaluation of most commonly used active radiation protection dosimeters

The aim of Task 3.2: *Overview of existing radiation protection dosimeters and current state of the art*, which is a part of Work Package 3: *Harmonization and update of type testing standards*, was to investigate the capabilities of most commonly used radiation protection dosimeters and the upcoming state-of-the-art instruments. For this purpose, historical and aggregated calibration data was collected, with an aim to evaluate dosimeter performance, and identify missing data. Afterwards, a measurement protocol was developed with the goal of improving the quality of acquired data and to evaluate the possibility of updating relevant IEC type testing standards.

### 2.1 Historical and aggregated calibration data

Most used radiation protection dosimeters were identified, and historical and aggregated calibration data was collected among calibration laboratories. Seven Secondary Standard Dosimetry Laboratories (SSDLs) participated in this study, including Vinča Institute of Nuclear Sciences – VINS – Serbia, Ruđer Bošković Institute – RBI – Croatia, Säteilyturvakeskus – STUK – Finland, Český Metrologický Institut – CMI – Czech Republic, Główny Urząd Miar – GUM – Poland, Greek Atomic Energy Commission – GAEC/EEAE – Greece, and National Institute for Metrology – INM – Moldova. The collected data from the calibration certificates contains sets of calibration factors, which can be used to determine the variation in dosimeter response to the radiation-based influence quantities. It should be noted that

usually the calibration procedures are done in S-Cs and S-Co radiation fields at different dose rates, and comparably less in the N-series radiation qualities. Dosimeter response was evaluated in a wide range of dose-rates, spanning from  $0.5 \mu\text{Sv h}^{-1}$  to  $50 \text{ mSv h}^{-1}$  in the case of active personal dosimeters (PDs), and from  $0.5 \mu\text{Sv h}^{-1}$  to  $100 \text{ mSv h}^{-1}$  in the case of active area workplace dosimeters (ADs). Additionally, variation in dosimeter response due to photon energy was evaluated in a wide range of photon energies, from 33.3 keV, including low photon energy radiation qualities, up to 1.25 MeV. The performance of PDs and ADs in terms of relative response based on aggregated historical calibration data is presented in <https://doi.org/10.1016/j.jrras.2026.102344> (Krzanovic et al., 2026; Performance evaluation of active dosimeters for area workplace and individual monitoring based on historical and aggregated calibration data. Journal of Radiation Research and Applied Sciences, 19(2): 102344).

### 2.2 Active personal dosimeter performance

Active personal dosimeters displayed good performance characteristics in terms of non-linearity of their response, in line with the IEC 61526:2024 requirements defined in the standard (0.87 - 1.18). The largest deviations from the reference response were noted for the lowest dose-rate values, which are on the lower end of the measurement range for some dosimeters. That, in addition to dosimeter resolution, could be a contributing factor for the noted deviations.

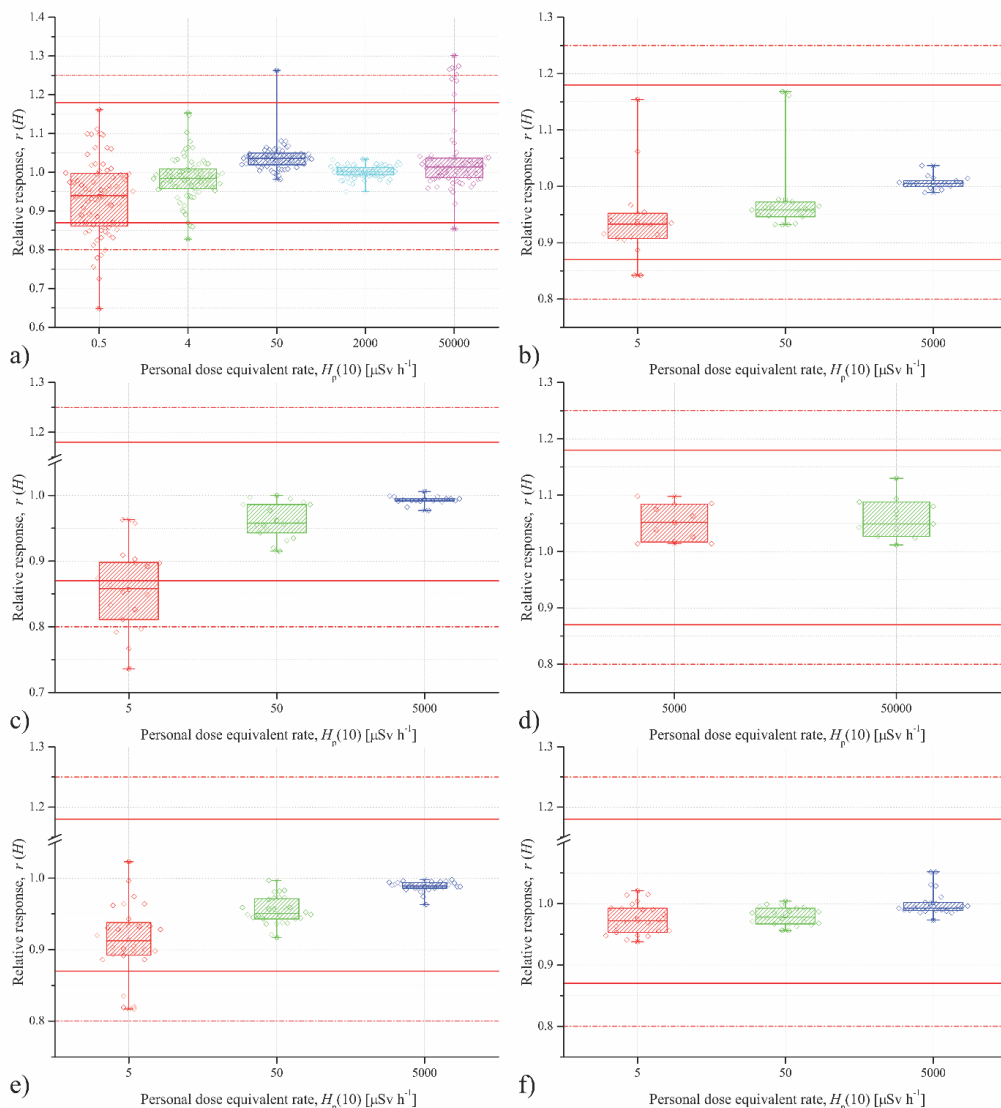


Figure 2-1. Non-linearity of the active personal dosimeter response in a wide range of dose rates. Different dosimeter models are presented in figures a) – f).

PDs complied with standard requirements (0.71 – 1.67) across the entire photon energy range, and in accordance with their manufacturer stated measurement ranges. Notably, one PD exhibited excellent performance, with an average deviation of ~10 % from the reference response.

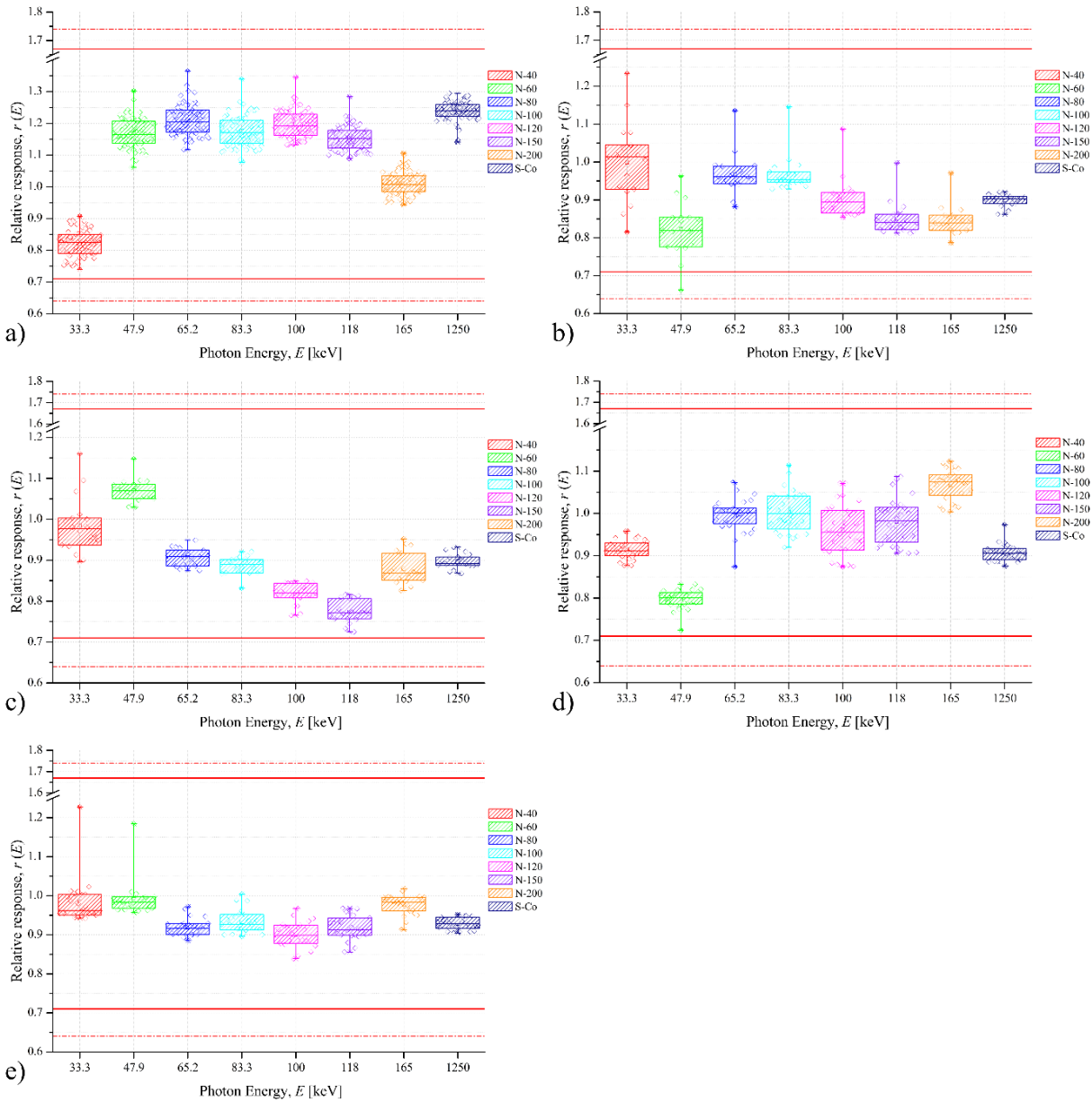


Figure 2-2. Energy response of active personal dosimeters in the range from N40 to S-Co. Different dosimeter models are presented in figures a) – e).

### 2.3 Active area dosimeter performance

Similarly, as with PDs, active area dosimeters exhibited good performance across the evaluated dose-rate range, satisfying the IEC 60846-1:2009 standard requirements (0.85 – 1.22). Again, the largest deviations from the reference response are noted for the lowest dose-rate values.

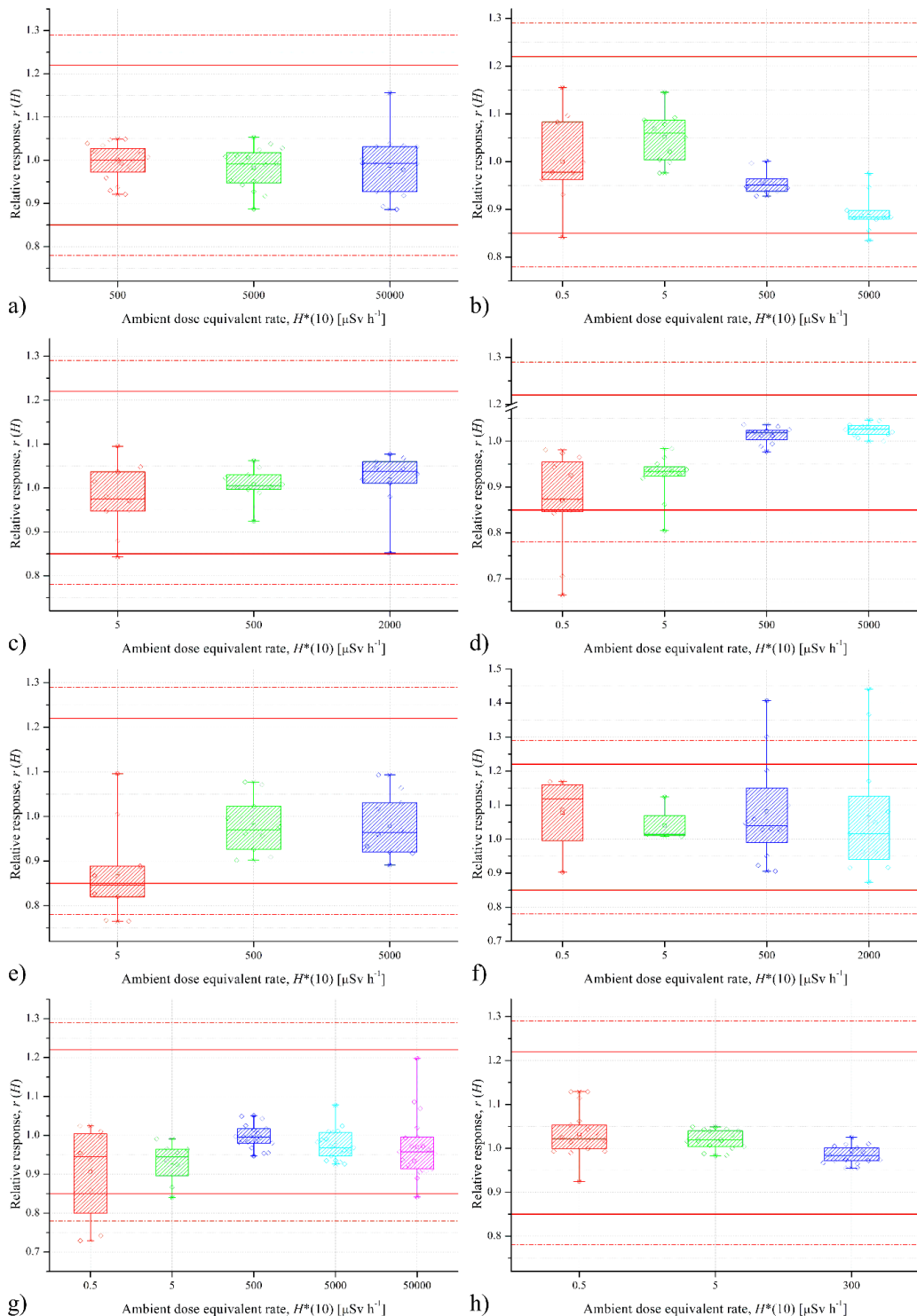


Figure 2-3. Non-linearity of the active area dosimeter response in a wide range of dose rates. Different dosimeter models are presented in figures a) – h).

ADs presented good performance in terms of their energy dependence and comply with requirements defined in the standard (0.71 – 1.67), down to the N-40 radiation quality (mean photon energy 33.3 keV). The differences in the response variation for each dosimeter model could be attributed to their individual energy compensation, since most of them utilize G-M tube-based detector technology.

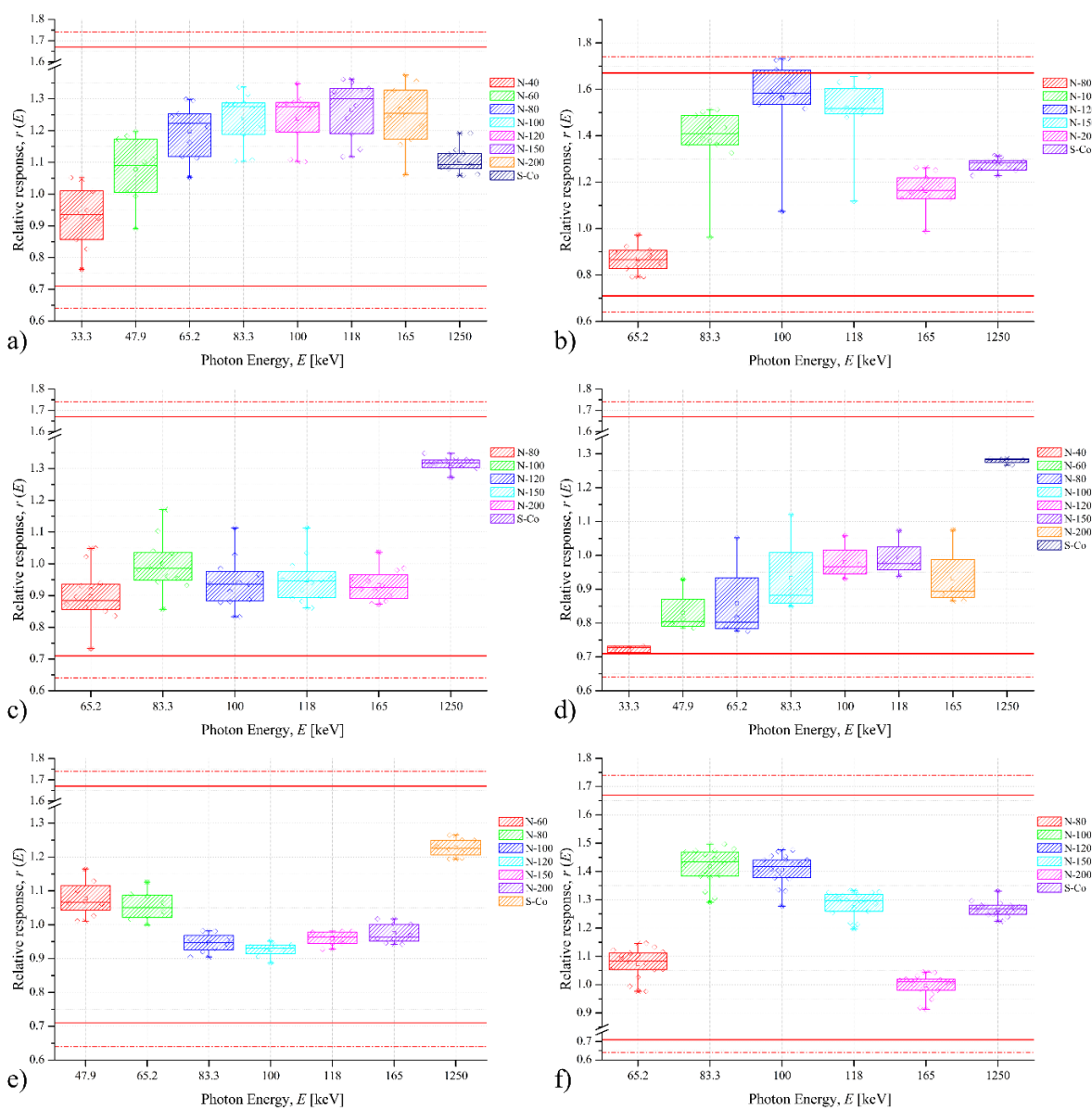


Figure 2-4. Energy response of active area dosimeters in the range from N40 to S-Co. Different dosimeter models are presented in figures a) – f).

### 2.4 Measurement protocol and data collection

A measurement protocol was developed based on identified missing data on dosimeter performance. Seven SSDLs participated in this study, including 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). Research results are presented in <https://doi.org/10.1016/j.jrras.2026.102159> (Vlahovic et al., 2026; Performance assessment of commonly used active radiation protection dosimeters for individual and area workplace monitoring. Journal of Radiation Research and Applied Sciences, 19(1): 102159).

A total of 34 active dosimeters were included in the study, out of which 28 were active area dosimeters (Figure 2-5), and 6 active personal dosimeters (Figure 2-6). The measurement protocol consisted of 5 tests, including dosimeter stability and overload, energy dependence, angular dependence and non-linearity of the response. Dosimeter short-term stability was evaluated for five consecutive days, by performing measurements under reference conditions, which implied irradiation with a dose-rate of  $100 \mu\text{Sv h}^{-1}$  utilizing a Cs-137 radiation source. Dosimeter overload behaviour was evaluated by irradiating the dosimeter with a dose-rate which is at least ten times above the upper limit of the

instruments measurement range. Following this, measurements under reference conditions were performed ( $100 \mu\text{Sv h}^{-1}$  at Cs-137), and the dosimeter response was recorded. Variation in dosimeter response due to photon energy and angle of incidence was evaluated in a broader photon energy and angle of incidence range, than the minimum rated range stated in the relevant standards (IEC, 2009; IEC, 2024), as well as the manufacturer-stated measurement ranges. The expanded photon energy range for this test covered mean photon energies from 33.3 keV up to 1.25 MeV. In the case of ADs, angular dependence was evaluated for the following angles  $0^\circ$ ,  $\pm 45^\circ$ ,  $\pm 60^\circ$ ,  $\pm 90^\circ$ ,  $\pm 120^\circ$ , and  $180^\circ$ . Whereas, for PDs the test was conducted for the following angles of incidence  $0^\circ$ ,  $\pm 30^\circ$ ,  $\pm 45^\circ$ ,  $\pm 60^\circ$ , and  $\pm 75^\circ$ . Variation in dosimeter response due to dose-rate non-linearity was evaluated for the following dose-rate range  $3 \mu\text{Sv h}^{-1}$  to  $7 \text{Sv h}^{-1}$  in the case of ADs, whereas in the case of PDs the dose-rate range spanned from  $3 \mu\text{Sv h}^{-1}$  to  $2 \text{Sv h}^{-1}$ .

Performance analysis implied evaluating whether the dosimeter response is in line with the manufacturer-stated specifications, and the IEC standard stated limits of variation. Additionally, whether any dosimeters exhibited good performance outside their manufacturer-stated specifications and were there any dosimeters which had small deviations from the reference response. The results represented input data for the possibility of updating type testing standards, in the sense of altering the minimum rated ranges, limits of variation and considering introducing two distinct dosimeter classes.

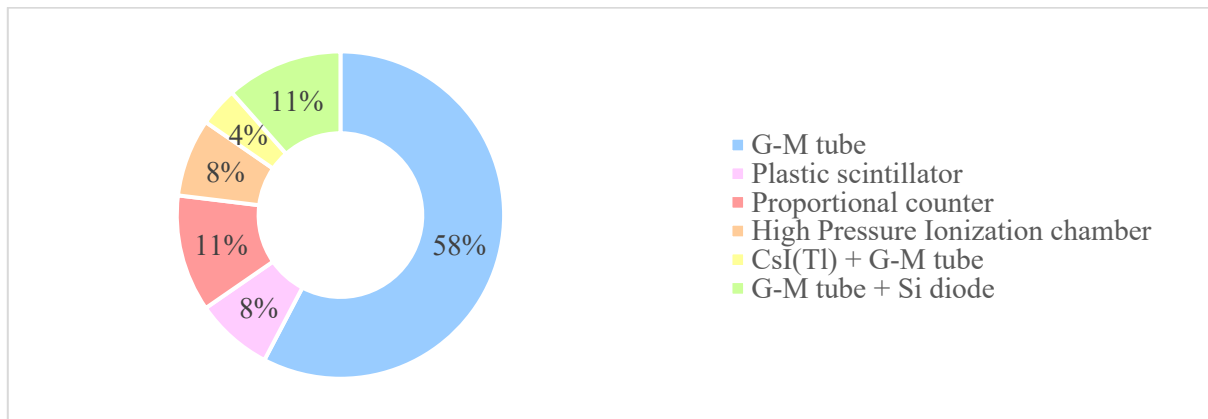


Figure 2-5. Detector active volume distribution between active area dosimeters included in the study.

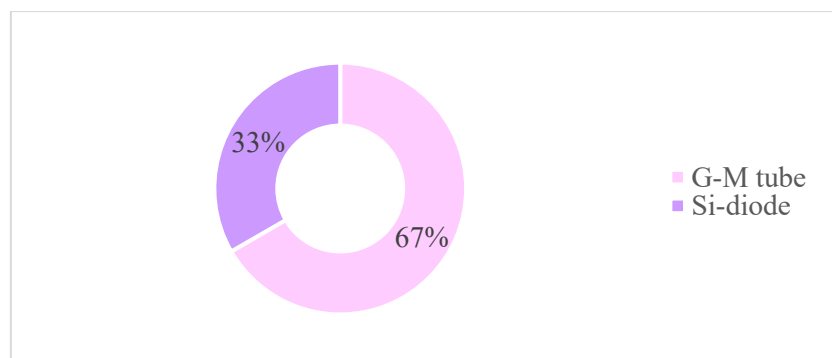


Figure 2-6. Detector active volume distribution between active personal dosimeters included in the study.

## 2.5 Active personal dosimeter performance

When it comes to variation in dosimeter response due to the influence of photon energy, the tested PDs displayed satisfactory performance, in line both with the manufacturer-stated specifications, as well as the standard stated limits of variation in the minimum rated range. Some devices showcased good performance across the entire evaluated photon energy range, even beyond their respective measurement range. However, in this case, the number of evaluated PDs is not sufficient, and it is necessary to extend the sample size in future work.

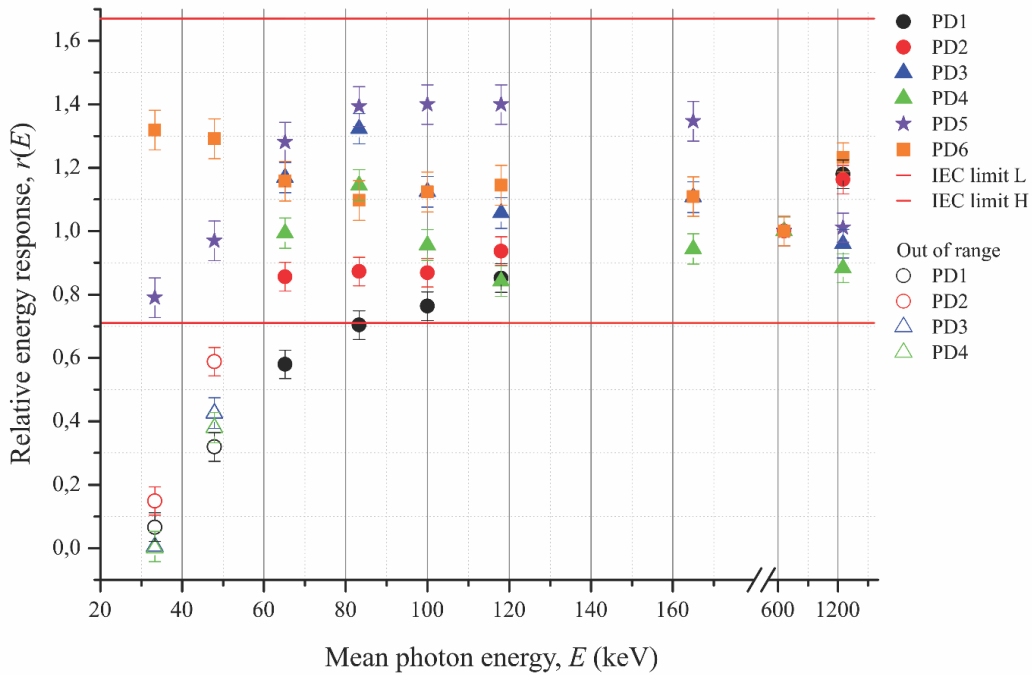


Figure 2-7. Energy response of active personal dosimeters in the range from N40 to S-Co.

Another significant radiation-based influence quantity is angle of incidence. Among the tested PDs, only two dosimeter models are designed for low-energy applications, which can be observed based on their performance. The dosimeters are in agreement with the standard criteria up to approximately  $\pm 45^\circ$ . Low photon energy and high angles of incidence represent unfavourable irradiation conditions. They can be encountered in some medical applications of ionizing radiation, which is why evaluating dosimeter performance under these conditions is important.

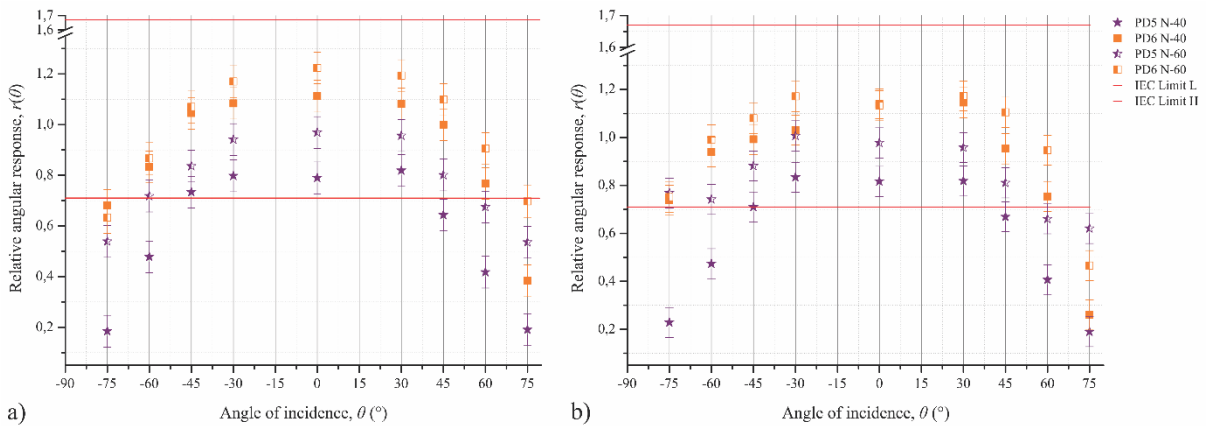


Figure 2-8. Angular response of active personal dosimeters in the N40 and N60 radiation fields: a) horizontal orientation; b) vertical orientation.

For higher photon energies, such as the N-80 radiation quality (mean photon energy 65.2 keV), most dosimeters satisfy standard requirements for angles of incidence going up to  $\pm 75^\circ$ , for both dosimeter orientations. In this case, PD1 and PD2 exhibited pronounced angular dependence, which could be attributed to the instrument design and geometry.

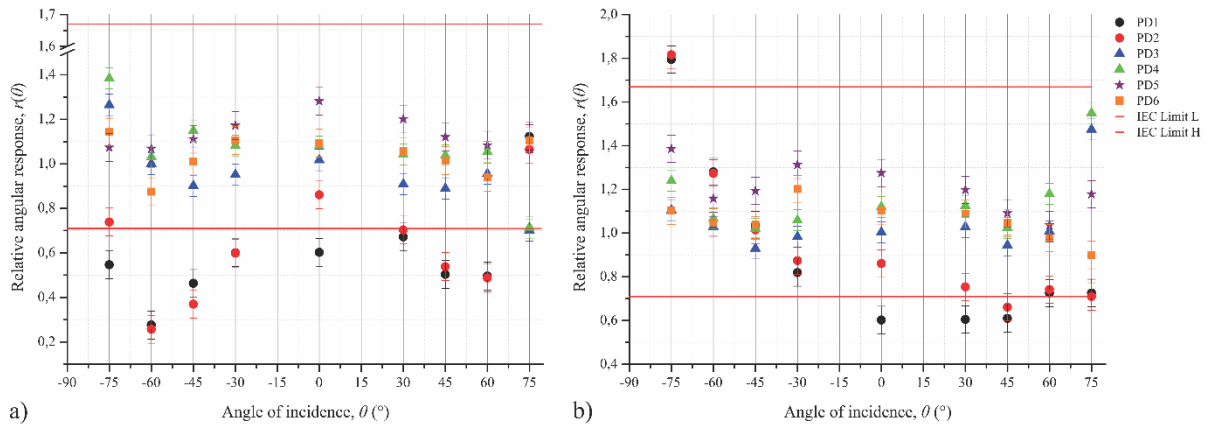


Figure 2-9. Angular response of active personal dosimeters in the N80 radiation field: a) horizontal orientation; b) vertical orientation.

Most of the tested PDs have complied with the standard requirements on non-linearity of the response, over the whole tested dose-rate range. Two instruments presented pronounced non-linearity for the lowest dose-rate values, which could be attributed to the instruments resolution, however the lowest dose-rate is outside the respective measurement range.

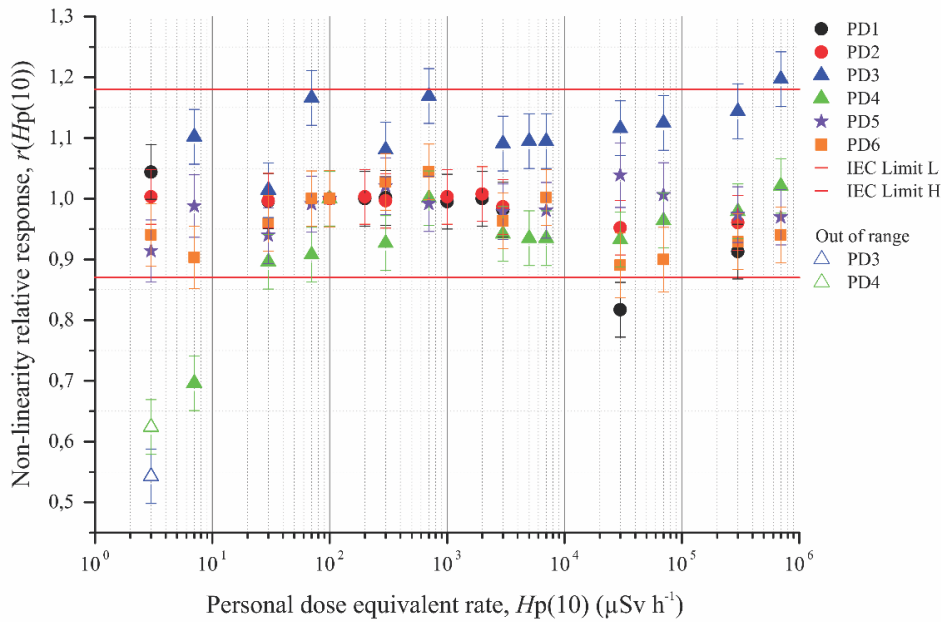


Figure 2-10. Non-linearity of the active personal dosimeter response in a wide range of dose rates.

### 2.6 Active area dosimeter performance

When it comes to dosimeter energy dependence, AD performance is mostly in line with the standard defined limits of variation (0.71 - 1.67) and the manufacturer-stated measurement ranges. Several dosimeters exhibited good performance even beyond their manufacturer-stated measurement range, including low photon energy radiation qualities, such as N-40 and N-60 (mean photon energies 33.3 keV and 47.9 keV, respectively).

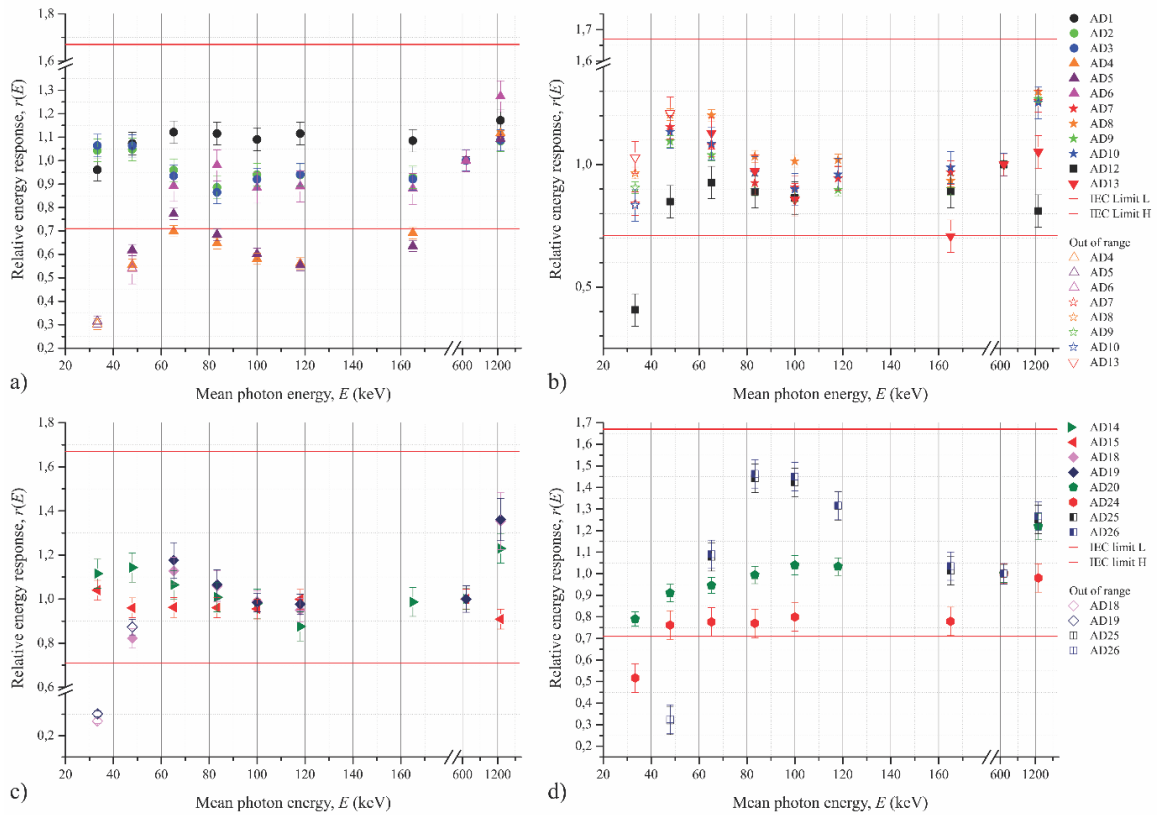


Figure 2-11. Energy response of active area dosimeters in the range from N40 to S-Co. Different dosimeter models are presented in figures a) – d).

Angular dependence of ADs, for vertical and horizontal dosimeter orientation, in N-60 and N-80 radiation qualities (mean photon energies 47.9 keV and 65.2 keV, respectively) is presented in Figures 2-12 and 2-13. Dosimeter performance is mostly in line with standard requirements, for the minimum rated range.

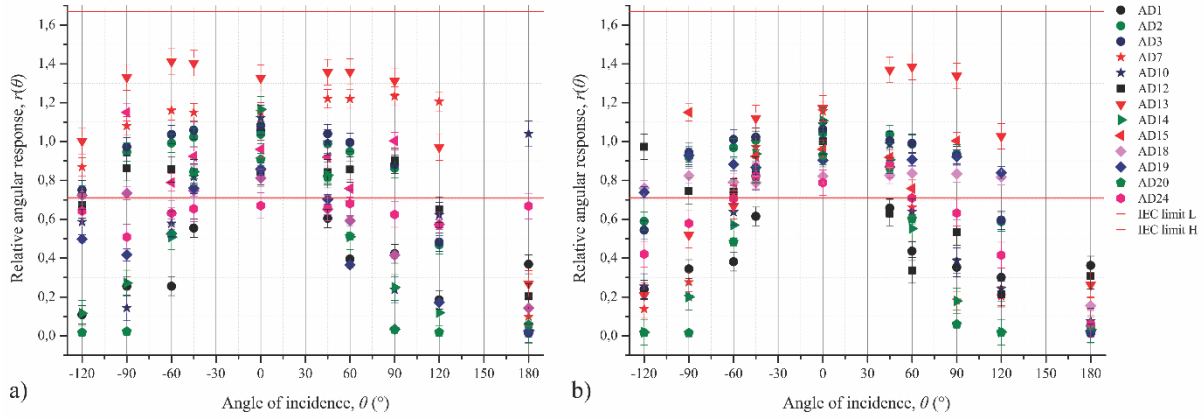


Figure 2-12. Angular response of active area dosimeters in the N60 radiation field.

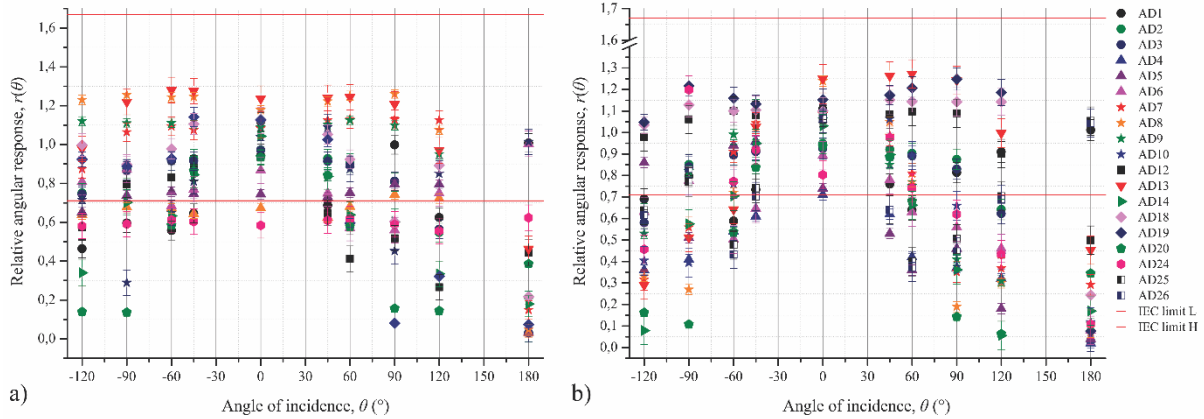


Figure 2-13. Angular dependence of active area dosimeters in the N80 radiation field. Different dosimeter models are presented in figures a) – d).

All of the evaluated ADs satisfy standard requirements (0.85 – 1.22) on non-linearity of the response. Across the entire evaluated dose-rate range, ADs displayed deviations from the reference response within  $\pm 10\%$ , making them suitable for usage in various exposure scenarios (Figure 2-14).

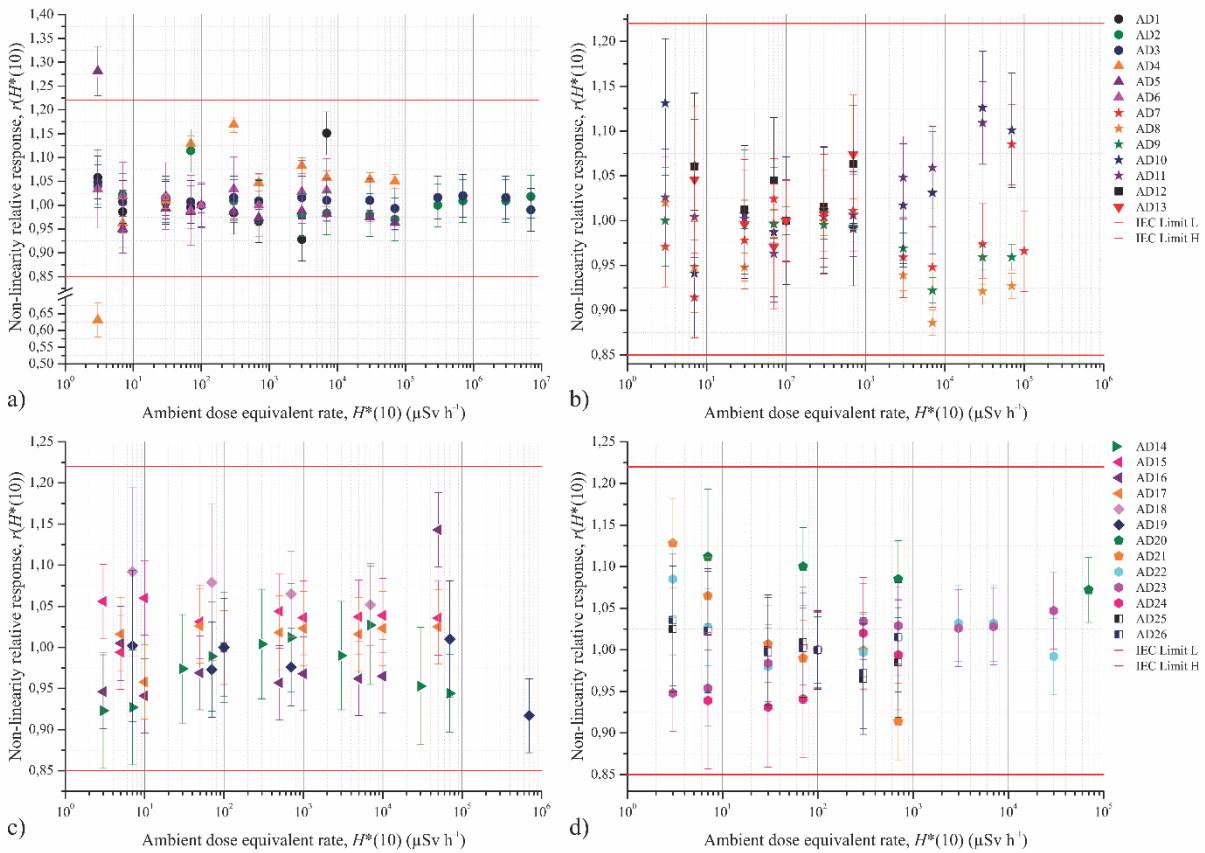


Figure 2-14. Non-linearity of active area dosimeter response in a wide range of dose rates. Different dosimeter models are presented in figures a) – d).

By collecting aggregated historical calibration data (evaluated as the energy dependence and non-linearity of dosimeter response) (Fig. 2.1 – Fig. 2.4), and the additional data on dosimeter performance including variation in response with photon energy, angle of incidence and dose equivalent rate (Fig. 2.7 – Fig. 2.14), the gaps in the missing data on dosimeter performance were addressed. The data presented can be used to evaluate to which extent the newly proposed ICRU 95 quantities would impact on the current performance indicators. By simple recalculation of the dosimeter relative responses, based on the change in the conversion coefficients from air kerma to the specific operational dosimetry quantity, most significant impact can be observed in the low-energy photon range (N-40 and N-60). Considering this, on the manufacturer’s side a possible redesign of the existing dosimeters (either adjustments to the software or to the hardware, e.g., changes in the energy compensation filters or other) would be necessary. On the other hand, changes in the limits of variation might be necessary if a certain rated range includes the lower photon energy radiation qualities which are most impacted by the change in the conversion coefficients (e.g., the minimum rated range for industrial applications is not expected to be affected by these changes, if the lower limit of photon energy is 80 keV).

Even though only one of the examined dosimeters utilized two different detector technologies to cover a wide range of dose rates, such “hybrid” dosimeter design might require additional considerations in the standards. If there are different detectors used in the dosimeter design, and if only one of the detectors is used at the time based on the dose rate, test procedures should be done above and below the internal threshold. In this way, both detectors’ properties are accounted for. For example, the energy dependence test should be done at two different dose rates. In the case that dose rate threshold is set at a relatively low value (e.g., 50  $\mu\text{Sv h}^{-1}$ ), this test procedure for the low-dose rate detector would require the use of larger source-to-detector distances and/or the use of very low X-ray tube currents. This could potentially lead to the need to include low air kerma rate radiation qualities (i.e., L-series) in addition to the N-series, whose dose rates might be too high. Also, having detectors which cover different measurement ranges would require different reference dose rates (in line with the reference and standard test conditions). For example, the reference dose rates for a dosimeter with the described 50  $\mu\text{Sv h}^{-1}$  threshold, would require e.g., reference dose rates of 10  $\mu\text{Sv h}^{-1}$  and 100  $\mu\text{Sv h}^{-1}$ , in the case of an active area workplace dosimeter. Moreover, same considerations would apply not only to the dosimeters utilizing different detector types, but also dosimeters which employ multiple detectors of the same type.

Additionally, even though no such dosimeters were included in this study, some of the state-of-the-art dosimeters may incorporate multiple detectors. Consequently, energy dependence and non-linearity might not be independent for such devices. This would require changes in the standard, so that these influence quantities are tested at the same time, similarly to the current evaluation of photon energy and angle of incidence simultaneously.

### 2.7 Previous research (prior to the 22NRM07 GuideRadPROS project)

Previously conducted research focused on a systematic performance analysis of Monitoring Instruments in Non-governmental Networks (MINNs) and evaluation of IEC type testing requirements and test methods for active area dosimeters used for environmental monitoring. In a paper by Kržanović et al., 2022 a measurement program was developed, and the performance of four instruments which could be used for area environmental monitoring was evaluated, three MINNs and one spectro-dosimeter based on  $\text{CeBr}_3$ .

Variation in dosimeter response due to photon energy was evaluated in a wide photon energy range spanning from 24.6 keV (N-30 radiation quality) to 1.25 MeV (Co-60). The IEC 60846-1:2009 standard sets the limits of variation for the energy dependence test from -29 % to +67 %, for the minimum rated range (80 keV; 1.25 MeV). Most of the tested dosimeters comply with these requirements, however none of them fulfil the standard stated criteria for the extended energy range. The spectro-dosimeter displayed an under-response for the two lowest photon energy radiation qualities, whereas the MINNs exhibited an over-response in this energy region, except for one MINN, which also showed an under-response.

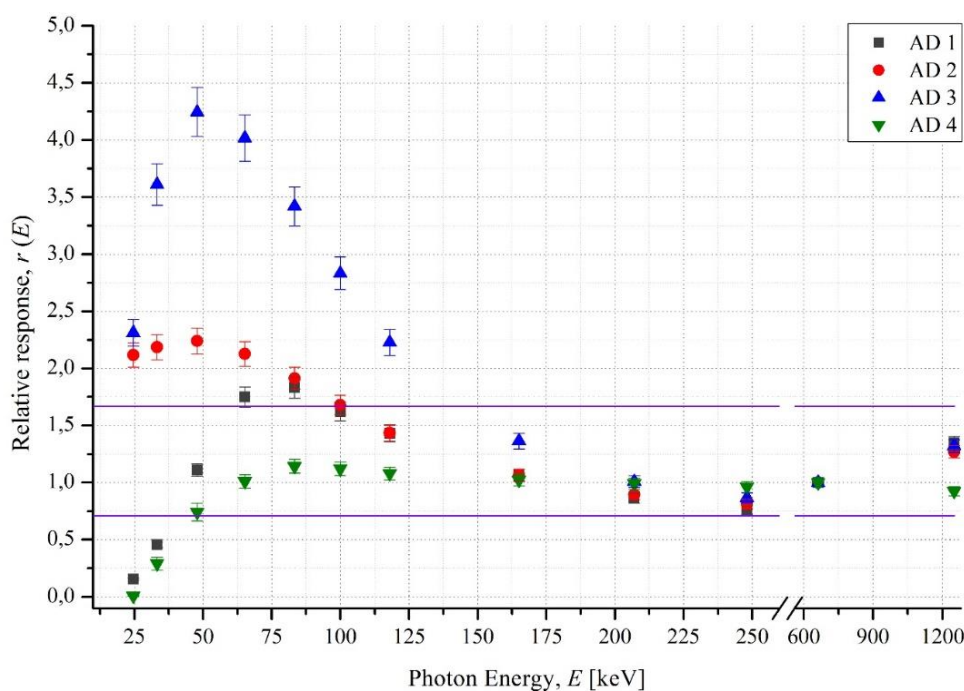


Figure 2-15. Energy response of active area dosimeters from previous research, where AD1, AD2 and AD3 are G-M tube-based MINNs and AD4 represents a spectro-dosimeter.

Non-linearity of the dosimeter response was evaluated for dose-rate values from  $30 \text{ nSv h}^{-1}$  to  $1 \text{ mSv h}^{-1}$ , with respect to the standard defined limits of variation (0.85 – 1.22). Two regions of non-linearity were observed, one being the dose-rate range below  $1 \mu\text{Sv h}^{-1}$  and the other being above  $100 \mu\text{Sv h}^{-1}$ . One of the MINNs and the spectro-dosimeter exhibited excellent performance, in line with the standard requirements, across the entire tested dose-rate range. The remaining MINNs displayed an increase in response for the lowest dose-rate values, with an expected increase in measurement uncertainty due to low-counting statistics, as well as a decrease in response for the highest dose-rate values, because of G-M tube dead time.

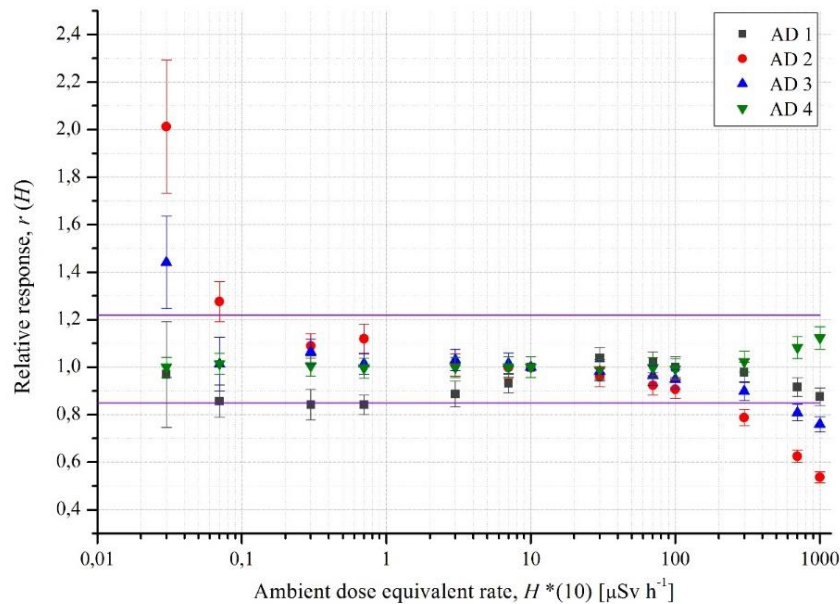


Figure 2-16. Non-linearity of the active area dosimeter response from previous research. AD1, AD2 and AD3 represent G-M tube-based MINNs, and AD4 is a spectro-dosimeter.

## 2.8 Summary of proposed changes

Based on the literature review presented research results and state-of-the-art technology overview it was observed that active radiation protection dosimeters display good performance, in line both with the relevant type testing standard requirements, as well as respective manufacturer specifications. Additionally, dosimeter response was commendable beyond the standard minimum rated range, and in some cases, beyond the manufacturer stated specifications. Furthermore, some dosimeters presented excellent performance characteristics, with small variations in their response.

Based on this, a potential update of type testing standards was considered. Currently both the IEC 60846-1:2009 standard and the IEC 61526:2024 standard distinguish two minimum rated ranges, for industrial (80 keV; 1.25 MeV) and medical (20 keV; 150 keV) applications of ionizing radiation. The presented findings supported the implementation of a unified minimum rated range, spanning from 48 keV (equivalent with the N-60 radiation quality) to 1.25 MeV (Co-60). However, the current standard stated minimum rated ranges and limits of variation are defined to accommodate various ionizing radiation applications, and it has been shown that these requirements are achievable by various manufacturers for different detector technologies. Moreover, this change may not be supported by manufacturers, increasing the development and type testing costs. Therefore, extending the minimum rated range would possibly not improve the quality of acquired dosimetry data. It should be noted that the current industrial photon energy range does not cover some of the specific industrial applications, such as the nuclear fuel cycle, where photon energies lower than 80 keV can be encountered. On the other hand, the medical photon energy range sufficiently well covers radiation protection needs for low photon energies characteristic for e.g., mammography and nuclear medicine.

On the other hand, by implementing two dosimeter classes, a clear distinction would be made between dosimeters which have small variations in relative response (supported by the research results acquired in Task 3.2) and those which have more pronounced dependence on radiation-based influence quantities. As previously mentioned, the minimum rated ranges would remain as they are currently defined, for both IEC 61526:2024 and IEC 60846-1:2009, but the limits of variation could be modified in the following way: In the case of the energy and angular dependence test, Class A dosimeters would pertain to more strict limits of variation in terms of relative response, 0.83 – 1.25, which correspond to the  $\pm 20\%$  variation in the calibration coefficient, whereas the limits of variation set for Class B dosimeters would remain unchanged (0.71 – 1.67); In the case of variation of dosimeter response due to dose rate, Class A dosimeter limits of variation in terms of relative response could be more strict than they are currently stated in the standard, and set to 0.91 – 1.11. Similarly, Class B dosimeter limits of variation would remain unchanged.

Table 2.1 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 - $\pm 45^\circ$	0.83 – 1.25	0.71 – 1.67
	Non-linearity	three orders of magnitude including $10 \mu\text{Sv h}^{-1}$	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 - $\pm 60^\circ$	0.83 – 1.25	0.71 – 1.67
	Non-linearity	$0.5 \mu\text{Sv h}^{-1}$ – $1 \text{ Sv h}^{-1}$	0.91 – 1.11	0.83 – 1.25

Introducing two dosimeter classes may lead to the improvement of dosimeters in use, and subsequently to optimization of radiation protection practices. Based on the observed performance of most commonly used and state-of-the-art devices it can be seen that many of them would already be in compliance with the proposed Class A criteria, leading to the conclusion that the current technology and design of the dosimeters are able to meet such requirements. Still, it is important to state that Class B dosimeters, by complying with the current IEC criteria, still exhibit sufficient performance characteristics to be used in all legally relevant applications of ionizing radiation.

While the introduction of these classes is supported by the measurement data, this suggestion could also lead to eventual effect on the market, by reducing the availability of Class B dosimeters. The distinction between proposed classes can be justified on application basis, where in some applications, the end-user might require better accuracy and lower uncertainty, which is especially significant for the workplaces where the exposure limits may be approached. Besides the specific user needs and requirements, it should be noted that regulatory framework and safety standards often set basic requirements on dosimeters, not explicitly stating any specific performance requirements, which are and can be set by radiation protection officers. The choice of dosimeter to be used would also be affected by availability and cost besides the technical specifications. It is evident that many different dosimeter types are available on the market, however for certain ionizing radiation practices it is important to use dosimeters which are suitable for accurate measurement of low energy X- and  $\gamma$ -rays, characteristic for medical applications of ionizing radiation (e.g., diagnostic radiology and low energy diagnostic nuclear medicine). Such dosimeters could be preferred by regulatory authorities and/or external dosimetry services, for shielding evaluation and/or calculation in medical or industrial applications as a part of regulatory control activities (inspections and licensing), as well as assessment of effective doses for exposed workers. In some specific applications (such as industrial radiography), by utilizing instruments with less pronounced variation in response more accurate designation of supervised and controlled areas could be done, leading to optimized radiation protection. Moreover, such applications include the use of radiation protection dosimeters in testing laboratories, which are accredited and have an established quality management system (e.g., monitoring of environmental radioactivity levels). The introduction of Class A and Class B dosimeters would not define the first category as the reference-class instruments and the latter as the field-class instruments, as both categories pertain to the active dosimeters used for individual and area dosimeters which are utilized by end-users in different workplaces, but rather introduce two classes of field instruments, for specific user needs. Due to their lower uncertainty, which is the consequence of lower expected variations in dosimeter response with tested radiation-based influence quantities, Class A dosimeters could be suitable for use as transfer instruments.

### 3 Guidelines on harmonized type testing

The performance tests of active dosimeters for individual (personal) and area (ambient) monitoring used for radiation protection include evaluation of dosimeter performance in terms of response to the radiation-based 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 through tailored performance tests, within the rated ranges of the influence quantity for which the dosimeter is designed to be used. The relevant International Electrotechnical Commission (IEC) type testing standards define minimum rated ranges and limits of variation, in terms

of relative response, which the dosimeters have to satisfy in order to be in compliance with the standard requirements. The IEC 60846-1:2009 standard defines criteria for active area workplace dosimeters, whereas IEC 61526:2024 defines criteria for active personal dosimeters. The most important radiation-based influence quantities include photon energy, angle of incidence and dose (rate).

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:

$$R = \frac{\bar{G}}{C} \quad (1)$$

where  $\bar{G}$  is the mean indicated value of the measured quantity, and  $C$  is the reference quantity value of the quantity to be measured.

The relative response,  $r$ , is defined as the dosimeter response normalised to the dosimeter (reference) response, which is determined under reference conditions:

$$r = \frac{R}{R_0} \quad (2)$$

where  $R_0$  is the reference response obtained in the following way:

$$R_0 = \frac{\overline{G_{r,0}}}{C_{r,0}} \quad (3)$$

$C_{r,0}$  is the reference value of the quantity to be measured under reference conditions, and  $\overline{G_{r,0}}$  is the corresponding indicated value. Reference conditions are defined in the type testing standards, for each influence quantity. During the performance test, all influence quantities which are not subject of a certain test should be within their respective reference conditions. In this case, reference conditions imply irradiations using S-Cs at  $0^\circ$ , unless otherwise stated by the manufacturer (e.g., some devices may utilize Am-241 as the reference radiation quality). In order for the dosimeter to exhibit compliance with standard requirements, the following inequality needs to be fulfilled:

$$r_{min} - U_{C,com} \leq \left( \frac{\bar{G}_i}{\overline{G_{r,0}}} \right) \cdot \frac{C_{r,0}}{C_i} \leq r_{max} + U_{C,com} \quad (4)$$

where  $U_{C,com}$  is the expanded measurement uncertainty of the conventional quantity value of the quantity. Limits of variation in terms of relative response ( $r_{min}$  and  $r_{max}$ ) are expanded by  $U_{C,com}$ .

All tests are performed in reference radiation fields established according to ISO 4037-1:2019, either by using radionuclides or by using an X-ray generator. Gamma radiation fields are produced using radionuclide sources of Cs-137 (mean photon energy 662 keV) and Co-60 (mean photon energy 1.25 MeV), abbreviated as S-Cs and S-Co, respectively.

Traceability, in terms of air kerma, is established by using calibrated reference class ionization chambers. In the case of X-ray radiation fields, corrections to both the reference value and the measured value that arise from variations in the X-ray generator output should be applied using a plane-parallel monitor ionization chamber. Reference values of operational quantities are determined by using appropriate conversion coefficients, defined by the ISO 4037-3:2019. These conversion coefficient values are determined for matched radiation fields with an expanded measurement uncertainty of 4.0 % ( $k = 2$ ). Conversion coefficients from air kerma to the operational quantities depend on photon energy, while for the personal dose equivalent they also depend of the angle of incidence.

Dosimeter testing should be performed using either the substitution method, the known radiation field method or the substitution method with the use of the monitor ionization chamber. A schematic representation of the setup is presented in Fig. 1. If active personal dosimeters are being tested, a standard ISO water slab phantom should be used for all irradiations. In the case of active area dosimeters tests are performed free in air. Additionally, for the S-Cs and S-Co reference radiations fields, a 3 mm polymethyl methacrylate (PMMA) should be placed in front of the dosimeters to

establish the secondary charged particle equilibrium. In the high energy radiation fields, R-C (4.4 MeV) and R-F (6 MeV to 7 MeV), a layer of 25 mm PMMA shall be used.

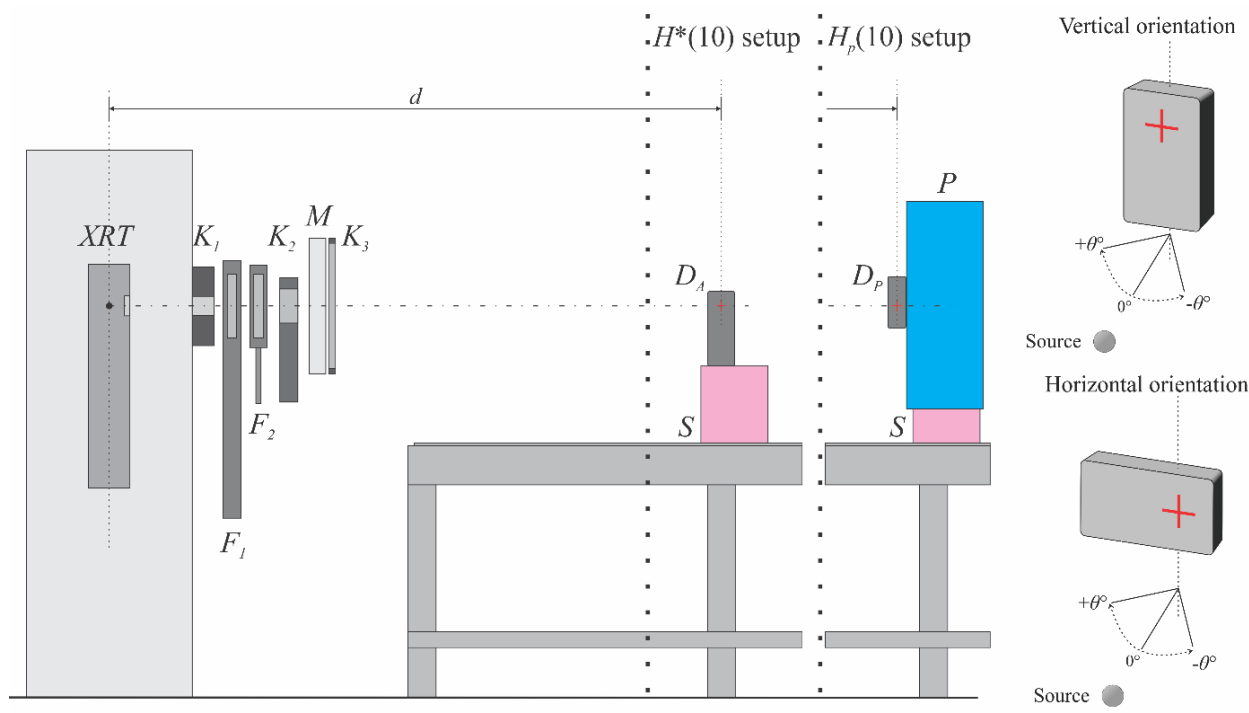


Figure 3-1. Schematic representation of the experimental setup. (left): XRT - X-ray tube; K1, K2 and K3 - apertures; F1 and F2 - additional filtration; M - monitor ionization chamber;  $d$  - source-to-detector distance; P - ISO slab phantom (used with PDs); S - positioning support (low Z material); DA - AD; DP - PD. (right): Dosimeter orientation and rotation for the angular dependence test.

### 3.1 Energy dependence

Both the IEC 61526:2024 standard for active personal dosimeters and the IEC 60846-1:2009 standard for active area workplace dosimeters define two minimum rated ranges for the energy dependence test, based on the dosimeter's intended use. Usually the N-series and S-Cs and S-Co radionuclide qualities are used for this test. These minimum rated ranges can be expanded to include broader range of photon energies if needed. In this case the set of radiation qualities used for the test is expanded to the low photon energy radiation qualities (N-80 and below), and to the high energy radiation qualities (R-C and R-F). Mean photon energies of the reference radiation qualities (N-series, S-qualities and R-qualities) are presented in Table 1.

The minimum rated range covering photon energies from 20 keV to 150 keV pertains to low energy X-ray radiation applications, such as diagnostic radiology, and corresponds to the N-series X-ray radiation qualities from N-25 to N-150, with the reference radiation quality being N-100. Whereas the second one, from 80 keV to 1.5 MeV is related to general workplaces and the use of high energy X-rays and gamma sources (e.g., industrial applications of ionizing radiation), and is achieved by using X-ray radiation qualities from N-100 to N-400, and radionuclide sources S-Cs and S-Co, with the reference radiation quality being S-Cs.

In the case of environmental area monitoring, when dosimeters whose measurement range includes low dose rates are tested, alternatively, the energy dependence test could be done in the L-series radiation qualities, if sufficiently low dose rates cannot be achieved by using the N-series radiation qualities. The following L-series radiation qualities could be used to cover the low energy range for such dose rates: L-20, L-30, L-35, L-55, L-70, L-100, L-125, L-170, L-210 and L-240. Even though S-Am is not covered in the current version of the ISO 4037:2019, this radiation quality could also be used, with proper characterization, to perform the energy dependence test for lower dose rates.

Table 3.1. Mean photon energies of the ISO 4037-1:2019 reference radiation qualities.

Radiation quality code	Mean photon energy [keV]
N-15	12.4
N-20	16.3
N-30	24.6
N-40	33.3
N-60	47.9
N-80	65.2
N-100	83.3
N-120	100
N-150	118
N-200	165
N-300	248
S-Cs	662
S-Co	1250
R-C	4400
R-F	6700

### 3.2 Angular dependence

Angular dependence of active electronic dosimeters is tested for the angles of incidence spanning from  $0^\circ$  to  $\pm 60^\circ$ . The measurements should be performed in two perpendicular planes containing the reference direction through the reference point of the dosimeter. If manufacturer specifications clearly state the dosimeter's angular rated range, the test should be performed for angles of incidence up to  $\pm\alpha_{max}$ , if  $\alpha_{max}$  is not included in the minimum rated range. Angular dependence test should be done for at least the three radiation qualities with the lowest photon energy for which the dosimeter complies with the limits of variation for the energy dependence test. Additionally, the test should be done for radiation qualities with maximum and minimum relative energy response. Variation in energy and angular response is determined relative to S-Cs at the reference direction of the incident beam ( $0^\circ$ ). Dosimeter angular dependence can be evaluated in the following radiation qualities N-15, N-20, N-30, N-40, N-60, N-80, N-100, N-150, N-200, N-300, S-Cs, S-Co, R-C and R-F, established according to ISO 4037-1:2019. The minimum rated ranges of photon energy are described in section 1.1.

If active area dosimeters are intended to be used for environmental area monitoring, test conditions should account for a broad range of angles of incidence, encompassing the full  $2\pi$  geometry. Furthermore, the angular range in which dosimeter performance characteristics are assessed can be expanded to evaluate dosimeter response even in extreme radiation conditions (e.g., high angles of incidence accompanied with low photon energy). In this case the angle rated range should be expanded to include the following angular ranges: ( $0^\circ$ ;  $\pm 60^\circ$ ), ( $180^\circ$ ;  $180^\circ \pm 60^\circ$ ), ( $\pm 60^\circ$ ;  $\pm 120^\circ$ ). If the measurement range of the dosimeter is limited, L-series radiation qualities could be used to perform the angular dependence test at low dose rates instead of N-series.

### 3.3 Non-linearity

The response non-linearity test should be performed utilizing S-Cs and S-Co radiation qualities, and for at least two dose (rate) values in each order of magnitude, covering the dosimeter measurement range (including the measurement range limits). If the entire dose rate range can't be covered by the reference radiation quality, another radiation quality can be used, and in this case, it is necessary to perform the correction for the energy dependence of the response.

Minimum rated range covers at least three orders of magnitude, including the reference dose rate (set either by reference conditions or standard test conditions). For active personal dosimeters reference conditions pertain to the dose rate value of  $0.3 \text{ mSv} \cdot \text{h}^{-1}$ , or in the standard test conditions range from  $0.1 \text{ mSv} \cdot \text{h}^{-1}$  to  $10 \text{ mSv} \cdot \text{h}^{-1}$ . For active area dosimeters the reference conditions pertain to the dose rate value of  $10 \text{ } \mu\text{Sv} \cdot \text{h}^{-1}$ , or in the range of standard test conditions from  $3 \text{ } \mu\text{Sv} \cdot \text{h}^{-1}$  to  $100 \text{ } \mu\text{Sv} \cdot \text{h}^{-1}$ .

### 3.4 Summary of the minimum rated ranges and limits of variation

Table 3.2. Minimum rated ranges (MRR) and expanded test ranges (ETR) with harmonized limits of variation (L) for active electronic dosimeters covered by IEC 60846-1:2009 and IEC 61526:2024.

Dosimeter	Photon energy		Angle of incidence		Non-linearity	
	MRR / *ETR	L	MRR / *ETR	L	MRR / *ETR	L
Active electronic dosimeters for individual and area monitoring	(80 keV; 1.5 MeV) (20 keV; 150 keV) *(20 keV; 6.7 MeV)	$r(E)$ : 0.71 – 1.67	0°; ± 60° **180°; 180°±60° ±60°; ±120°	$r(E, \alpha)$ : 0.71 – 1.67 ***0.62 – 2.50	Three orders of magnitude including the reference condition *All orders of magnitude within the instrument measurement range	$r(H)$ : 0.87 – 1.18

\*Expanded test range of influence quantities include test ranges for photon energy, angle of incidence and non-linearity.

\*\*Expanded angle of incidence test range for area workplace monitoring.

\*\*\*Limits of variation for the expanded angle of incidence range for active area dosimeters.