22NRM07 GuideRadPROS

D8 Guidelines on the implementation of new operational quantities of ICRU 95 into standards and regulations and recommendations for incorporation of this information into future standards

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1 Summary

The document summarizes the impact of ICRU Report 95 on reference field standards used for dosimeter calibration and dosimeter type testing standards. The scope is limited to the photon energies listed in the ISO 4037 standard series.

It gives guidance on which requirements in ISO 4037 might need an update when moving from the present to the new operational quantities. Additionally, existing devices are checked for compliance with the current type testing standards with respect to the proposed operational quantities.

2 Introduction

The International Commission on Radiation Units and Measurements (ICRU) and on Radiological Protection (ICRP) have published a joint report, ICRU 95, introducing new operational quantities for radiation protection dosimeters, which are meant to replace the currently used ones. The demand for new operational quantities arises from the need to include a wider range of radiation types and energies, as well as to incorporate the changes in current ionizing radiation practices and to reduce the gap between operational and protection quantities which increase when adopting protection quantities calculated with ICRP 103 and 116 instead of the one used previously and taken from ICRP60 and 74. This is specifically of importance in the range of diagnostic radiology energies, where the use of the current operational quantities leads to strong over-estimation of the effective dose (Gilvin et al., 2022).

The possible adoption of the ICRU 95 operational quantities would result mainly in the modification of the value of the conversion coefficients from air kerma to the operational dose equivalent quantities, so that the shape of the response, as a function of energy and angle of incidence of the photons, of the dosimeters must be adjusted in a way to prevent disagreement with the type test criteria. These modifications could require adaptations to the dosimetry system, either in the information processing algorithms, or in the physical design of the detectors, or both, in order to remain in compliance with the type test acceptance criteria.

Some of the requirements in ISO 4037 are based on calculations using the present conversion coefficients. Therefore, it is expected that some of these requirements need an update.

3 Impact on ISO 4037

3.1 General

Some requirements, e.g. for filter thickness and high voltage accuracy, are based on permitted influence on the conversion coefficient for a certain radiation quality of not more than 2 %. These requirements will need an update when changing to the new operational quantities.

Furthermore, the second set of conversion coefficients without kerma approximation in ICRU report 95 (instead of just one set with kerma approximation, i.e. assuming charged particle equilibrium for calibration purposes), may require new reference fields for the calibration or type testing of dosimeters. These new reference fields may need to be developed in close connection with the relevant type testing standards. Their development would require further research and are beyond the scope of this project.

This document will focus on the existing reference fields used under charged particle equilibrium.

3.2 Results from simulations

The limits for matched fields in ISO 4037-1:2019 are re-evaluated during the project. The same procedure is applied by CIEMAT using the conversion coefficients from ICRU 95 for calibration fields. The calibration coefficients in ICRU report 95 will change from the currently published values due to a further change in the calculation of the effective dose in the foreseeable future. Therefore, differences are not calculated for all qualities in this document, instead two representative radiation qualities were selected, namely N-30 and N-250. When updating ISO 4037-1 with respect to the ICRU 95 quantities in the future, the calculation methods can be applied using the then published conversion coefficients to come to new requirements for all radiation qualities.

The target quantity for the calculations was H_p and the limits for high voltage and filter thickness were analysed. For assessing the limits, the high voltage was varied in the range of ± 5 % (13 values) while the filter thickness was varied in the range of ± 10 % (9 values) from their respective nominal values. In total, 528 simulations were conducted.

Simulations of spectral models were performed using SpekPy v2, an open-source software toolkit for the Python programming language that allows modelling reflection geometry X-ray tubes with thick target anodes consisting of the elements W (20–300 kV), Mo or Rh (20–50 kV). The most important keywords that can be specified in a SpekPy model are tube potential, anode angle, target material, filtration thickness and materials, and source attenuation coefficients.

The basic inputs used for the simulations are:

- Distance from x-ray tube focus: 1 m
- X-ray tube anode: W with 20° anode angle
- Filtration materials and thicknesses of the evaluated radiation quality as defined in ISO 4037
- Monoenergetic mass energy transfer coefficients: PENELOPE version 2018
- Monoenergetic conversion coefficients: calculated by PTB (Endo, 2017) for table A.5.2b of ICRU 95

For the calculation of the $\mu_{tr}/\rho(E)$ and $h_p(\varphi, E)$ for spectrum energies the Akima spline on log-log axes was used.

The results and the code are hosted on GITHUB and can be shared with the experts updating ISO 4037 if needed.

The data allow the determination of new limits for the high voltage and filter thickness requirements. An example is given in Table 1. Further tables are given in Chapter 6 Results from simulations.

High voltage variation (%)	**h_p 0°**	**Relative change of conversion coefficient**
-5	0,2043	-9%
-3	0,2127	-6%
-2	0,2169	-4%
-1,5	0,2191	-3%
-0,5	0,2233	-1%
-0,1	0,2251	0%
0	**0,2255**	**0%**
0,1	0,2259	0%
0,5	0,2276	1%
1,5	0,2320	3%
2	0,2341	4%
3	0,2385	6%
5	0,2472	10%

Table 1 Impact of high voltage variation for N-30 on conversion coeffienct h_p

3.3 Summary for ISO 4037

When possibly updating the ISO 4037 series to include the operational quantities suggested by ICRU in report 95, these results can be used to derive new limits for high voltage variation and filter thickness accuracy. This update should use the re-calculated mono-energetic conversions coefficients based on the newest ICRP recommendation. Additionally, an update is needed every time the mono-energetic conversion coefficients change due to changes of effective dose calculation.

4 Impact on current dosimeters and type testing standards

4.1 General

The type testing standards are most likely only slightly affected by the change of the operational quantities. Most requirements in these standards are oriented on the protective goal and not on the quantity itself. Nevertheless, the quantities have to be updated in the standards for personal and area dosimeters which currently include the present operational quantities. As the abilities of the existing or upcoming dosimeters to measure the new quantities may differ, adoption of new limits based on the state of art and consensus might be needed. This chapter reports tests of current dosimeters with respect to the current and new operational quantities, applying the current limits of IEC standards. The results can be used to discuss during an update of these standards, whether a change of the limits seems appropriate or necessary.

4.2 Current dosimeter performance

Based on the data on dosimeter performance collected for the GuideRadPROS Work Package 3 testing protocol, relative responses were recalculated according to the newly proposed conversion coefficients, h_k (Behrens and Otto, 2022). Figures 1-2 represent the relative energy dependence of both active area and active personal dosimeters, in comparison to the currently used h_k conversion coefficients. Figures 3-7 represent the angular dependence of both active area workplace and active personal dosimeters (abbreviated respectively as AD and PD), for radiation qualities N-40, N-60 and N-100, for vertical dosimeter orientation. The obtained relative responses were evaluated against the relevant standard stated limits of variation for the energy and angular dependence test (-29 %, +67 %) (IEC 60846-1:2009; IEC 61526:2024). The results were evaluated in a broader range of energies and angles than both the standard stated minimum rated range and the manufacturer stated specifications.

4.3 Variation in dosimeter response with photon energy and angle of incidence

For the most part, the AD relative response shown in Figure 1 follows a similar trend for both conversion coefficient values across the entire energy range. Discrepancies can be noticed when it comes to low energy radiation qualities, such as N-40 (mean photon energy 33.3 keV), which could be attributed to the large difference in conversion coefficient values. Due to this, almost half of tested dosimeters have failed to comply with the standard stated limits of variation. The maximum noted deviations from the reference response were +113.3 % for AD14, and -48.8 % for AD18. Whereas, with the current conversion coefficients, dosimeter relative response predominantly falls between ±20 %.

The relative response improves for the radiation quality N-60 (mean photon energy 47.9 keV), with only two dosimeters, AD25 and AD26, not satisfying the standard stated limits of variation. However, these are two units of the same dosimeter model, and this energy is outside the energy range stated by the manufacturer.

For higher energies, the differences in dosimeter relative response are negligible and follow the same trend.

Similar findings have been reported by Bossin et al. (2024). Their research investigated the response of several personal dosimetry systems, including radiophotoluminescence, optically stimulated luminescence, direct ion storage and thermoluminescence, and showed that, regardless of the detector material, dosimetry systems overestimated the new operational quantity H_p by a factor of 3 or 4 for low energy x-rays.

Similarly, as for ADs, the largest difference in PD response can be noted for the N-40 radiation quality (Figure 2), where two dosimeter models had a significant increase in their response, with the maximum deviation from the reference response of +152.3 % noted for PD6. Again, for higher photon energies the response curve follows a similar trend, with no significant discrepancies.

To study the impact of new conversion coefficients on the angular response, the low-energy N-40, N-60 and N-100 radiation qualities were selected, since low energies and high angles of incidence represent unfavourable irradiation conditions, and are characteristic for diagnostic radiology applications of ionizing radiation, in this way covering different medical imaging modalities. When comparing the two graphs presented in Figure 3, it can be noted that dosimeters exhibit a noticeable over-response with the new h_k coefficients. In this case, none of the dosimeters comply with the standard stated limits of variation, for the minimum rated range of the angle of incidence.

Figure 4 shows the angular response in the radiation quality N-60, where all the dosimeters satisfy the standard stated limits of variation for the minimum rated range of the angle of incidence. However, an increase in dosimeter relative response can be noted for all tested angles of incidence.

Figure 5 shows the response for the radiation quality N-100. Dosimeter response follows a similar trend for both sets of conversion coefficients, with most dosimeters complying with the standard defined limits of variation in the minimum rated range of angle of incidence.

Similarly, as with ADs, PDs also exhibited an increase in response for the radiation quality N-40 (Figure 6), which can be attributed to the large difference between the current conversion coefficients, and the newly proposed ones. In this case, PD5 performed satisfactory even beyond the standard stated minimum rated range for the radiation quality N-40 and N-60, whereas PD6 exhibited an over response for the radiation quality N-40 across the minimum rated range.

In the case of the N-100 radiation quality (mean photon energy 83.3 keV), all dosimeters satisfy the standard stated limits of variation. However, an increase in their relative response can be noted for all tested angles of incidence.

4.4 Summary for type testing standards

The results indicate a necessity for re-evaluation of the limits stipulated in the type testing standards, when possibly moving to the proposed operational quantities outlined in ICRU Report 95, with a particular emphasis on low energies. It is evident that no fundamental alterations to the stipulated requirements are required; however, it seems reasonable that the limits are adapted to reflect the performance of dosemeters that are available for the operational quantities stipulated in ICRU Report 95 at the time of transition.

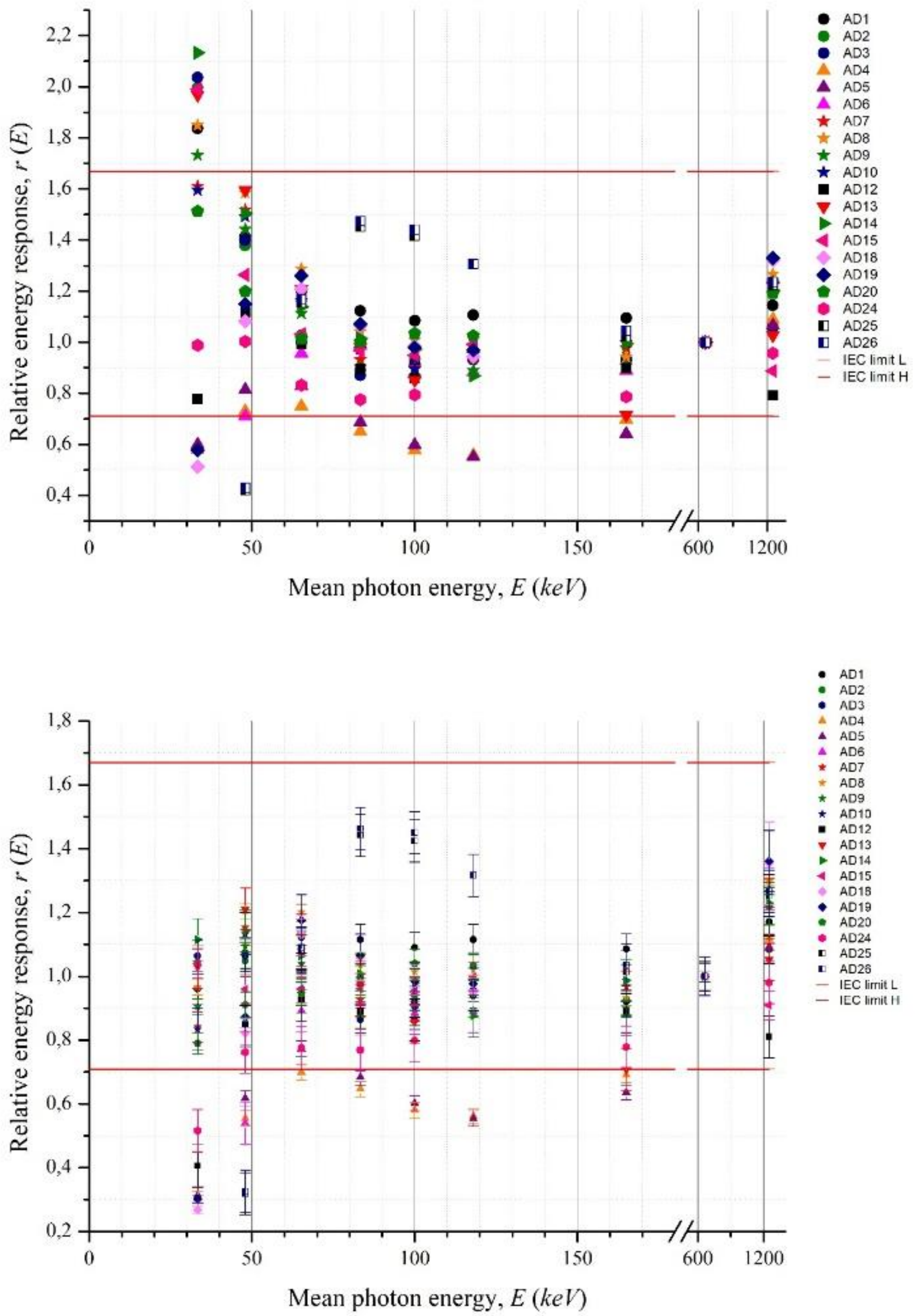


Figure 1 Energy dependence of active area dosimeter (AD) response in the range from 33 keV (N-40) to 1.25 MeV (S-Co). The limits of variation (-29 %; +67 %) in terms of relative energy response are displayed (IEC 60846-1:2009). Upper graph presents responses with new h_k values, and lower graph with current h_k values.

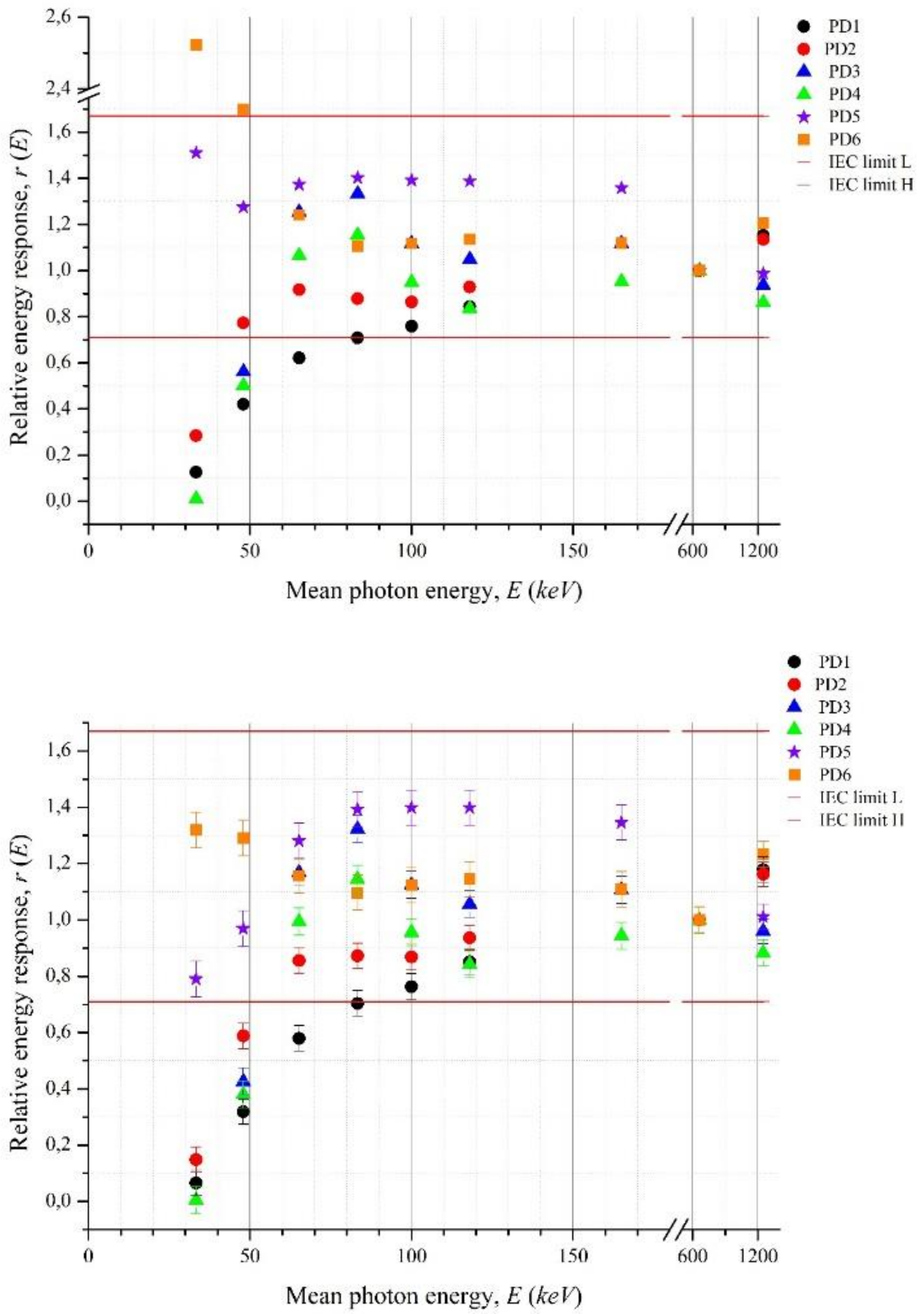
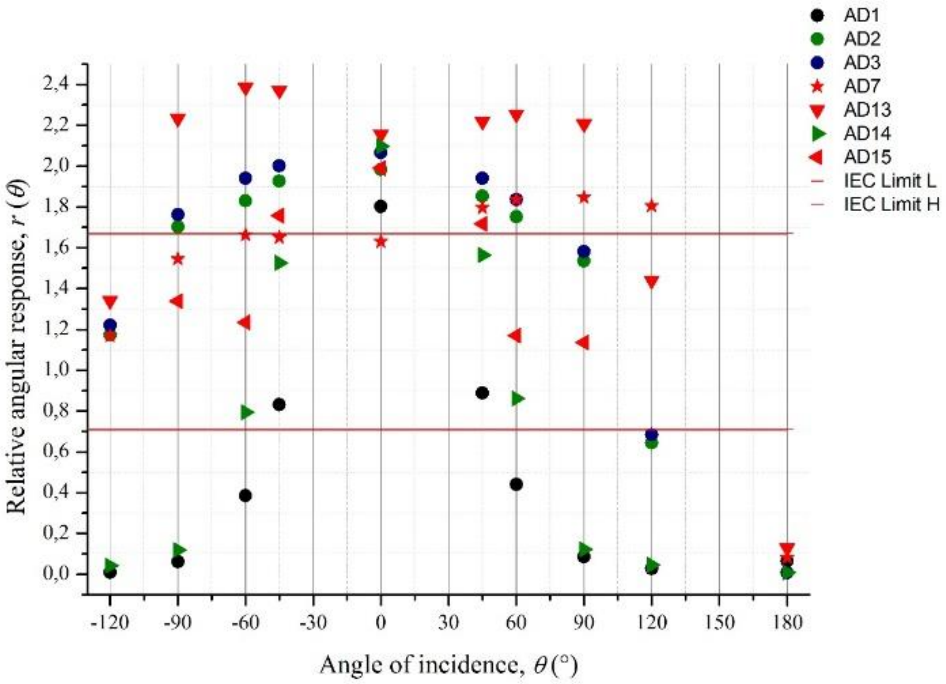


Figure 2 Energy dependence of active personal dosimeter (PD) response in the range from 33 keV (N-40) to 1.25 MeV (S-Co). The limits of variation (-29 %; +67 %) in terms of relative energy response are displayed (IEC 61526:2024). Upper graph presents responses with new h_k values, and lower graph with current h_k values.



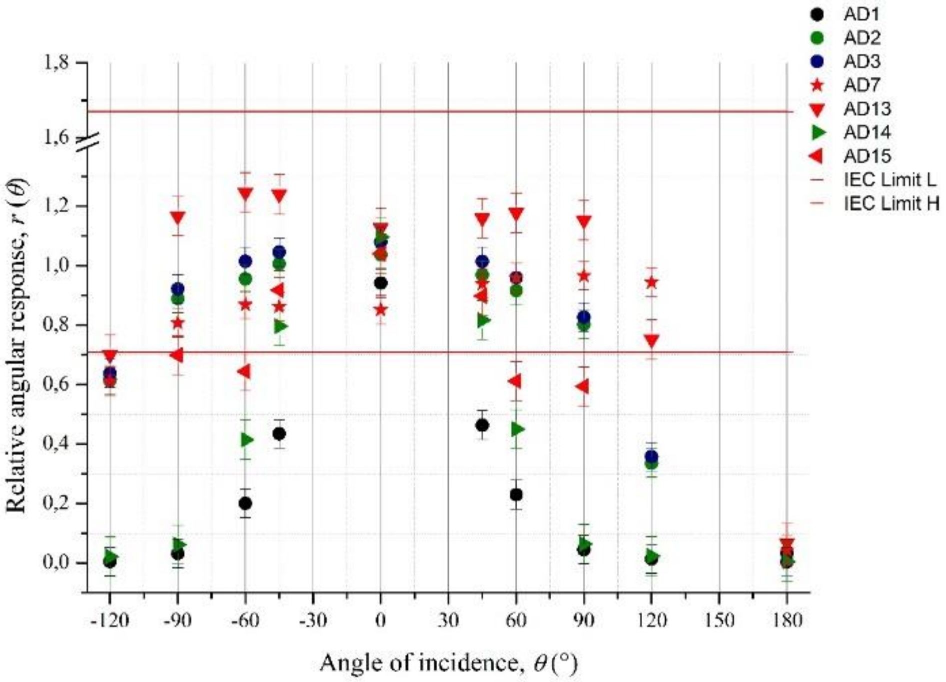


Figure 3 Angular dependence of active area dosimeter (AD) response for the N-40 (mean photon energy 33.3 keV) radiation quality in vertical dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed (IEC 60846-1:2009). Upper graph presents responses with new h_k values, and lower graph with current h_k values.

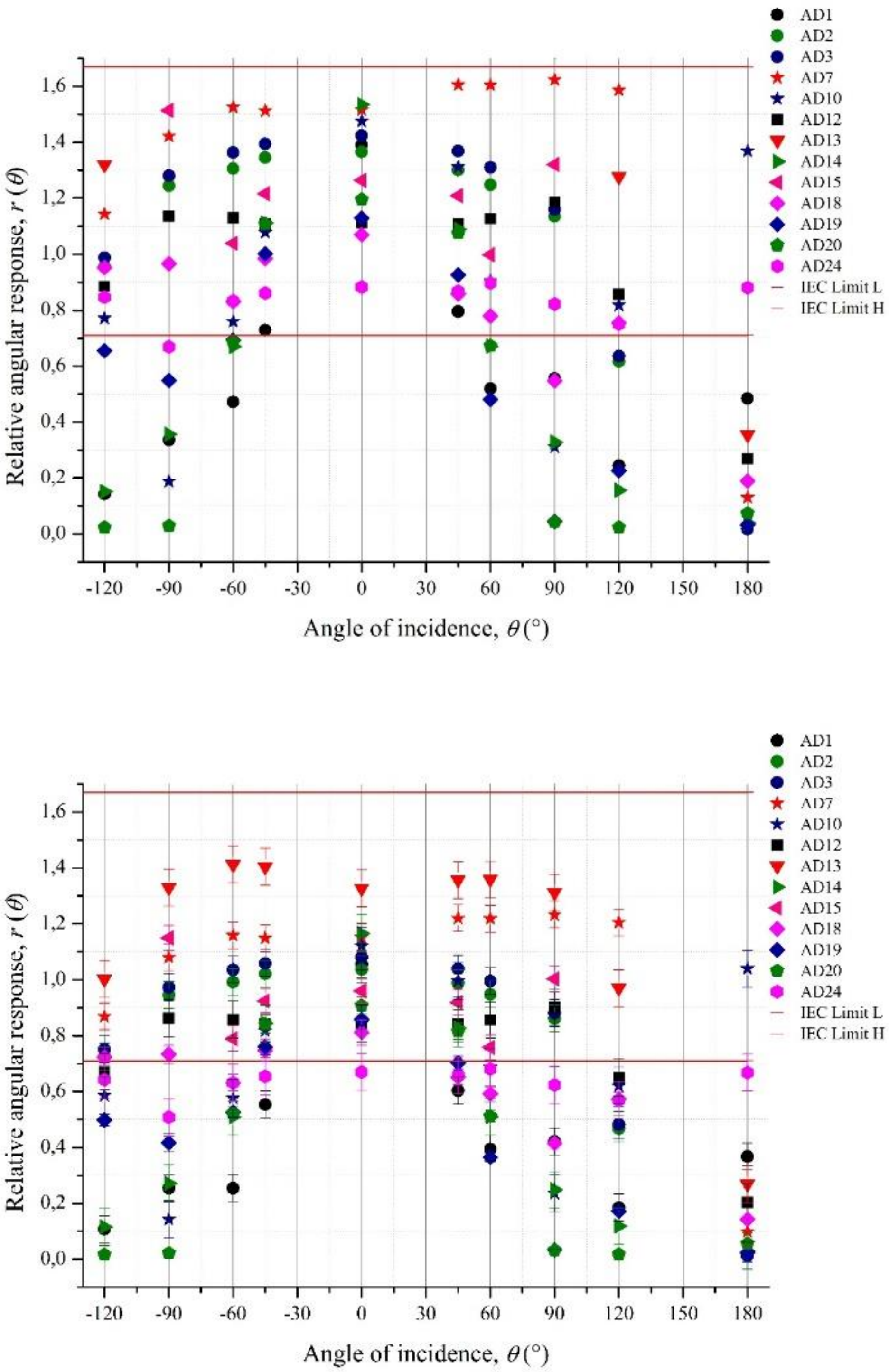
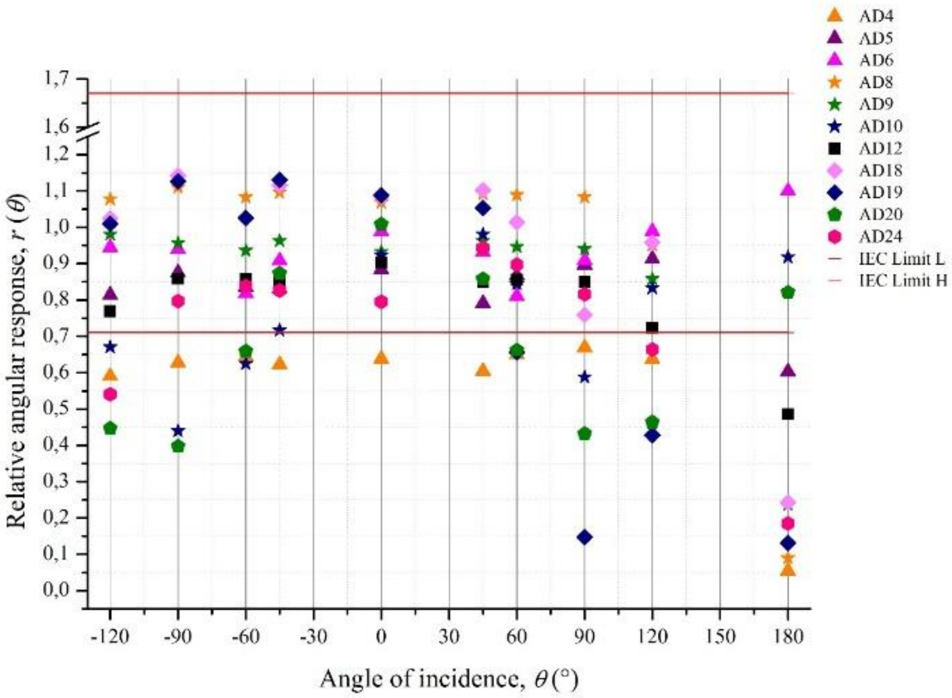


Figure 4 Angular dependence of active area dosimeter (AD) response for the N-60 (mean photon energy 47.9 keV) radiation quality in vertical dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed (IEC 60846-1:2009). Upper graph presents responses with new h_k values, and lower graph with current h_k values.



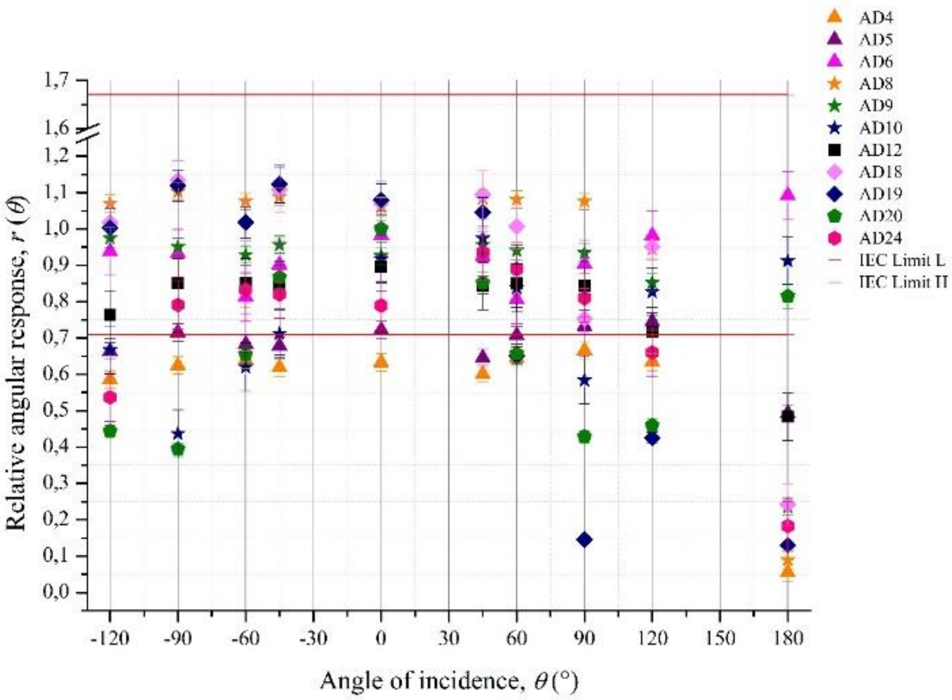


Figure 5 Angular dependence of active area dosimeter (AD) response for the N-100 (mean photon energy 83.3 keV) radiation quality in vertical dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed (IEC 60846-1:2009). Upper graph presents responses with new h_k values, and lower graph with current h_k values.

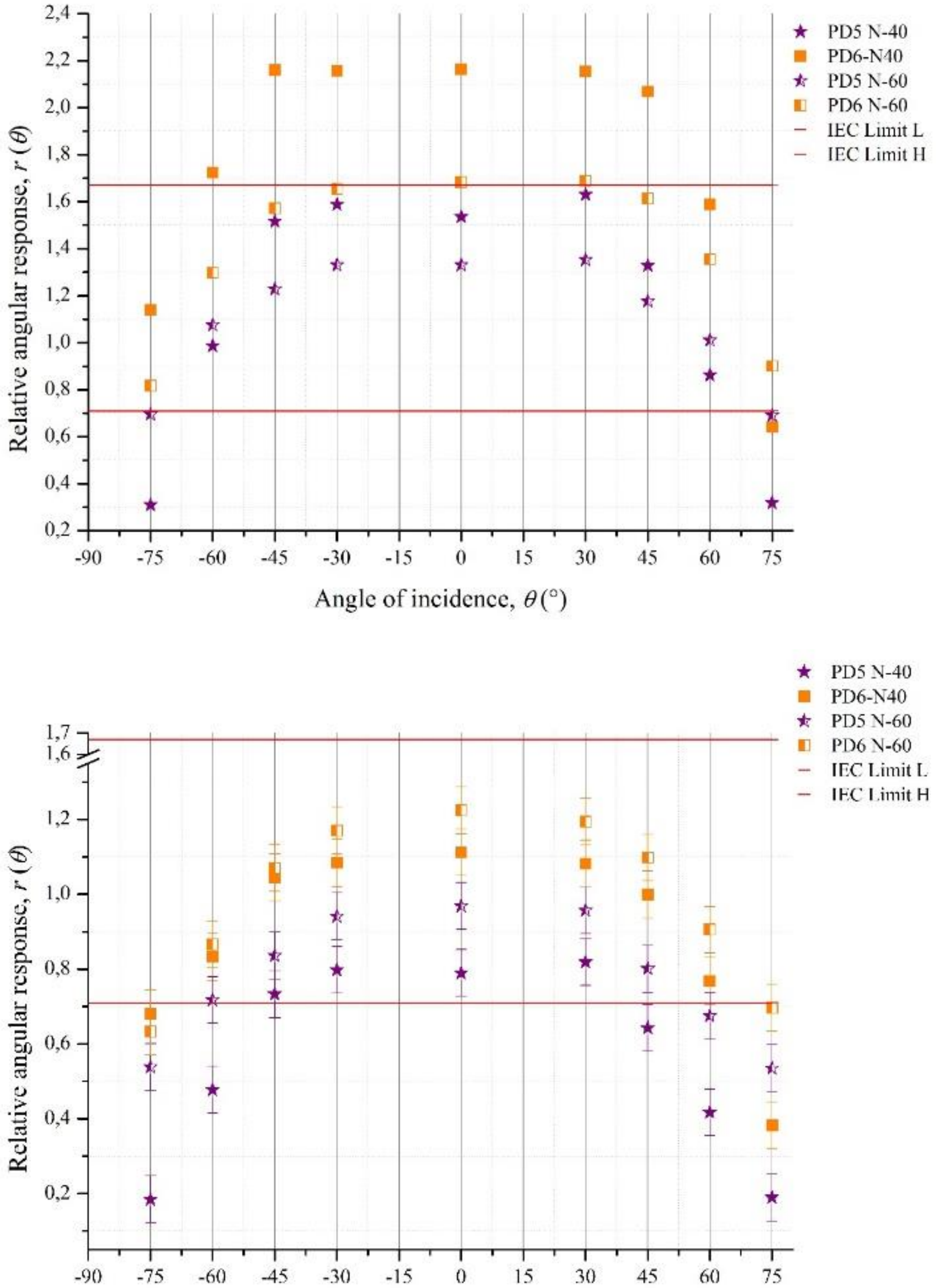
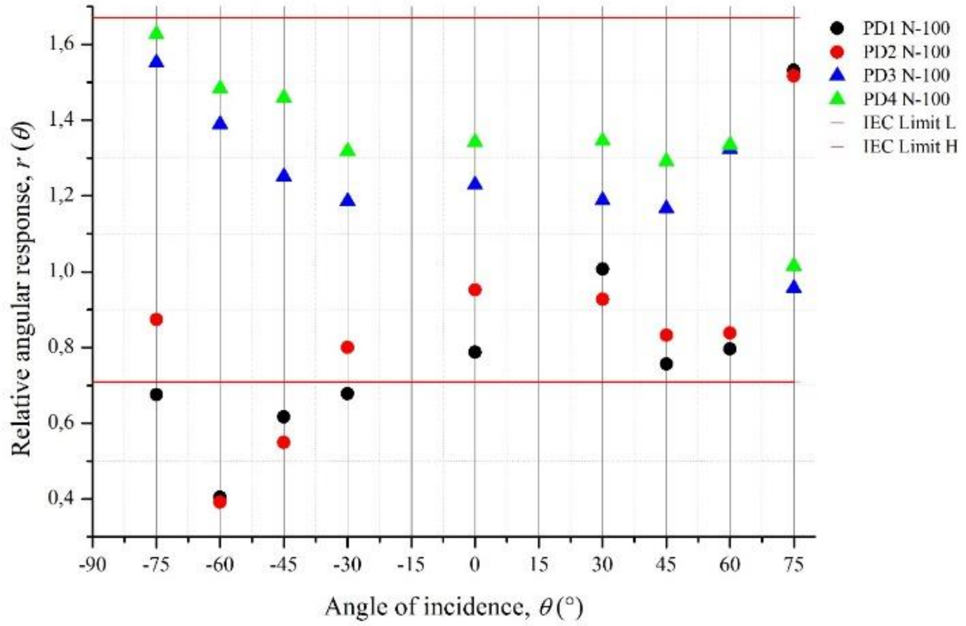


Figure 6 Angular dependence of active personal dosimeter (PD) response for the N-40 and N-60 (mean photon energies 33.3 keV and 47.9 keV) radiation qualities for vertical dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed (IEC 61526:2024). Upper graph presents responses with new h_k values, and lower graph with current h_k values.



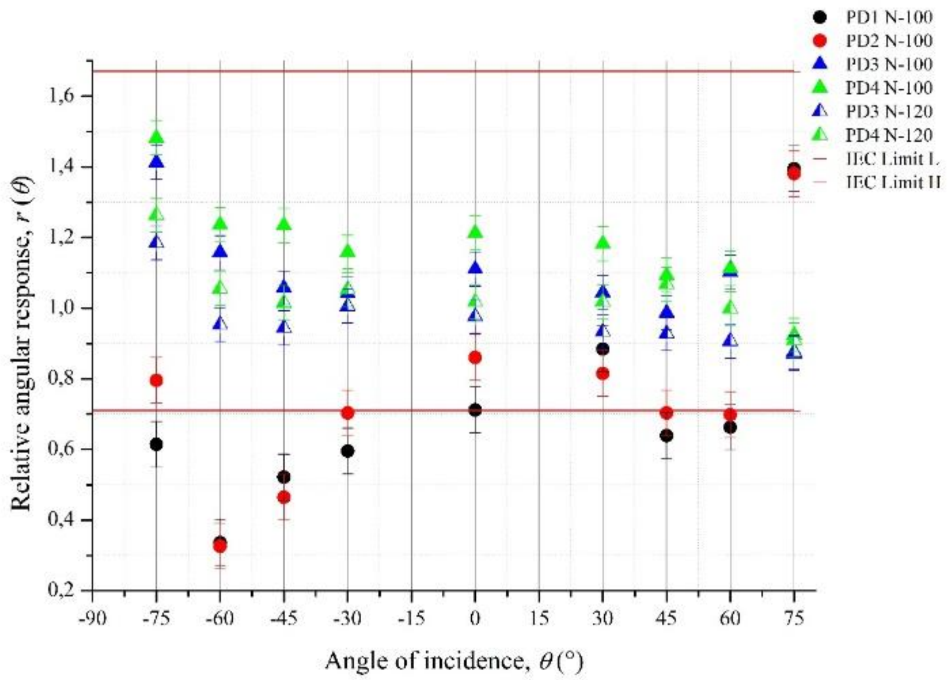


Figure 7 Angular dependence of active personal dosimeter (PD) response for the N-100 (mean photon energies 83.3 keV) and N-120 (mean photon energies 100 keV) radiation quality for vertical dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed (IEC, 2024). Upper graph presents responses with new h_k values, and lower graph with current h_k values.

5 References

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6 ANNEX - Results from simulations

h_p conversion factors for N-30 for high voltage variation

High voltage variation (%)	0°	avg (±15°)	avg (±30°)	avg (±45°)	avg (±60°)	avg (±75°)	avg (±90°)	180°	ROT	ISO	SS-ISO	IS-ISO
-5	0,204	0,200	0,188	0,167	0,134	0,094	0,059	0,041	0,097	0,077	0,078	0,075
-3	0,213	0,209	0,196	0,174	0,140	0,098	0,061	0,044	0,102	0,081	0,082	0,079
-2	0,217	0,213	0,200	0,177	0,143	0,101	0,063	0,046	0,104	0,083	0,084	0,080
-1,5	0,219	0,215	0,202	0,179	0,144	0,102	0,063	0,047	0,105	0,084	0,084	0,081
-0,5	0,223	0,219	0,206	0,182	0,147	0,104	0,065	0,049	0,107	0,085	0,086	0,083
-0,1	0,225	0,221	0,207	0,184	0,148	0,105	0,065	0,049	0,108	0,086	0,087	0,084
0	**0,225**	**0,221**	**0,208**	**0,184**	**0,149**	**0,105**	**0,066**	**0,049**	**0,109**	**0,086**	**0,087**	**0,084**
0,1	0,226	0,222	0,208	0,184	0,149	0,105	0,066	0,050	0,109	0,086	0,087	0,084
0,5	0,228	0,223	0,210	0,186	0,150	0,106	0,066	0,050	0,110	0,087	0,088	0,085
1,5	0,232	0,228	0,214	0,189	0,153	0,108	0,068	0,052	0,112	0,089	0,090	0,087
2	0,234	0,230	0,216	0,191	0,155	0,109	0,068	0,053	0,113	0,090	0,091	0,088
3	0,238	0,234	0,220	0,195	0,158	0,112	0,070	0,055	0,115	0,092	0,093	0,089
5	0,247	0,243	0,228	0,202	0,164	0,116	0,073	0,058	0,120	0,095	0,097	0,093

h_p conversion factors for N-30 filter for thickness variation

Filter thickness variation (%)	0°	avg (±15°)	avg (±30°)	avg (±45°)	avg (±60°)	avg (±75°)	avg (±90°)	180°	ROT	ISO	SS-ISO	IS-ISO

-10	0,218	0,213	0,200	0,178	0,143	0,101	0,063	0,047	0,104	0,083	0,084	0,081
-4	0,222	0,218	0,205	0,182	0,147	0,103	0,065	0,048	0,107	0,085	0,086	0,083
-3	0,223	0,219	0,205	0,182	0,147	0,104	0,065	0,049	0,107	0,085	0,086	0,083
-2	0,224	0,220	0,206	0,183	0,148	0,104	0,065	0,049	0,108	0,086	0,087	0,083
0	**0,225**	**0,221**	**0,208**	**0,184**	**0,149**	**0,105**	**0,066**	**0,049**	**0,109**	**0,086**	**0,087**	**0,084**
2	0,227	0,223	0,209	0,185	0,150	0,106	0,066	0,050	0,109	0,087	0,088	0,085
3	0,228	0,223	0,210	0,186	0,150	0,106	0,066	0,050	0,110	0,087	0,088	0,085
4	0,228	0,224	0,210	0,187	0,151	0,106	0,067	0,050	0,110	0,087	0,088	0,085
10	0,233	0,228	0,214	0,190	0,153	0,108	0,068	0,052	0,112	0,089	0,090	0,087

h_p conversion factors for N-250 for high voltage variation

High voltage variation (%)	0°	avg (±15°)	avg (±30°)	avg (±45°)	avg (±60°)	avg (±75°)	avg (±90°)	180°	ROT	ISO	SS-ISO	IS-ISO
-5	1,164	1,156	1,114	1,040	0,930	0,780	0,599	0,858	0,834	0,694	0,709	0,668
-3	1,160	1,153	1,110	1,038	0,929	0,779	0,599	0,857	0,833	0,693	0,708	0,667
-2	1,158	1,151	1,109	1,037	0,928	0,779	0,599	0,856	0,832	0,692	0,708	0,666
-1,5	1,158	1,150	1,108	1,036	0,927	0,778	0,599	0,855	0,832	0,692	0,707	0,666
-0,5	1,156	1,148	1,107	1,035	0,927	0,778	0,599	0,855	0,831	0,691	0,707	0,666
-0,1	1,155	1,147	1,106	1,035	0,926	0,778	0,599	0,854	0,831	0,691	0,707	0,665
0	1,155	1,147	1,106	1,035	0,926	0,778	0,599	0,854	0,831	0,691	0,707	0,665
0,1	1,155	1,147	1,106	1,035	0,926	0,778	0,599	0,854	0,830	0,691	0,707	0,665
0,5	1,154	1,146	1,105	1,034	0,926	0,778	0,599	0,854	0,830	0,691	0,706	0,665
1,5	1,152	1,145	1,104	1,033	0,925	0,777	0,599	0,853	0,829	0,690	0,706	0,665
2	1,151	1,144	1,103	1,033	0,925	0,777	0,599	0,853	0,829	0,690	0,706	0,665
3	1,150	1,142	1,102	1,032	0,924	0,777	0,599	0,852	0,828	0,690	0,705	0,664
5	1,146	1,139	1,099	1,030	0,922	0,776	0,599	0,851	0,827	0,689	0,705	0,663

h_p conversion factors for N-250 for filter thickness variation

Filter thickness variation (%)	0°	avg (±15°)	avg (±30°)	avg (±45°)	avg (±60°)	avg (±75°)	avg (±90°)	180°	ROT	ISO	SS-ISO	IS-ISO
-10	1,158	1,150	1,108	1,036	0,927	0,778	0,599	0,856	0,832	0,692	0,708	0,666
-4	1,156	1,148	1,107	1,035	0,927	0,778	0,599	0,855	0,831	0,691	0,707	0,666
-3	1,156	1,148	1,106	1,035	0,927	0,778	0,599	0,855	0,831	0,691	0,707	0,666
-2	1,155	1,148	1,106	1,035	0,926	0,778	0,599	0,855	0,831	0,691	0,707	0,666
0	**1,155**	**1,147**	**1,106**	**1,035**	**0,926**	**0,778**	**0,599**	**0,854**	**0,831**	**0,691**	**0,707**	**0,665**
2	1,154	1,147	1,105	1,034	0,926	0,778	0,599	0,854	0,830	0,691	0,707	0,665
3	1,154	1,147	1,105	1,034	0,926	0,778	0,599	0,854	0,830	0,691	0,706	0,665
4	1,154	1,146	1,105	1,034	0,926	0,778	0,599	0,854	0,830	0,691	0,706	0,665
10	1,152	1,145	1,104	1,033	0,925	0,777	0,599	0,853	0,830	0,690	0,706	0,665