

22NRM07 GuideRadPROS

D5 Report on the current state of the art and overview of commonly used radiation protection dosimeters and their capabilities

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1 Literature review

1.1 Introduction

The literature review included a total of 80 papers which contain research related to the different applications of radiation protection dosimeters (active dosimeters and passive dosimetry systems) for both individual and area monitoring. Data on the performance of these dosimeters was collected and examined, by reviewing scientific publications, for a specific application and dosimeter type. The focus of the literature review was on the photon radiation protection dosimeters which measure operational dosimetry quantities.

Individual and area monitoring represent crucial topics in radiation protection, due to the importance of proper acquisition of reliable and accurate dosimetry data, reflecting the exposure of professionally exposed workers who are involved in ionizing radiation applications. The review will look into the performance of active and passive dosimeters separately, for specific application-related monitoring situation. To ensure that the acquired dosimetry data is reliable, all these dosimeters should comply with the requirements set by the international standards for specific applications. Even though passive dosimetry systems are not the topic of further activities in the Task 3.2, they are also reviewed here, since the performance tests, and corresponding limits of variation are mostly equivalent to the ones valid for active dosimeters.

Monitoring of ionizing radiation is realized through either individual monitoring of professionally exposed workers or by performing area monitoring of the workplaces in different ionizing radiation practices (including medical and industrial applications, in research, military and other). Having in mind the general safety of the general population, the radiation protection of the environment is also increasingly important. For the acquisition of the dose of legal record in most countries passive dosimetry systems are mandatory, while in some countries additional data is gathered in real-time by using active dosimeters. The passive dosimeters are most widely used for radiation protection and monitoring, and despite this fact the data they provide is evaluated by accredited individual monitoring services or similar institutions is with a certain delay which is in line with the regulatory requirements on individual monitoring. Often, in some applications of ionizing radiation additional data is collected by using active electronic dosimeters, both for individual and area monitoring. Their advantage mainly lies in the ability to acquire dosimetry data in real-time and provide the end-user with prompt information, followed by aural or visual warnings and signals if a certain threshold has been surpassed. Active electronic dosimeters bring different detection mechanisms based on different radiation detector types, being either gaseous or solid-state, and therefore require evaluation of performance under various radiation field conditions (described with different influence quantities, radiation and environment based), which correspond to the conditions encountered in specific practices. In the research on individual monitoring the focus of most papers was towards the use of active personal dosimeters and passive dosimetry systems in medical applications, and the difficulties of their use in pulsed radiation fields were highlighted. The use of passive dosimeters for the measurement of personal dose equivalent for extremities and the eye lens was also evaluated. The research on active area dosimeters was in general more focused on their applications in environmental monitoring, and on the difficulties regarding identifying adequate testing conditions, which separate environmental area monitoring from the workplace. Besides conventional active dosimeters, the use of hybrid dosimeters and spectro-dosimeters for monitoring of ionizing radiation was also studied.

1.2 Individual monitoring

Personal (individual) monitoring for legal dosimetry purposes is mostly done by using passive dosimetry systems, prevalently based on thermoluminescent detectors - TLDs, and less so, on optically stimulated luminescence detectors – OSLDs, and photoluminescent detectors - RPLDs associated with sets of filters to cover the widest energy range. Besides widespread passive dosimetry systems, active personal dosimeters (APDs) may also be used, and, in some cases, required for use, due to their advantage of real-time dose display with visual and aural alarm functionalities. Active personal dosimeters are mostly used to estimate effective dose through measurement of personal dose equivalent for the whole body ($H_p(10)$). Passive dosimetry systems are used for the estimation of effective dose, equivalent dose for the extremities and the eye-lens, through the measurement of the personal dose equivalent ($H_p(10)$, $H_p(0.07)$ and $H_p(3)$, respectively).

In the paper by Vanhavere and Hoey, 2022 an overview of the use of passive dosimetry systems as well as the advantages and challenges of use of APDs were presented. Most legal dosimetry is done by using passive dosimetry systems, which are read out after the wearing period. These dosimeters do not provide any alarm in high exposure situations, instead they give afterwards an information of the dose received. Historically passive dosimetry systems started off with film dosimeters, were then replaced with now widespread TLDs and more recently with OSLDs and RPLDs. Energy dependence of passive dosimetry systems has improved by using detection materials which are more tissue equivalent and low-Z materials such as LiF and BeO. The performance of Individual Monitoring Services (IMS) which use various passive dosimetry systems, is frequently evaluated in intercomparisons, and European Radiation Dosimetry Group (EURADOS) is an organizer of large-scale international intercomparisons. If data from a EURADOS whole-body dosimeter intercomparison is analysed, where 103 different IMSs had participated, a significant over-response can be seen for TLDs and film dosimeters over lower energies and larger angles of incidence, such as N-40 radiation quality and 60° angle of incidence (Stadtman et al., 2020). In terms of ALARA principles (as low as reasonably achievable), use of

APDs is beneficial due to the measurement of doses below minimum measurable dose (minimum detection limit) by the passive dosimeter (in the order of μSv), and due to the possibility of immediate feedback to the occupationally exposed workers. In this way doses which are not significantly larger than the background level can be readily measured, and the exposures to high intensity radiation fields can be limited. Despite these advantages, some APD models are still quite unreliable in low-photon energy fields and in pulsed radiation fields, both characteristic for interventional radiology. Still, APDs are widely used in nuclear industry, and are increasingly used in various fields for radiation protection of workers working in ionizing radiation environment in medicine (radiotherapy, interventional procedures, nuclear medicine, etc.).

1.3 Active personal dosimeters (APDs) for individual monitoring

There are several papers in which performance of different types of APDs was examined according to the requirements of IEC 61526:2010. An important note is that this standard has been withdrawn, and a new version was published, IEC 61526:2024, which also covers specific requirements for hybrid dosimeters as well. Hybrid dosimeters are also covered by the current version of the passive dosimetry standard IEC 62387:2020.

Ciraj-Bjelac et al., 2018 have presented the frequency of use of APDs in hospitals which are the results of an EURADOS survey. In medical applications of ionizing radiation APDs are most frequently used in interventional cardiology and radiology (54 %), followed by nuclear medicine (29 %) and radiotherapy (12 %). Often the end-users in hospitals have these APDs calibrated under inadequate conditions, which do not correspond to their regular use in practice. In the survey it was found out that most of the APDs used by the hospitals are calibrated in S-Cs radiation quality, while somewhat smaller number of calibrations is done in the ISO 4037 N-series X-ray radiation qualities. Reported typical dose rates measured by the APDs in the hospitals are in a wide range from 1 $\mu\text{Sv/h}$ up to a few mSv/h , most commonly in the range from 10 – 100 $\mu\text{Sv/h}$.

In a paper by Krzanovic et al. 2017, 10 models of APDs were tested for the effects of radiation-based influence quantities, including photon energy, angle of incidence, non-linearity in terms of relative response and dosimeter accuracy in terms of absolute response (calibration coefficient). A wider range of photon energies (than the minimum rated range recommended by the standard, i.e., 80 keV – 1.25 MeV) was used to assess the dosimeter performance. The overall finding is that the dosimeters fulfil the criteria of the standard for the minimum rated range but fail to do so for the low-energy radiation fields such as N40 (33 keV mean photon energy), and in some cases N60 (48 keV mean photon energy). In interventional procedures common X-ray tube voltages used are in the range from 80 kV to 100 kV (whereas the bulk of the scattered photon energy spectra is approximately in the 30 – 60 keV range, or similar), and the radiation doses to the occupationally exposed workers can be relatively high, due to longer exposure times and high dose rates, due to the nature of the procedure, especially for extremity. The minimum rated range does not fully cover these procedures, even though, based on the data from Krzanovic et al., 2017 (Fig. 1), tested APD models have relatively good performance for N60 radiation quality. On the other hand, high-dose rates are also evident for orthopaedical fluoroscopy procedures where the most common X-ray tube voltages used in C-arms are lower than 70 kV, with approximate range of mean energies from 30 keV to 50 keV, depending on the beam filtration and automatic exposure control parameters (influenced by the patient size). The IEC defined limits of variation for relative response (to reference conditions, Cs-137 and 0°) from -29 % to +67 % for photon and angular response of APDs is defined for the minimum rated range. In practice, APDs worn by the occupationally exposed workers can be exposed at different angles of incidence, and it is reported by Krzanovic et al., 2017 that at high angles of incidence and low-photon energies the dosimeter response greatly deteriorates.

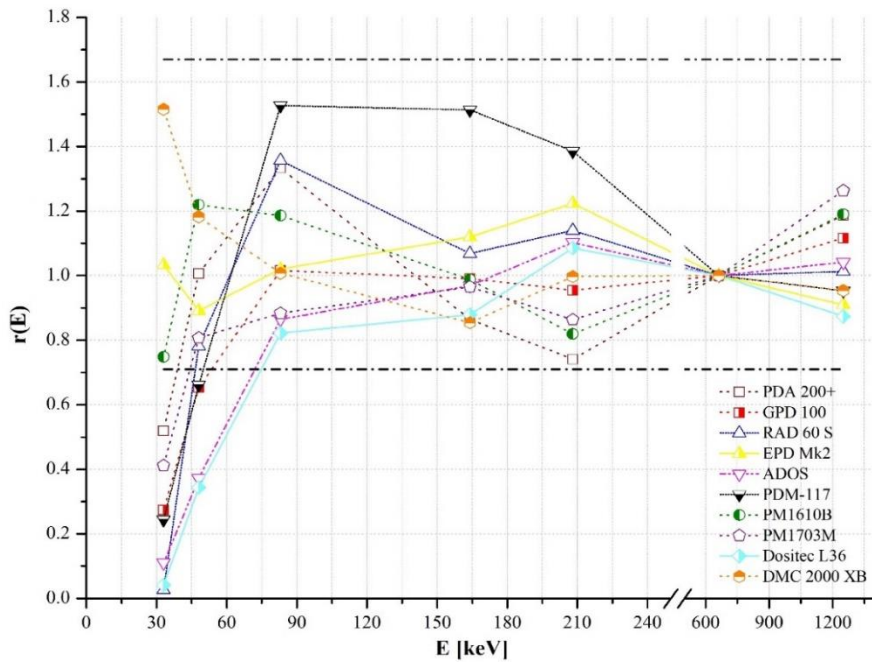


Figure 1-1. Energy dependence of APD response, with IEC 61256:2010 limits of variation in terms of relative energy response normalized to Cs-137 photon energy at 0° angle of incidence (Krzanovic et al., 2017).

In the light of medical applications of APDs, Ankerhold et al. 2009 and Zutz et al., 2012, have examined the performance of active dosimeters in situations of non-continuous radiation exposures, i.e. in pulsed radiation fields. The term pulsed radiation field is primarily related to the dosimetry properties of the APDs and not to the properties of the X-ray generators. According to Zutz et al., 2012, one of significant disadvantages of APDs is the limited maximum measurable dose rate in pulsed fields, where even though the dose rate is acceptable according to the measurement range, the dose rate in the radiation pulse may be significantly larger. To evaluate if an APD can be used in pulsed fields it is important to examine the following radiation field parameters: minimum pulse duration, maximum dose rate per pulse, and the maximum dose value delivered in a radiation pulse, and pulse frequency in some cases. Relevant properties of APDs which are to be used in pulsed fields include maximum measurable dose rate per pulse and dead time of the dosimeter. In addition, information on the behaviour of the dosimeter in terms of the type of detector based on dead time, whether it is paralyzing or non-paralyzing, i.e., if the dead time extends or remains constant is also relevant for pulsed fields. In the paper by Zutz et al., 2012 test methods and evaluation criteria for the dosimeters to be used in pulsed fields are examined and discussed. An alternative method to determine the maximum measurable dose rate of the dosimeter in pulsed fields was proposed, by keeping the dose per radiation pulse constant and shortening the pulse duration, consequently increasing the dose rate per pulse. The APD response significantly decreases with the increase in dose rate per pulse (Fig. 1-2).

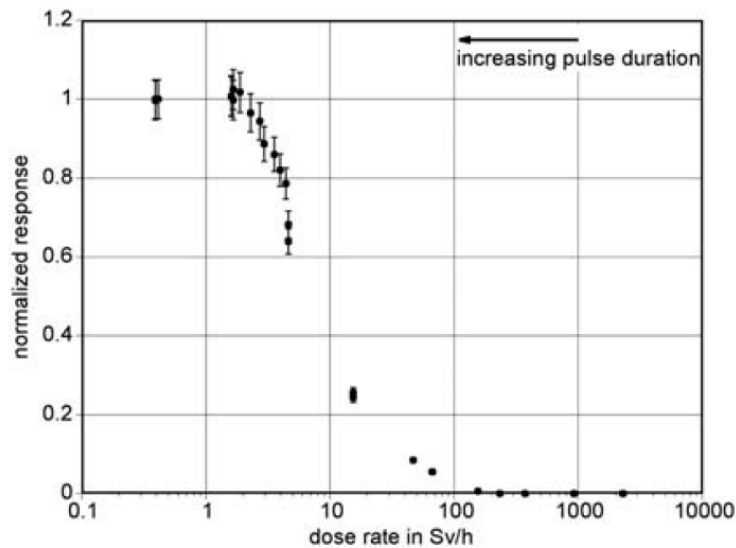


Figure 1-2. Dose rate dependence of the tested APD for constant dose per pulse of approximately 1 mSv at the RQR9 radiation quality ($U = 120\text{ kV}$). The response is normalized to the value obtained at 10 s pulse duration, resulting in 0.39 Sv/h dose rate per pulse (Zutz et al., 2012).

Bordy et al., 2008, have evaluated the calibration procedure for APDs for their use in interventional radiology. In this paper it is also stressed that it would be useful to calibrate these dosimeters in RQR and RQA radiation beams defined in IEC 61267, besides the usual N-radiation quality series defined in ISO 4037:2019. These reference radiation beams are defined for the quality control of X-ray generators in diagnostic radiology. The RQR and RQA radiation qualities are representative of the medical irradiation conditions, while the N-series radiation fields are highly filtered to evaluate the energy dependence of dosimeter response. Conversion coefficients from air kerma to the personal dose equivalent for the RQR and RQA beams were estimated by using Monte Carlo simulations, where the ISO water slab was used to substitute the patient. The APD was positioned on another ISO slab phantom which was not in the direct beam (Fig. 3). Different software versions were used, as well with different cross-section data libraries (MCNP4C, MCNP5, MCNPx2.5f, MCNPx2.5.0 and Penelope 2006). Average ratio of the estimated personal dose equivalent and air kerma from this software packaged was used to determine the conversion coefficient. Monte Carlo calculations were validated by measuring the photon spectra with a CdTe spectrometer.

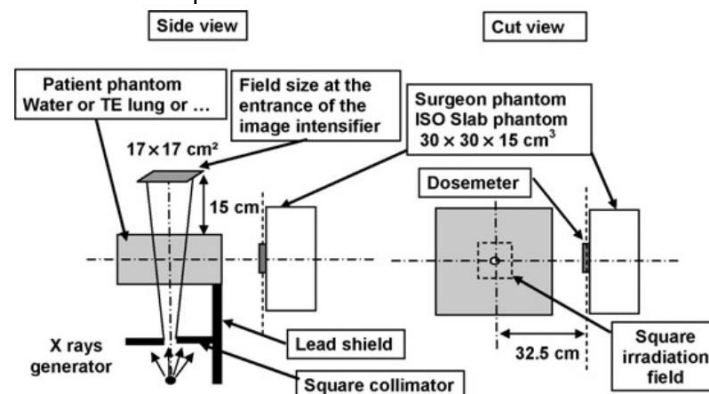


Figure 1-3. Realistic measurement setup for the calibration of APDs under clinical conditions in interventional procedures. The dosimeter is positioned on the ISO slab phantom, which is not in the direct beam, while the patient (main source of scattered radiation) is represented by another ISO slab phantom and positioned on the table (Bordy et al., 2008).

In the research by Ankerhold et al., 2009, according to the standards for active radiation protection instrumentation, continuous fields are radiation fields whose exposure is with constant dose rate for period longer than 10 s, since this time period is the maximum permitted time for dosimeters to react when exposed to radiation, while for high dose rates this time is reduced to 2 s. In terms of APDs, any exposure with shorter pulse duration than the maximum time allowed are considered pulsed radiation fields. Important parameters of such pulsed radiation fields are the dose delivered per pulse and the dose rate in the pulse, as well as pulse duration and frequency. APD indicated dose values were not within the

range of acceptable values, while the passive dosimetry systems had indications in line with their energy response. In some cases, when exposed to the pulsed fields, APDs were insensitive and unable to acquire measurements. When exposed to the pulsed field of 40 ms pulse duration with the dose rate of 3.9 mSv/s which corresponds to a very high dose rate of approximately 14 Sv/h, TLDs had the response of 0.78 compared to the reference value, while the tested APD had the response of only 0.05. In the pulsed field of 50 ns pulse duration, and pulse dose rate of 36 Sv/s with 99 pulses, TLDs had response of 0.74 while APD had response of 0, being unable to produce any meaningful indication.

In research by Chirriotti et al., 2011, Clairand et al., 2011 and Clairand et al., 2008, intercomparisons and performance tests of several different types of APDs were done in order to evaluate their behaviour for the use in interventional radiology procedures. Advances in fluoroscopy X-ray generators have resulted in increased radiation exposure of occupationally exposed workers, which is why the use of APD would prove very useful in addition to the widespread TLDs. Fluoroscopy procedures utilize pulsed fields with pulse duration up to 80 ms, with pulse frequency of up to 30 pulses/s. Photon energies are usually in the range from 20 to 120 keV, with the dose rates even up to 10 Sv/h, depending on the position of the exposed personnel.

In paper by Chirriotti et al., 2011, conventional APDs were calibrated in the RQR6 and N80 radiation beams (which have the same X-ray tube voltage of 80 kV), while S-Cs (Cs-137, 662 keV) was not used in this study due to the energy range specific for interventional procedures. Besides the conventional APDs (Thermo EPD and MGP DMC 2000 XB), Philips DoseAware and Unfors EDD-30 which are APDs specifically designed for radiation protection in diagnostic radiology were tested. All of these dosimeter models are based on Si-diode solid-state detectors. In addition, the Mirion Instadose direct ion storage (DIS) hybrid dosimeter was also involved in this study. The $H_p(10)$ values measured with APDs were compared to the TLD reference values at RQR6 radiation quality. This reference radiation field has the closest exposure conditions to the clinical radiation fields used. The conversion coefficients from air kerma to the personal dose equivalent were estimated by Monte Carlo simulations (PENELOPE) for these two diagnostic radiology radiation fields. Thermo EPD and DMC 2000 XB have displayed a slight underestimation of the response compared to TLDs, while the designated dosimeters for radiation protection in medical procedures have displayed an overresponse. Three irradiation protocols were examined, cardiology fluoroscopy, cardiology cine and vascular (Fig. 4). It is evident that regardless of the pulse frequency and pulse width tested APDs had similar behaviour.

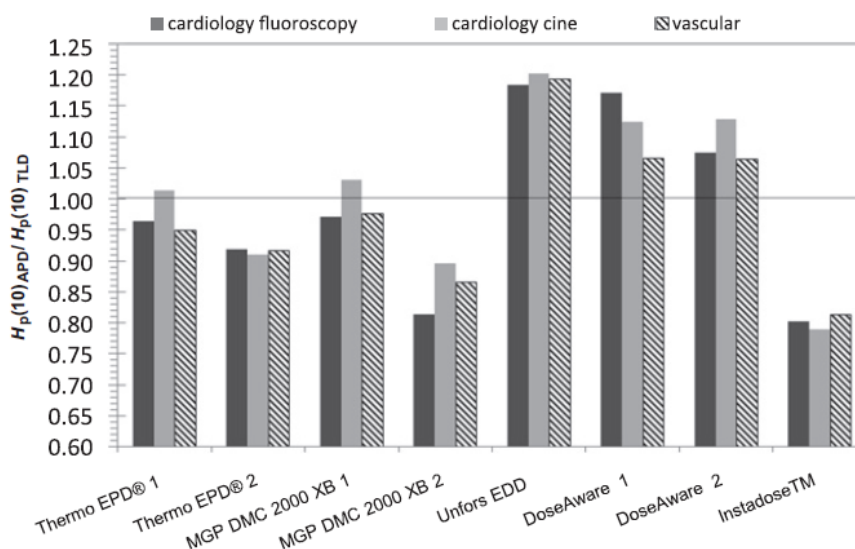


Figure 1-4. APD response for three selected protocols in interventional radiology/cardiology. The standard deviation of the presented response values is in the order of 15 % ($k = 2$). APD response is determined by comparing the indication with TLD value as a reference (Chirriotti et al., 2011).

In the scope of the ORAMED project research was conducted to test the suitability of use of APDs in interventional cardiology and radiology, presented in papers by Clairand et al., 2011 and Struelens et al., 2011. Paper by Clairand et al., 2011 focuses on laboratory tests, where 8 types of commercially available APDs were tested in continuous and pulsed X-ray radiation fields, which are proven to have a good response to low-energy photon radiation, specific for interventional radiology and cardiology procedures. Based on their manufacturer specifications and the technical notes these dosimeters can be used in the photon radiation fields with energies down to 15 keV – 33 keV (depending on the APD model) (Table 1). All the tested APDs besides DoseAware and EDD-30 had response within 0.71 – 1.67, in the range from N-30 up to S-Co (Co-60, 1.25 MeV). In the case of DoseAware and EDD-30 the response is within limits for the low-photon energies

(from approximately N-30 up to N-120). During the non-linearity test it was concluded that the APDs can in general measure dose rates that are higher than stated by the manufacturers. Most tested APDs satisfy the IEC criterion for non-linearity in terms of relative response (0.83 – 1.25) for dose rates up to 1 Sv/h, and many models even though they do not comply with the criterion, have a response larger than 0.5 for dose rates up to 10 Sv/h.

Table 1. Manufacturer specifications of tested APDs. (Clairand et al., 2011). EDD30 Unfors has no photon energy range provided, but it is indicated that the dosimeter is designed to be used in diagnostic radiology.

APD	Energy range		Personal dose equivalent rate range	
	Min	Max	Min	Max
DMC2000XB MGPI	20 keV	6 MeV	0.1 $\mu\text{Sv h}^{-1}$	10 Sv h^{-1}
EPDMk2.3 Thermo	17 keV	6 MeV	1 $\mu\text{Sv h}^{-1}$	4 Sv h^{-1}
EDMIII Dosilab	20 keV	6 MeV	0.5 $\mu\text{Sv h}^{-1}$	1 Sv h^{-1}
PM1621A Polimaster	10 keV	20 MeV	0.01 $\mu\text{Sv h}^{-1}$	2 Sv h^{-1}
DIS-100 Rados	15 keV	9 MeV	1 $\mu\text{Sv h}^{-1}$	40 Sv h^{-1}
EDD30 Unfors	^a	^a	0.03 mSv h^{-1}	2 Sv h^{-1}
AT3509C Atomtex	15 keV	10 MeV	0.1 $\mu\text{Sv h}^{-1}$	5 Sv h^{-1}
DoseAware Philips	33 keV	118 keV	10 $\mu\text{Sv h}^{-1}$	50 mSv h^{-1}

It was observed that the APD performance is very similar to the continuous radiation fields when the pulse duration is larger than 1 s. In pulsed fields the APD indicated value decreases with the increase of the pulse dose rate. The PM1621A was unable to provide any measured signal in pulsed fields since it is based on Geiger-Müller tube detector. The rest of tested APDs are based on Si-diodes and DIS-100 is a hybrid dosimeter which uses Si semiconductor and ionization chamber. The response dependence of APDs on pulsed radiation field dose rate, with pulse duration of 20 ms and pulse frequency of 10 s^{-1} is presented on Fig. 5. It can be observed that the DIS dosimeter displays a quite stable response in pulsed radiation fields compared to the semiconductor APDs.

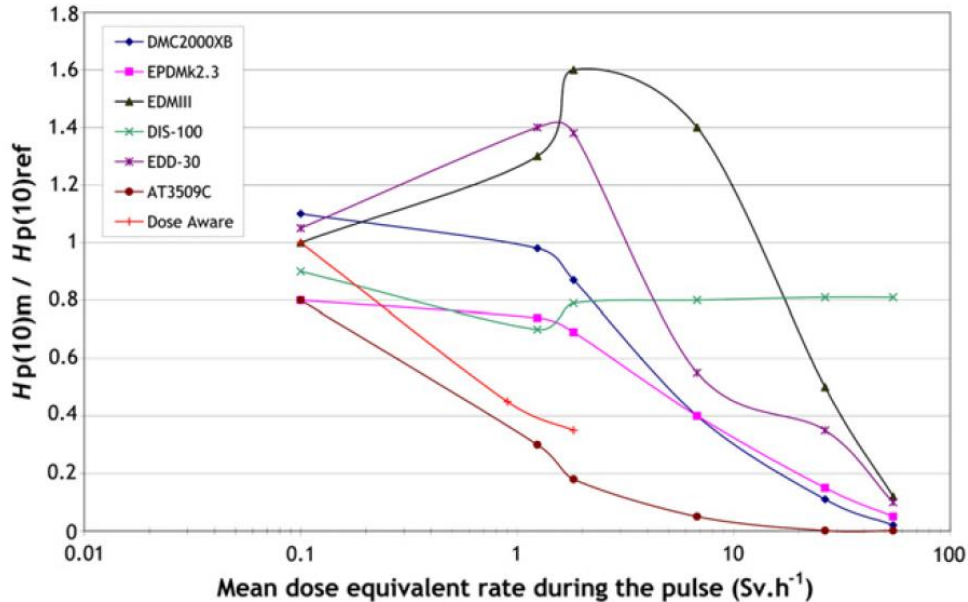


Figure 1-5. Dose rate response of tested APDs in pulsed radiation fields, with pulse duration of 20 ms and pulse frequency of 10 pulses per second. It can be observed that the hybrid direct ion storage dosimeter has a stable response compared to semiconductor detectors (Clairand et al., 2011).

In the research by Struelens et al., 2011, 5 dosimeter types were tested in clinical radiation fields, where the goal was to compare the behaviour of APDs and TLDs worn in routine practice, due to variation in dose rate, X-ray tube voltage and pulse width. The dosimeters were exposed to the scattered radiation produced by positioning the anthropomorphic Rando-Alderson (RA) phantom, representing the patient. Influence of the detector position on the ISO slab phantom was investigated for different clinical irradiation setups (AP – anterior-posterior direct/indirect and lateral direct/indirect) for two different energies. In this way, photon energy and angle of incidence influence quantities were considered. Deviation of APD indication related to TLDs which were used as the reference, was roughly within $\pm 30\%$. Since the APDs in clinical conditions were exposed to scattered radiation beam (which is a realistic irradiation situation for occupationally

exposed workers), the encountered dose rates were lower than 1 Sv/h, therefore no issues related to pulsed radiation were observed in terms of dose rate, as with the pulsed fields in the laboratory (Clairand et al., 2011). In routine practice, the operators wore one TLD and one APD above the lead apron. APDs had in general an under-response of approximately 20 % compared to TLDs. In the paper by Clairand et al., 2008, in the APD intercomparison both pulsed fields (single pulse) and continuous fields were used, where 4 out of 5 tested models are sensitive to pulsed radiation. Systematically larger response, averaged at 13 %, for pulsed fields compared to the continuous fields was observed for these models.

In the research by O'Connor et al., 2021, the focus was also on the use of APDs in interventional procedures since the highest doses to the occupationally exposed personnel in medical applications can be expected in this practice. In general use of APDs is recommended by the European Commission RP160 document and the IAEA General Safety Guide GSG-7. It is stated that APDs should be used in monitoring situations where unexpected and significant increase in dose (rate) can occur, and in workplaces where it is necessary to operate in high intensity radiation fields. Specifically in interventional procedures, APDs can be used for dose optimization to personnel since they are able to provide immediate information on dose rate. For interventional procedures, compliance with IEC 61526:2010 is necessary, with focus on energy response, angular response, maximum measurable dose equivalent rate and response in pulsed radiation fields. Requirements for dosimeters to be used in pulsed radiation fields are defined in IEC 63050:2019. APDs were rarely used in the hospitals in the early 2000s, while in the recent period they have been increasingly used in radiotherapy, nuclear medicine, and interventional procedures, while on the other hand they are regularly used in radiation monitoring of personnel involved in nuclear facilities.

As presented in Fig. 5 the direct ion storage hybrid dosimeters have remarkable performance at very high dose rates, making them suitable for pulsed radiation fields. In research by Zutz et al., 2012 a multi-element detector (DIS-1) was examined in the pulsed fields of very short pulse durations of approximately 115 ns at an X-ray flash unit XR200. Similarly to passive dosimetry systems hybrid dosimeters collect and store the information on the dose, with a difference that the dose can be readout instantly. The tested dosimeter is able to measure both whole-body personal dose equivalent, $H_p(10)$, as well as the personal dose equivalent for the extremities, $H_p(0.07)$. DIS-1 utilizes several detectors for different dose ranges, e.g., from 1 to 3000 μSv , 0.1 to 500 mSv and 0.1 to 40 Sv. For the very high dose rates from the order of 100 kSv/h up to 1 MSv/h the dosimeter performance was evaluated against the $H_p(10)$ standard ionization chamber. For all of the dose rates the dosimeter had deviation from the reference less than 40 %. This deviation from the reference value can be explained due to DIS-1 under-response in the 15 – 150 keV energy range which is used by the XR200 flash unit.

Another hybrid dosimeter with the Dosepix detector was characterized in research by Haag et al., 2020. The dosimetry system utilizes a hybrid, pixelated, photon-counting X-ray detector. The energy dependence and angular dependence tests were done in the energy range from 12.4 keV up to 1250 keV (N-15 to N-300 and S-Cs, S-Co, for angles of incidence of 0° , 30° and 60°) for both $H_p(10)$ and $H_p(0.07)$ quantities. The largest deviation from unity is observed for the N-60 radiation quality and 60° angle of incidence, being 1.179 (for $H_p(10)$). Overall, the performance of Dosepix is excellent for both quantities, with a low coefficient of variation. Even though, the dosimeter requires further testing, especially for the influence of angle of incidence at low-photon energies when the final housing of the dosimeter is included, whose optimal thickness has yet to be determined. Results of the energy dependence are presented in Fig. 6a (for $H_p(10)$) and Fig. 6b (for $H_p(0.07)$).

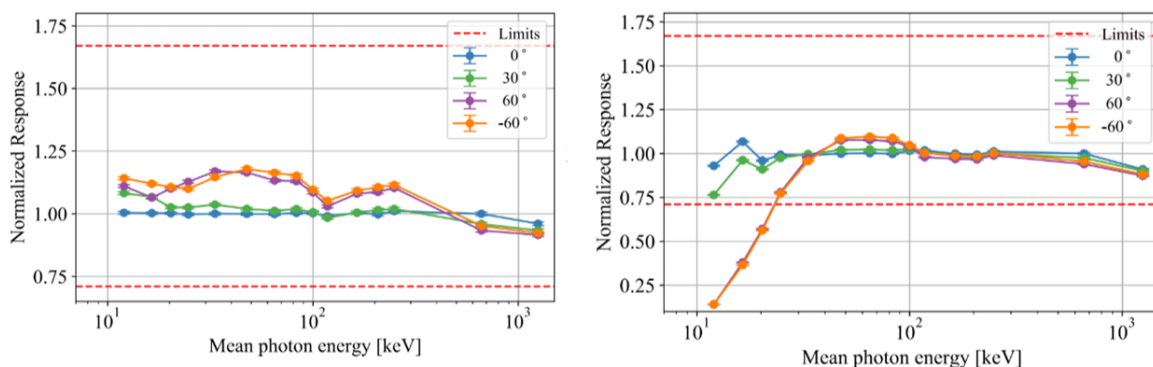


Figure 1-6. Relative energy and angular response of the Dosepix hybrid dosimeter for $H_p(10)$ (left) and $H_p(0.07)$ (right). Testing was done in a wide energy range from N-15 up to N-300 with S-cs and S-Co (Haag et al., 2020).

Similar findings to Krzanovic et al., 2017 (Fig. 1), regarding APD energy dependence of response has been reported by Bolognese-Milsztajn et al., 2004, where the dosimeter indication greatly varies at low-photon energies, and where only a few devices fulfil the IEC criterion for a wide range of energies. In a paper by Boziari and Hourdakakis, 2007, a large sample

of APDs was calibrated with the reported mean calibration factor of 1.034 ± 0.046 (within the range 0.967 – 1.238). Out of the 116 tested APDs only 5 had exceeded the IEC limits of acceptable performance. Besides the general use APDs which are intended to be used in a wide range of energies and radiation protection situations, there are specific models which are intended to be used for radiation protection purposes in the medical radiation fields. In research by Cardoso et al., 2016, the RaySafe i2 APD was tested for radiation-based influence quantities. In the low-energy photon range the intended reference radiation field is usually N100 (with the 88 keV mean photon energy), as opposed to Cs-137. Energy dependence of the relative response was in the range from -73 % (for N-30 radiation quality) to +26 % (for N-80 radiation quality). This dosimeter has a strong energy dependence, as well as pronounced angular dependence with significant asymmetry of the response, indicating that due to detector design it can occur that the detector is not inherently symmetrically sensitive to radiation. Therefore, besides testing for the influence of photon energy, the tests for angular dependence of the response should be done for low-energy radiation fields since the effects of angle of incidence are not as pronounced at higher photon energies (such as the S-Cs reference radiation field). Still, response in low-energy radiation fields remains a critical parameter for many APD models that are even used in medical applications (Ginjaurme et al., 2007).

In research by Hupe et al., 2019 ten APD types were tested in the standardised pulsed radiation fields according to ISO 18090-1:2015. The dosimeter models to be tested were selected based on the results of a survey distributed to European hospitals. Energy dependence of the dosimeters was evaluated in the RQR diagnostic radiology reference radiation fields (RQR5, RQR8 and RQR9) as well as the radionuclide radiation fields S-Co and S-Cs. Some of the models that are reportedly used in clinical conditions do not have appropriate manufacturer specifications and are therefore not intended for low-energy X-rays. An example of such device is Mirion Rad-60SE, whose energy dependence of the response is in line with the manufacturer specifications, where the under-response becomes very pronounced for energies below 60 keV. In addition, some of the APDs exhibited poor energy dependence of the response, even though it is stated differently in the manufacturer specifications (e.g., Dositec L36). Along with the energy dependence, main influence quantity specific for pulsed radiation fields was examined, being dose rate dependence. The influence of dose rate (Fig. 7) was examined in the continuous S-Co radiation field and at the pulsed X-ray radiation field of RQR8 radiation quality (with a single pulse duration of 10 ms). The non-linearity response was normalized to the 0.1 Sv/h value (which corresponds to the 10 s radiation pulse duration) for RQR8 and to 0.01 Sv/h for S-Co. In the case of Raysafe i2 its response deteriorates at high-photon energies since it is designed to be used at medical X-ray diagnostic level radiation fields. Three out of ten APD models have had good performance in pulsed radiation fields, and only DMC 3000 and EPD Mk2 have acceptable response in pulsed fields (despite Rad-60SE having good linearity, its energy dependence does not fit medical applications).

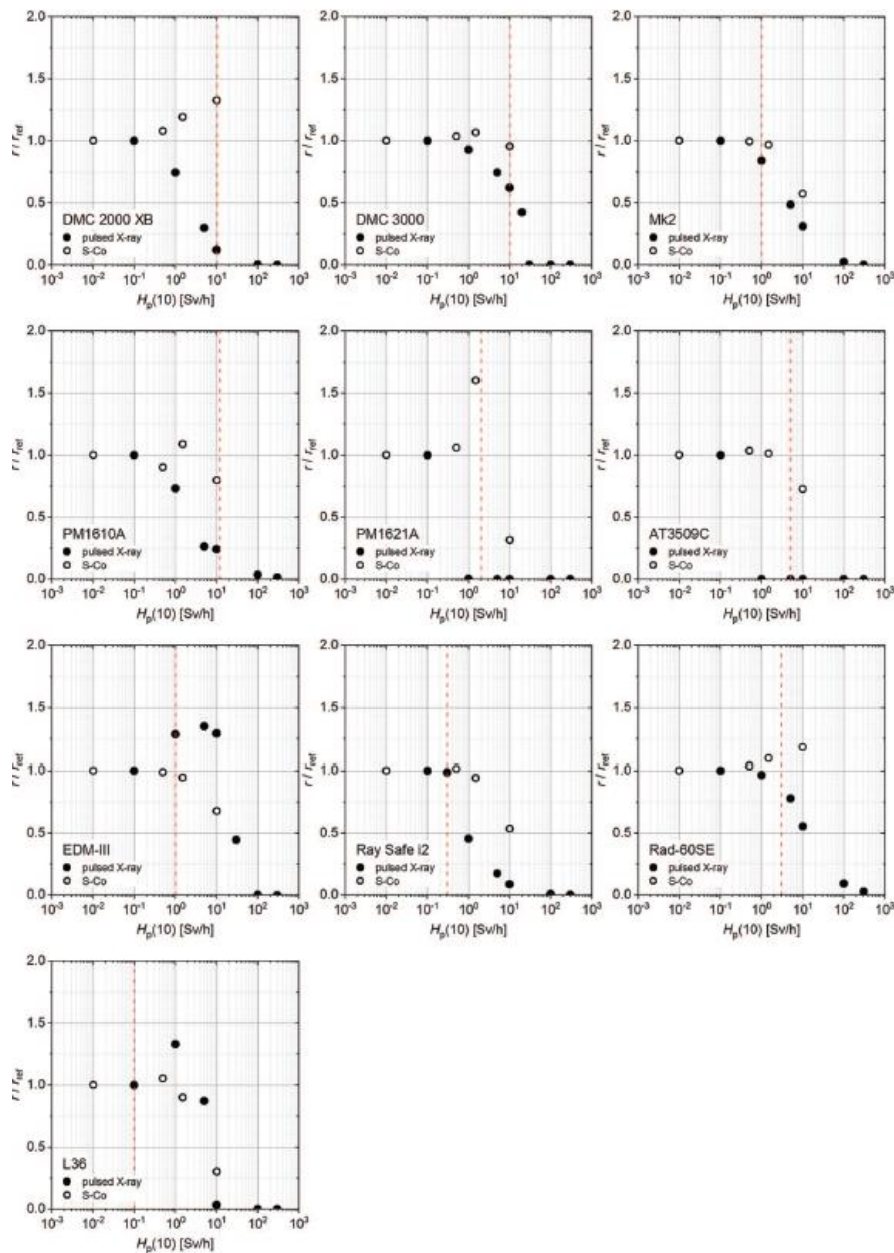


Figure 1-7. Non-linearity response of 10 selected APD models used in European hospitals. Response was normalised to 0.01 Sv/h for continuous S-Co radiation field and to 0.1 Sv/h (10 s pulse duration) for the RQR8 radiation field (Hupe et al., 2019).

As previously mentioned TLDs are generally used in individual monitoring of occupationally exposed workers. In research by Lee et al., 2016 the performance of selected types of APDs (Thermo EPD-Mk2, EPD-N2, EPD-G, MGP DMC 2000S and DMC 2000XB, FUJI NRF 30) was compared to TLDs. Linearity and energy dependence of the response were evaluated. The energy dependence was evaluated according to IEC 61526:2010, with the limits of variation 0.71-1.67 for the energy range from 80 keV to 1.5 MeV. NIST photon radiation beams were used for this test (M30 with 20 keV, M60 with 35 keV, M100 with 53 keV, M150 with 73 keV and H150 with 118 keV, mean energies). Relative response was determined by normalizing the response values to the S-Cs reference radiation field (Fig. 8). It can be observed that some dosimeters have a significant under-response at low-photon energies which is in line with the results presented in previous papers.

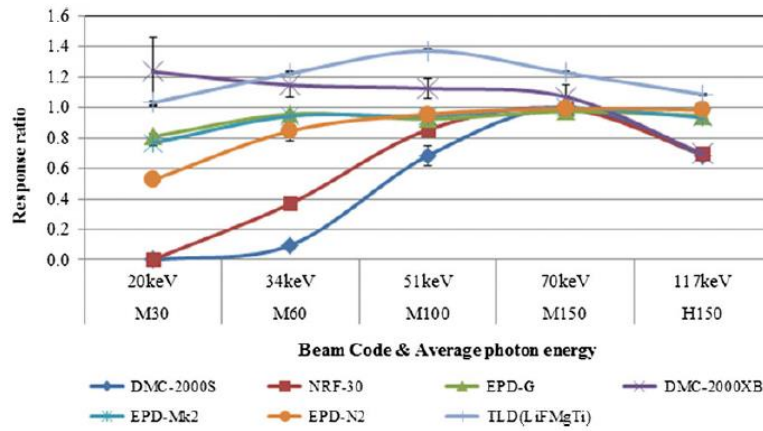


Figure 1-8. Relative energy response of several APDs and TLD normalized to S-Cs with NIST radiation beams (Lee et al., 2016).

Commercially available APDs are mostly based on Geiger-Müller tubes and silicon (Si) diodes. An ideal APD would have a flat energy response, a linear response in a wide range of dose (rates), negligible angular dependence and no dead time. To perform data acquisition in individual monitoring, these devices should also have a low power consumption and they should be designed as compact to be easily worn on the body (Pavelic et al., 2019).

In a paper by Zivanovic et al., 2022, it was investigated if the field-class dosimeters can be used for interlaboratory comparison purposes, to examine if the calibration factors provided by different calibration laboratories are comparable. Due to its unpronounced energy dependence of the response, a well-energy compensated APD which is in line with the requirements set by IEC 61526:2010 can be used as a transfer instrument for intercomparisons. In this research, this was not the case with all the selected area dosimeter models, mostly due to poor energy dependence and lack of energy compensation.

1.4 Passive dosimetry systems for individual monitoring

Passive dosimetry systems are regularly used in individual monitoring of occupationally exposed workers and are mandatory in various ionizing radiation practices. A passive dosimetry system consists of passive radiation detectors and the associated unit for accumulated dose readout (dosimeter reader). Several detectors are inserted into a housing, each under a specific filter. An algorithm combines the responses of the detectors under different filters in order to cover the widest possible energy range. With appropriate combination of filters and algorithm, these dosimeters can be used for the measurement of operational dosimetry quantities in various radiation fields. Passive dosimetry systems utilize detectors based on the luminescence effect, where the secondary charged particles are being collected and trapped in the detector material, until provided with enough energy, above a certain threshold which is a characteristic of the detector material. This energy induces the release of the collected charge which is followed by the emission of photons from the visible light spectrum. This delayed emission of light is termed luminescence. Commonly used passive dosimetry systems are based on thermoluminescence, where the release of collected charge is caused by providing heat to the detectors, and on optically stimulated luminescence where the detectors are exposed to a certain wavelength of visible light. The intensity of emitted light is directly related to the absorbed dose in the detector. Besides commonly used thermoluminescence dosimeters (TLDs) based on LiF:Mg,Ti or LiF:Mg,Cu,P and optically stimulated luminescence dosimeters (OSLDs) based on Al₂O₃:C, novel materials are also investigated such as BeO (Yukihara, 2020). Passive dosimetry systems are evaluated according to the test methods and requirements defined in the IEC 62387 standard. The standard covers requirements for both individual monitoring and area monitoring with passive dosimetry systems. The updated version of this standard (2020) also includes hybrid dosimeters. Tests included in the standard cover both the detector properties and the tests for the associated dosimeter readout unit.

Passive dosimeters based on the luminescence effect have almost completely replaced passive dosimetry systems which use film dosimeters. Luminescence based passive dosimetry systems are mostly used in personal dosimetry, especially due to their high sensitivity (ability to measure low-dose values such as 1 μ Sv) and good linearity up to 1 Sv. Important consideration is their performance in radiation fields with different photon energies and angles of incident radiation. The effects of energy and angular dependence were examined in several papers. The limits of these influences on the dose readout are defined in the IEC 62387 standard as $\pm 40\%$, which results in the limits of the response as a range from -29% to $+67\%$. (Olko, 2010). Usually, the luminescence detectors are energy compensated with high Z-filters such as Al, Sn or Cu. In this way low-energy photons are attenuated, reducing their absorption rate and flattening the energy response but may introduce an energy detection threshold, so the use of various filter in one dosimeter is necessary. Compared to TL dosimeters, OSL dosimeters have high luminescence efficiency, stable sensitivity, high readout speed, and elimination of complex thermal annealing steps. On the contrary, TLDs have no light sensitivity issues and are therefore more easily handled, and the TL glow curve which is recorded during readout can be used as a quality control measure. Luminescence dosimeters are not very likely to be completely replaced by APDs mainly because of their low price, high accuracy and better resistance to environmental conditions.

In the paper by Apostolakopoulos et al., 2019, the performance of commonly used LiF:Mg,Cu,P (MCP-N) and LiF:Mg,Ti (MTS-N) TLDs and Al₂O₃:C OSLDs (InLight) was evaluated. The dosimetry influence quantity effects were examined in a wide range of photon energies from 24 keV up to 1.25 MeV with an extended angle of incidence range from 0° to 80°. The tests were done using the criteria of, at the time current version of the IEC 62387:2012 standard, which was updated in 2020. Energy dependence of three passive dosimetry systems is presented in Fig. 1. Comparison of the responses of two TLD systems displays that they greatly differ due to different doping materials used for the same base material. The MTS-N response greatly increases with the decrease of photon energy, even as high as $+80\%$, and MCP-N, while having lower increase in the response at low-energies, exhibits lower values of response in the energy range from 100 to 150 keV. On the other hand, the OSLD have somewhat less pronounced trend in energy response with the decrease of photon energy. The criteria set by the standard for the energy and angular dependence are set for the mandatory energy range from 80 keV up to 1.25 MeV, expressed with the limits of variation from -29% to $+67\%$. The limitation of this study is that, even though the tests were done in the wide range of photon energies and angles of incidence to account for poly-energetic and multi-directional real radiation fields, tests on non-linearity influence quantity were not performed, and the angular dependency test for two dosimeter orientations was not conducted.

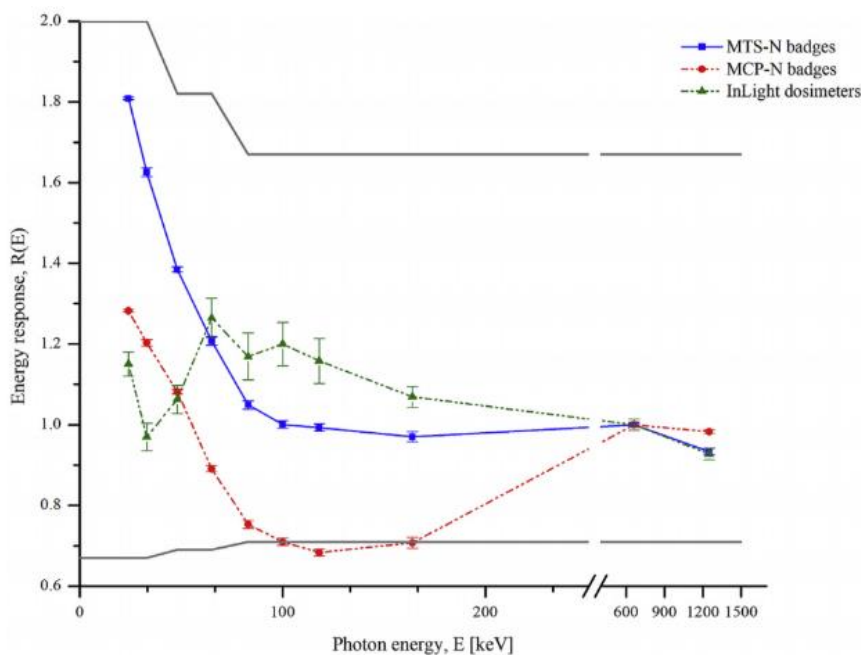


Figure 1-9. Energy dependence of the LiF:Mg,Ti (MTS-N) and LiF:Mg,Cu,P (MCP-N) TLDs and Al₂O₃:C (InLight) OSLDs (Apostolakopoulos et al., 2019).

In similar research by Krzanovic et al., 2023 and Pereira et al., 2019, influence of photon energy, angle of incidence and non-linearity on the response of LiF:Mg,Ti (TLD-100) and LiF:Mg,Cu,P (TLD-100H) dosimeters was examined according to IEC 62387, respectively. The tests were done for the measurement of both personal dose equivalent for the whole body, $H_p(10)$, and the extremities or skin, $H_p(0.07)$. Both TLD-100 and TLD-100H are used in various applications of individual and area monitoring. TLD-100H is becoming more used compared to TLD-100, mainly due to their higher sensitivity, lower detection limit and almost negligible fading. In the paper by Krzanovic et al., 2023, the influence of dosimeter holder was also examined, by performing the tests on the same dosimeter material which used two different dosimeter holders, type 8814 and 8850. Overall, the dosimeters with the 8850 holder have displayed a slightly less pronounced energy response, as well as less pronounced non-linearity effects at low dose values, compared to the 8814 holder. The largest over-response for TLD-100 is recorded for N-40 being approximately +45 % for $H_p(10)$, and +60 % $H_p(0.07)$. The recorded trend in energy dependency is in line with the findings of Apostolakopoulos et al., 2019 for MTS-N due to this dosimeter employing the same material LiF:Mg,Ti. Energy response for TLD-100 is somewhat less pronounced, compared to MTS-N. Non-linearity response improvement in 8850 over 8814 may not be as significant due to large measurement uncertainty at the lowest dose values (below and at 100 μ Sv). Angular dependence was evaluated at low-photon energies and larger angle of incidence values, since these represent most challenging irradiation conditions for radiation protection dosimeters. The angular dependence test was done for both dosimeter orientations (vertical and horizontal), symmetrically for both rotations and angle values of 45° and 60°. In Fig. 2 it can be observed that the dosimeter with 8814 holder has a larger over-response for all orientation/rotation setups compared to 8850, and that TLDs with 8850 holder comply with IEC 62387:2020 even at 60°, having response below the upper limit of variation. An important insight is that besides the IEC defined tests which cover different categories of influence quantities, the dosimeter holder can also greatly influence the dosimeter response.

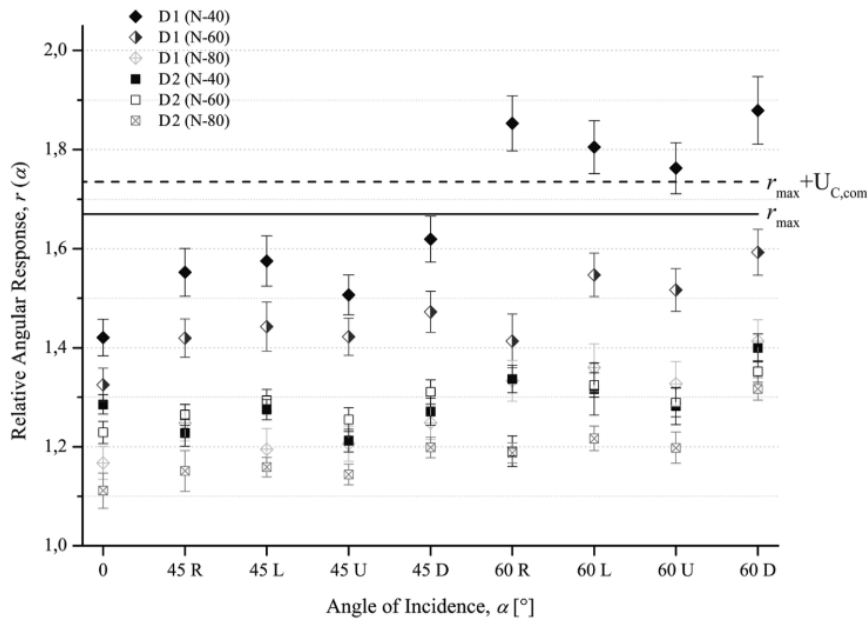


Figure 1-10. Energy and angular response of LiF:Mg,Ti TLD-100 with holder type 8814 (D1) and 8850 (D2). The test was done for two dosimeter orientations and in both rotation directions (Krzanovic et al., 2023).

In the research by Pereira et al., 2019 the energy dependence of TLD-100H was examined in the energy range from N-30 up to N-120 and S-Cs, S-Co. Angle of incidence was also examined in two orientations for angles up to $\pm 60^\circ$ with an increment of 20° . Satisfactory angular dependence is recorded even for the N-40 radiation quality, while the intensity of this effect lowers with the increase of energy as expected. In this paper it is also claimed that the influence of the dosimeter holder can greatly influence the angular response of the detector. For both quantities, the system shows linear behaviour, being close to unity for most of the examined values with the slight increase (less than 10 %) for both the lowest dose (0.1 mSv) and the highest dose (300 mSv) tested. The energy response function has a local minimum at approximately 100 keV (which is in line with the findings of Apostolakopoulos et al., 2019 for MCP-N, based on the same material, LiF:Mg,Cu,P).

Luo et al., 2017 have performed tests on the LiF:Mg,Cu,P with the 8850 holder in terms of radiological, environmental and mechanical performance tests, for both $H_p(10)$ and $H_p(0.07)$, as well as for photon, beta and neutron radiation. The tested dosimeters have shown sensitivity to a wide range of photon energies from 16 keV to 1.25 MeV, and a wide range of dose values from 10 μ Sv. For the energy dependence test N-radiation quality series, S-Am (Am-241), S-Cs and S-Co were used. As with the results presented by Pereira et al., 2019 and Apostolakopoulos et al., 2019 the LiF:Mg,Cu,P dosimeters exhibit an under-response of approximately -20 % near the energy of 100 keV. The non-linearity for photon radiation was examined in the range from 10 μ Sv up to 10 Sv. The estimated response values are mostly in line with the criteria of the standard, with a noticeable increase in measurement uncertainty for the highest and the lowest dose values, more pronounced for the $H_p(0.07)$ measurements, compared to $H_p(10)$ (Fig. 3).

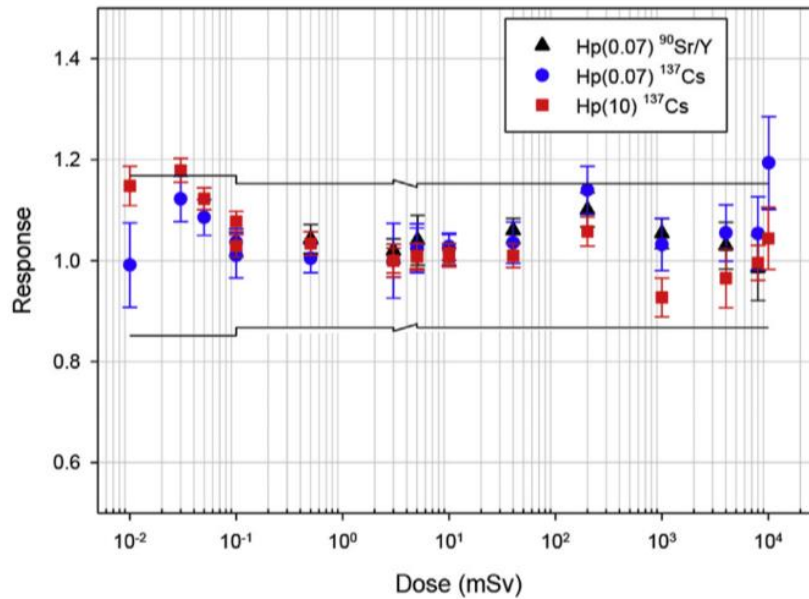


Figure 1-11. Non-linearity test results for the LiF:Mg,Cu,P with 8850 holder in a wide range of dose values ranging from 0.01 mSv up to 10 Sv (Luo et al., 2017).

Presented research results comply, well-describing the energy dependence, angular dependence, and non-linearity of the response for most used TLD materials (LiF:Mg,Ti and LiF:Mg,Cu,P) and their associated holders (8814 and 8850). Energy dependence was evaluated in a wide range of photon energies, covering different applications of ionizing radiation. Since these dosimeters have good performance in general, passive dosimetry systems are regularly used for monitoring.

Less commonly used nowadays are the radio-photoluminescent dosimeters based, RPLDs. Radio-photoluminescence occurs when the glass-based dosimeter, previously irradiated with ionizing radiation is exposed to ultraviolet (UV) light. As reported by Yamamoto et al., 2020, most prevalent material used for RPLDs is the silver (Ag) activated phosphate glass. These dosimeters have good dosimetry characteristics in terms of radiation sensitivity and negligible fading. Radiation based characteristics of these dosimeters are presented in Fig. 4. Followed by the accident at Fukushima Nuclear Power Plant (NPP), developments of different variations of the glass detector have been ongoing. The detectors should be able to stand severe environments with high temperature, high humidity, and high dose rate (in the order of 100 mSv/h - 1 Sv/h).

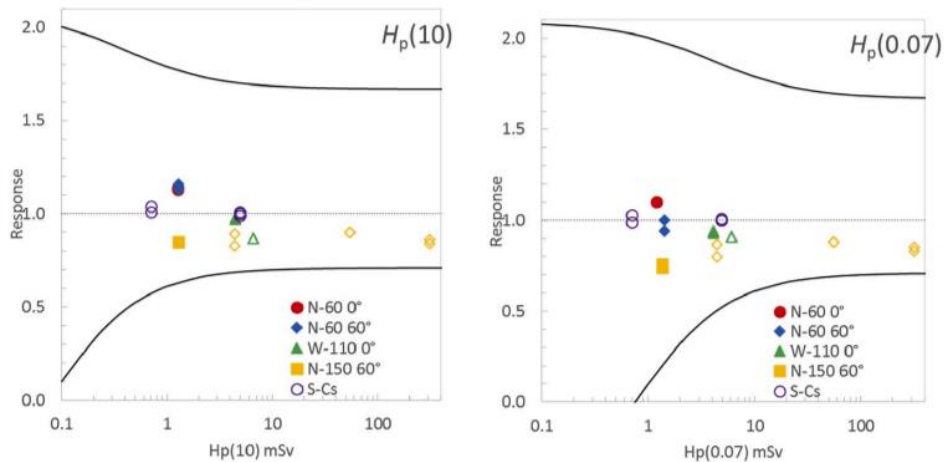


Figure 1-12. Trumpet curve of RPLD response for the measurement of personal dose equivalent at various energies, angles of incidence and dose values (Yamamoto et al., 2020).

In the paper by Yukihiro, 2020, specificity of the OSL signal generated from a BeO ceramics was examined and discussed in detail. The term thermally transferred optically stimulated luminescence (TT-OSL) was explained. BeO is used as a novel alternative material to the widely used Al₂O₃:C OSLD. The TT-OSL

process is specific for BeO since annealing of the charges with visible light does not empty all the charge “traps” in the energy gap. Some of the deep traps require thermal excitation, which causes the charge to migrate to the optically active energy levels, which can then be further read out by using visible light.

Passive dosimetry systems can utilize differently designed dosimeters in order to measure different personal dose equivalent values, including the whole body $H_p(10)$, extremities $H_p(0.07)$ and eye-lens $H_p(3)$. In research by Oliveira et al., 2018 a LiF:Mg,Ti based TL ring dosimeter was evaluated according to the IEC 62387:2012. Tests included non-linearity, energy dependence and angular dependence of the response as well as passive dosimetry system specific tests: dose build-up and fading. Non-linearity was tested in a range from 0.2 mSv to 2 Sv. As in line with the findings for the whole-body TLDs (both for $H_p(10)$ and $H_p(0.07)$ measurement) the non-linearity becomes quite pronounced for dose rates below 1 mSv. For the value of 0.4 mSv a significant drop, with under-response of approximately -40 % is recorded. In case of energy and angular dependence the dosimeters were evaluated in the photon range from 20 keV up to 662 keV, and for the angles of incidence up to 60° for the three lowest energies (20, 24 and 33 keV). Both energy and angular dependence of the response are presented in Fig. 5. In the case of energy dependence, the dosimeters do not comply with the standard for 24 keV, where the response curve has the maximum value in proximity of 1.8. By applying the energy correction factor of 0.9, the IEC standard criterion is met.

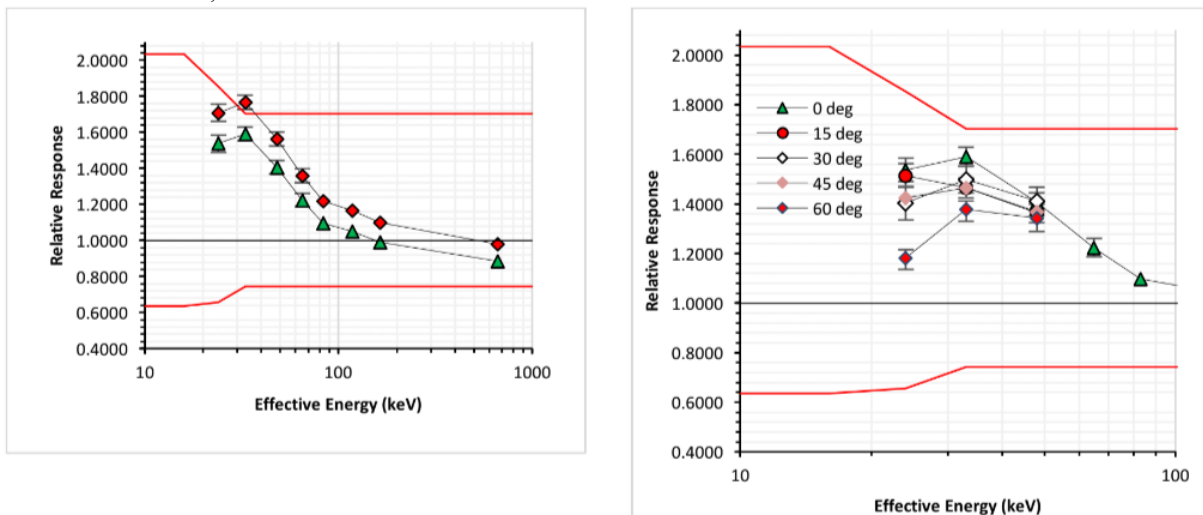


Figure 1-13. Energy response (left) and angular response (right) of LiF: Mg,Ti ring dosimeters. To meet the IEC criteria, an energy correction factor was applied. Angular dependence was tested for four angle of incidence values at the three lowest energies (Oliveira et al., 2018).

Analysed papers related to eye lens personal dose equivalent, $H_p(3)$, measurements can be categorized into three topics: type testing and calibration of $H_p(3)$ dosimeters, direct measurements of $H_p(3)$ in order to establish correlation with other quantities, measurements of $H_p(3)$ in hospital case studies. Performance tests were performed according to test methodology and recommendations set by IEC 62387:2020 (or its previous versions).

Accurate eye-lens dose measurement is very important in prevention of the radiation induced eye damage. This is specifically relevant for interventional procedures in radiology, as well as for the occupationally exposed workers in nuclear facilities and industrial radiography. In recent research by Stankovic Petrovic et al., 2023, evaluation of a passive dosimetry system also based on LiF:Mg,Ti detectors for eye-lens dosimetry according to IEC 62387:2020 was done. DXT-100 dosimeters were irradiated in the energy range from 33 keV up to 1.25 MeV, with angles of incidence of 45°, 60° and 75°, and with dose value range from 0.05 mSv to 10 Sv. The DXT-100 detectors were placed in the modified ring holders, and positioned on the cylindrical phantom of similar dimensions for the standard ISO cylinder phantom for $H_p(3)$ measurements. The phantom employed in this research is regularly used for quality control in computerized tomography. Even though the linearity test requirements are met for the range of dose from 0.3 mSv to 3 Sv. The upper limit of this range is reduced to 1 Sv due to high statistical fluctuations at higher dose values. As with the energy dependence of this material in other individual monitoring applications the energy response increases with the decrease of photon energy to the maximum value of approximately +50 % at N-40. The highest energy and angular response value is recorded at N-40 radiation quality for 75° angle of incidence.

Stadtman and Hranitzky, 2014 have researched if the passive dosimeters which are intended to measure the whole-body dose or the dose for extremities are able to measure the dose to the eye-lens. Both of these dosimeter types were tested in terms of $H_p(3)$ after some modifications. For the whole-body dosimeter changes in the dose calculation algorithm were introduced, while the extremity ring dosimeter was adapted to a headband dosimeter. Whole-body dosimeter response

was normalized to S-Cs and it was positioned on the ISO slab phantom, while the extremity dosimeter response was normalized to N-100 and it was positioned on a ORAMED water filled cylindrical head phantom (20 cm diameter and 20 cm height). The requirements of the IEC 62387:2012 were met for both dosimeters in terms of energy dependence and angular dependence in the mandatory range of these influence quantities.

Kowatari et. al., 2020 showed the measured results of the energy and the angular dependences of the response of the ED3 did not satisfy the IEC requirement of personal dosimeters for eye lens dosimetry, and improvements in the response were needed. By introducing an Sn filter with a thickness of 0.1 mm, the improved energy response of the ED3 fully met the criteria, except for a mean energy of 33 keV (N-40 of the ISO narrow series). The ED3 with an Sn-made filter could provide reliable readings when used for eye lens dose monitoring of medical workers. Results of the study by Borges, et. al. 2014 showed that the energy dependence of the dosimeter was lower than 10 % in the energy range from 83 to 118 keV, but it reached 30 % in energies down to 33 keV. In terms of the energy response that is given by the inverse of the calibration coefficient, all results complied with the ISO requirements.

Dubeau et. al., 2021 addressed the topic of use of passive dosimetry systems which are regularly used for extremity monitoring in terms of $H_p(0.07)$. Several passive dosimetry systems based on TL and OSL dosimeters were examined in this paper. Tested dosimeters exhibit relative response, in terms of $H_p(3)$ measurements, fairly close to unity in most cases, with the dosimeters calibrated using the standard protocols of the different dosimetry services. UD-817 A1 exhibited a slightly lower response compared to other systems. TLD-700 and EXT-RAD had energy response which had a slight increase at lower energies. One of the tested dosimetry systems based on OSLDs (nanoDot) had a steep increase in response at low photon energies (Fig. 6). All $H_p(0.07)$ dosimeters used in this study, when used in conjunction with adequate filtration, appear to provide fairly accurate $H_p(3)$ response.

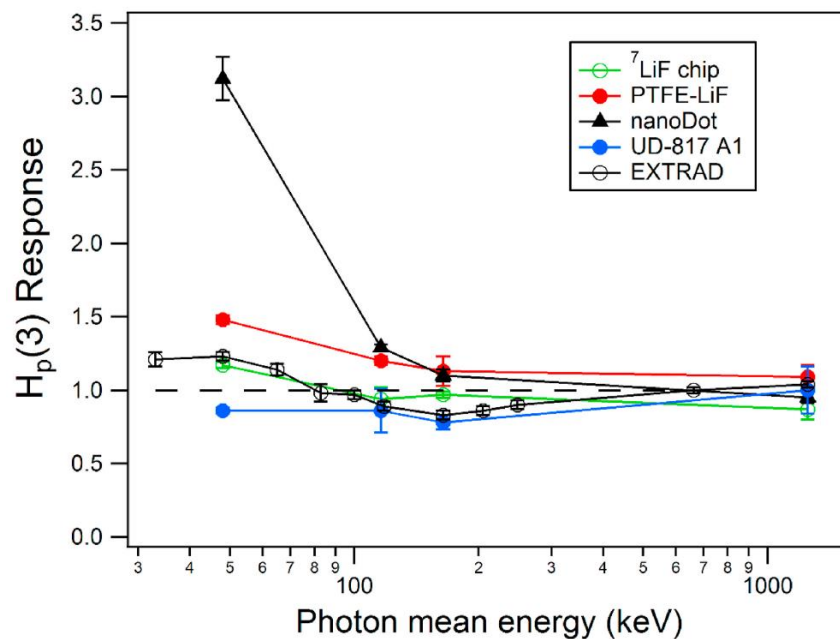


Figure 1-14. Energy response of passive dosimetry systems used for $H_p(0.07)$ monitoring, as eye-lens dosimeters. Three passive dosimetry systems exhibit less pronounced energy dependence of the response (Dubeau et al., 2021).

Hoedlmoser et al., 2019, examined the passive dosimetry system based on BeO OSL detector for use in eye-lens dose monitoring, $H_p(3)$, which is increasingly important for radiation applications where individual doses to the eye can be relatively high (such as interventional radiology or cardiology procedures). Its performance was evaluated against the IEC 62387 standard, and by comparing with the performance of the EYE-D TL dosimeter which is based on LiF:Mg,Cu,P. Energy dependence of the response was evaluated in the energy range from N-15 up to S-Co. Having a look at the energy and angular response (at 0° and 60° angles of incidence, for each radiation quality) the BeOSL dosimeter complies with the standard criteria for most of the irradiation setups (Fig. 7). The angular dependence becomes more pronounced for the lowest photon energies, while for the higher energies the shift is not as significant. Comparison with EYE-D energy response displays a less pronounced energy response of the BeO-based detector, which is crucial to their use in interventional procedures. The tested OSL dosimetry system also has a very linear response with dose complying with the IEC criterion of (-13 %; +18 %). The relative response had deviations less than ± 2 % for the wide range of dose values from 0.1 mSv up to 1 Sv.

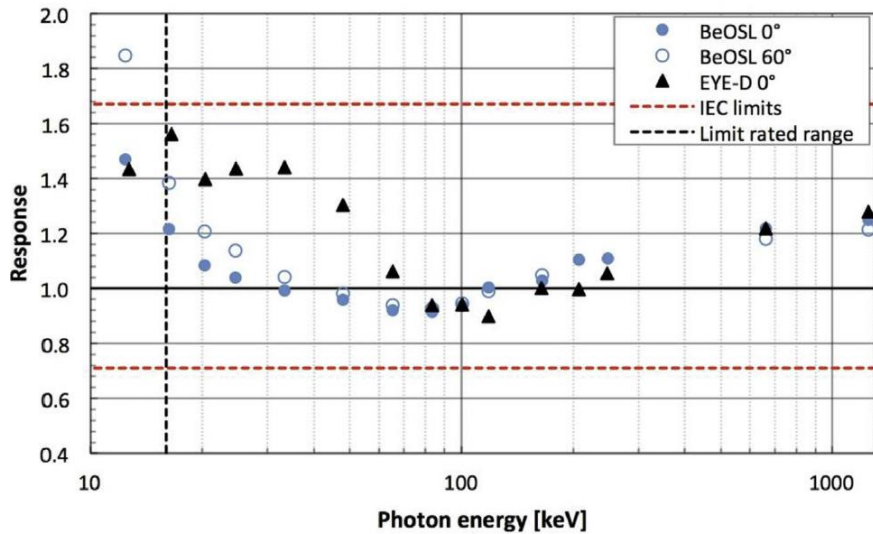


Figure 1-15. Energy and angular response (at 60° angle of incidence) of the BeO OSLD, compared to the EYE-D designated TLD for $H_p(3)$ measurements (developed in ORAMED project) (Hoedlmoser et al., 2019).

In a Vasconcelos Filho et al., 2024 have explored the influence of dosimeter for eye-lens monitoring in reference radiation fields. Influence of dosimeter position was evaluated on a realistic dosimetric phantom. All three dosimeter groups in different configurations, being EYE-band dosimeter assembly, two units of the RED – Realistic Eye Dosimeter, and commercial BeOSL eye lens dosimeter, are based on BeO OSL dosimeters. RED is positioned in dosimeter enclosures which represent average human eye, and the dosimeters can be positioned to radiation sensitive depths in the eye lens, typically from 2.8 mm to 3.82 mm. Angular dependence was evaluated for 0°, 30°, 60° and 90° angles of incidence for a wide range of photon energies (N-30 up to N-200, and S-Cs, S-Co). Results for the energy dependence of the central EYE-band dosimeter at each angle of incidence showed that the deviation in dose to the most exposed eye (right eye) between RED and the central Eye-Band dosimeter ranged from 0 % to ~20 % across all energies and angles. These results show that the angular dependence of the dosimeter on the most exposed side of the head is critical to ensure adequate results between the doses registered by the worn dosimeters at the side or center positions and the actual dose delivered to the most exposed eye.

1.5 Ambient monitoring

Radiation measurements in the areas which involve the use of ionizing radiation sources are routinely performed with various types of installed or portable radiation protection instrumentation. Usually, measurements are done in terms of ambient dose equivalent (rate), $H^*(10)$. The term ambient monitoring is not solely related to occupational exposure, but also considers radiation monitoring of eventual variations in the natural background radiation levels in the environment. Therefore, ambient (area) monitoring can be classified into area workplace monitoring, covering radiation monitoring in various ionizing radiation applications where dose to professionally exposed workers is evaluated, and area environmental monitoring, related to changes in the background radiation level due to release of artificial man-made radiation source in the environment. Ambient dose equivalent, like other operational quantities is also used to estimate the effective dose and compare these values with limits of exposure. Besides active dosimeters, passive dosimetry systems can also be used for area monitoring, and in some papers their performance for environmental monitoring applications is examined. In papers which are a result of EURAMET project 16ENV04 Preparedness, performance of active area dosimeters and passive dosimetry systems for monitoring in post-accidental situations is examined. Research results of paper by Morosh et al., 2021 have presented performance of monitoring instruments used in non-governmental networks, inciting research on performance tests and limits of variation for area dosimeters in different monitoring situations (recognising the need for differentiation between area workplace and area environmental monitoring). This was partly covered by the 17RPT01 DOSEtrace project and is a subject of Task 3.1 of 21NRM07 GuideRadPROS project.

1.6 Active area dosimeters for ambient monitoring

Radiation protection instrumentation based on active dosimeters used for area monitoring are mostly based on Geiger-Müller (GM) detectors, but also include pressurized ionization chambers, scintillation detectors and other. Active area dosimeters (AADs) are regularly used for radiation monitoring and surveillance in different workplaces. It is not uncommon that the end-users use inappropriate detector models, which are designed for different purpose (e.g., contamination monitors), or have poor energy response and non-adequate energy compensation of the response. Therefore, harmonization of the requirements for these devices as well as enforcement of legal requirements in different countries would reduce acquisition of questionable dosimetry data.

In a paper by Ceklic et al., 2014, seven different radiation survey meters which are used for area workplace monitoring were examined, for the effects of photon energy and angle of incidence on dosimeter response. The examined AAD models included three detector types: ionization chamber, GM counter and scintillator. For these tests reference air kerma rate of 1 mGy/h was used for most of the selected dosimeter models, with an exception for the scintillator, where the reference dose rate was 70 μ Sv/h. Energy dependence was examined for the N60, N100, N120 and N250 ISO 4037 N-series radiation qualities and S-Cs, S-Co radionuclide radiation qualities. Angular dependence was examined in one plane for 2π geometry with increments of 20° for the N100 and S-Cs radiation fields. The studied survey meters have pronounced energy dependence at low-photon energies, and for some devices (MRK-M87) this effect can lead to an over-response of +400 %. Such dosimeter behaviour is a clear indication of inadequate energy compensation of the GM tube in the dosimeter. Dosimeter performance was evaluated according to the requirements in the IEC 1017-2 standard, which has been withdrawn and replaced with the IEC 60846-1 standard. In these standards the requirements for radiation protection instruments which are used for area workplace monitoring are defined. To be compliant with the IEC 1017-2, the response of an instrument should not differ more than ± 30 % from the standard conditions (0° for S-Cs radiation quality). Out of seven tested models, two have slightly less pronounced energy dependence, complying with the standard criteria even out of the rated range (Victoreen 451P, which is a pressurized ionization chamber and Automess 6150 AD-b, which is a scintillation counter). In terms of angular dependence, the survey meters had the best response for the angle range up to $\pm 80^\circ$, with the most pronounced angular dependence at 180° , which is directly related to the device design limitations in terms of its geometry and associated electronics.

In a more recent paper by Krzanovic et al., 2019, the response of a GM tube-based area workplace dosimeter was evaluated according to the IEC 60846-1:2009 standard. This standard sets the requirements for radiation protection instruments which are used for area workplace monitoring. To be standard-compliant the dosimeter should be able to achieve energy and angular response within the limits of variation from -29 % to +67 % (normalised to S-Cs, which is the reference irradiation condition, unless stated otherwise by the manufacturer) for the minimum rated range of photon energy from 80 keV to 1.25 MeV. Evaluation of the energy, angle of incidence and non-linearity influence on the dosimeter response was evaluated for a non-compensated cylindrical GM tube, and for the compensated detector. Several energy compensation possibilities were explored, including full coverage of the detector active volume in the range from 90 μ m up to 1.2 mm of lead (Pb). In addition, an air gap was introduced to the thin lead sheets, for two selected compensation filter thicknesses (400 μ m and 600 μ m) where the energy response was significantly reduced compared to the non-compensated tube, but not strongly compensated to induce pronounced under-response. Air gap width was also varied to achieve optimal energy compensation of the detector active volume in regard to the criteria of the IEC 60846-1

standard. For the selected parameters (lead thickness and air gap width), angular dependence and non-linearity were also evaluated. Angular dependence was evaluated separately at S-Cs radiation quality, and jointly with the photon energy influence for the N-40 and N-100 radiation qualities. In Fig. 1 the energy response of the 600 μm Pb compensated GM tube with and without the air gap, as well as the non-compensated GM tube is presented.

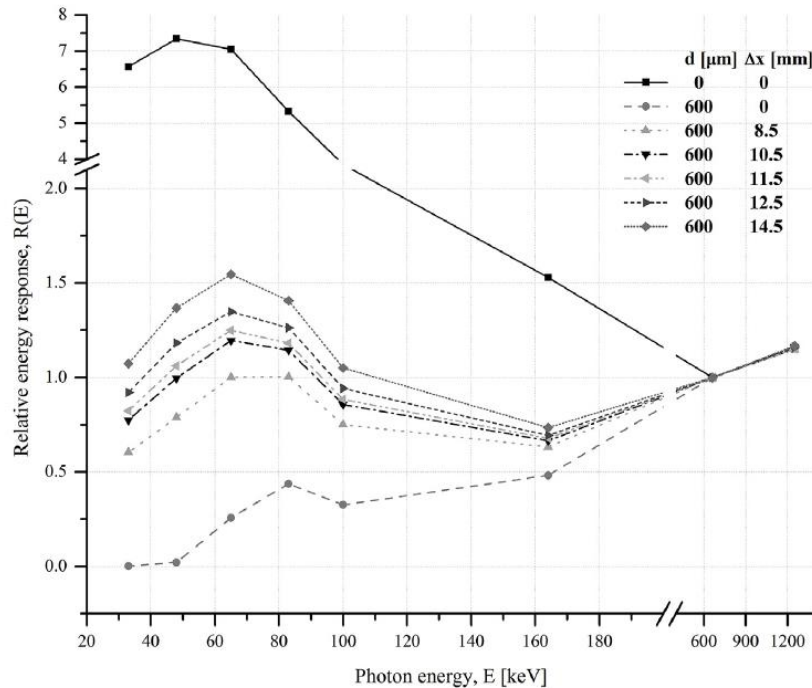


Figure 1-16. Energy dependence of a compensated and non-compensated GM tube AAD. Compliance with the IEC 60846-1 standard is achieved if the energy response is between -29 % to +67 % (Krzanovic et al., 2019).

Energy dependence of an uncompensated GM tube (model SBM-20) is very pronounced, with an over-response above +700 %. With filter thicknesses less than 400 μm (e.g., 110 μm) the energy compensation is not fully achieved, as the over-response at low energies is still high. If the compensation filter thickness is as large as 400 μm or 600 μm (and larger), the absorption of low-energy photons in the compensation material becomes pronounced and a strong under-response out of the limits of variation is observed. By introducing the air gap and varying its width, optimal energy compensation is achieved for an expanded energy range beyond the minimum rated range.

In a paper by Wang et al., 2018, a portable dose rate detector was designed to monitor radioactive pollution and radioactive environments. The developed portable area dose rate detector is suitable for measurement of a wide range of dose rates from background radiation levels (0.1 $\mu\text{Sv/h}$) to nuclear accident radiation levels (>10 Sv/h). Automatic switch technology of a double GM counter and time-to-count technology were adopted to broaden the measurement range of the instrument. Global positioning systems and the 3G telecommunication protocol were installed to prevent radiation damage to the human body. In addition, the Monte Carlo N-Particle (MCNP) code was used to design the thin layer of metal for energy compensation, which was used to flatten the energy response. Compensation with different materials (Sn, Al, Cu and Pb) was explored. For each of the materials four different thicknesses were evaluated by using 24 gamma photon energies. The dosimeter employs two GM tube models, a tube of smaller active volume, LND 78017, and a tube of larger volume, LND 71629. Both tubes are filled with a mixture of Ne and Br. Effect of energy compensation with different filters of varying thicknesses is presented in Fig. 2, for the large-volume GM tube.

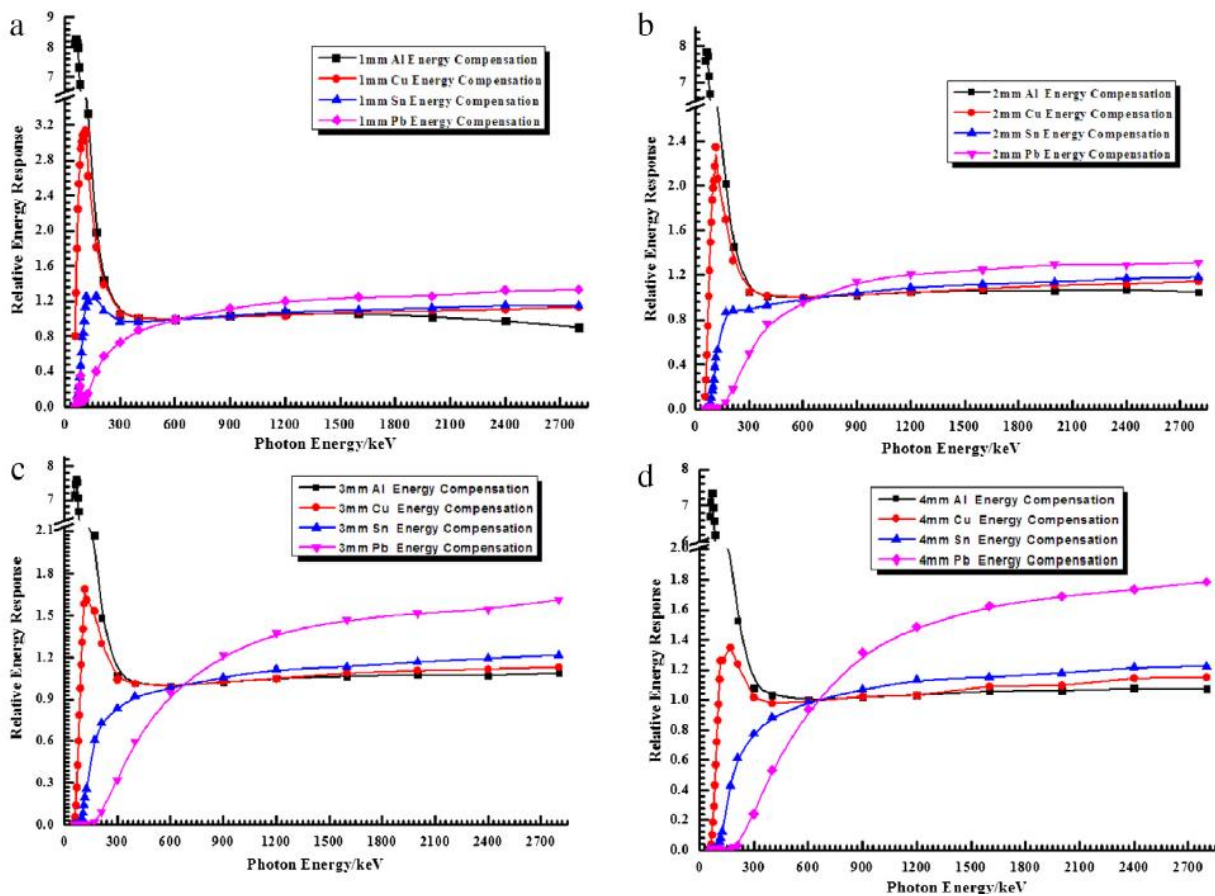


Figure 1-17. Energy compensation of the LND 78017 large volume GM tube (Wang et al., 2018).

Aluminium is not appropriate for the energy compensation as the energy response is still very pronounced. Even though tungsten and lead have good compensation properties the absorption of low energy photons in these materials is evident. Therefore, the active volume was not fully covered with the compensation material to achieve proper energy compensation. In this way, mitigation of very pronounced energy response was achieved. The portable dose rate detector has been calibrated in the standard radiation fields, and it can be used alone or in combination with additional radiation detectors. The double GM tube-based dose rate detector described was developed for daily regular radiation monitoring and nuclear accident emergency. It has a wide dynamic range and is suitable for varieties of application. This instrument is a new approach on the traditional GM counter detectors. By adding the GPS, 3G, and RF functions, the application scope was broadened. The calibration of the standard dose rate and testing experiments demonstrates that the detector can be applied commendably in practice.

Morosh et al., 2021 have examined the behaviour of commercially available area monitoring instrumentation in terms of their use for environmental monitoring following a nuclear accident. The focus was on the instruments which are used in the non-governmental radiation monitoring networks, which rapidly expanded after large-scope nuclear accidents (e.g., Chernobyl in 1986 and Fukushima in 2011). Since these devices mostly utilize GM tubes, they are in general lower cost compared to other detector types, and therefore are easily accessible to the public. The GM tube devices are termed as Monitoring Instruments in Non-governmental Networks (MINNs) in this paper. MINNs utilize GM tubes of different geometries and volumes (cylindrical and plane-parallel tubes), fill-gases (gas mixtures of inert gases such as neon and argon, with halogen), measurement ranges, sensitivity, and different radiation-based characteristics. MINNs often have poor dosimetry characteristics and can produce unreliable dosimetry data which is readily available to the public. In this paper the performance of MINNs was evaluated according to the IEC 60846-1 standard whose focus is on the active area monitoring instruments for use in area workplace monitoring. Effects of photon energy and dose rate on the MINN response were tested in laboratory conditions, since in the environment the dosimeters can encounter photons of any energy in general, and these devices should be able to detect variations in the background radiation level as eventual large increases in dose rate due to artificial source release and spread in the environment. In regular environmental monitoring, expected dose rates are on the level of background radiation. Besides tests in the laboratory conditions, MINN response to background radiation components was determined in realistic environmental monitoring scenario. Prior to the

radioactive plume measurement setup, components of the MINN indication of the background radiation were extracted and analysed. Namely, MINN indication of the background radiation level can be divided into the MINN indication due to inherent background of the device, contribution of the terrestrial radiation, contribution of the secondary cosmic radiation, and eventual contribution due to the release of radioactive material into the environment. MINN inherent background is the property of the device itself and is related to the electronics and the built-in computation algorithm. This background radiation component was extracted by eliminating all other contributions, by positioning the detectors in the low-background laboratory UDO II which is located approximately 430 m underground in a salt mine in Germany. The facility allows very low dose rate measurements and is maintained and operated by the National Metrology Institute of Germany (ger. Physikalisch Technische Bundesanstalt, PTB). Under these conditions almost no terrestrial or secondary cosmic radiation exists in the underground laboratory, with the dose rate being in the order of 1 nSv/h and by using lead shielding dose rates of even 0.1 nSv/h were achieved. Out of the 18 tested MINN types some display inherent background less than 20 nSv/h, while other models have indication larger than 40 nSv/h even up to 60 nSv/h for one MINN type. On Fig. 3 inherent background of individual MINNs can be seen (for mostly 4 devices per device model). For most of the models which had automatic data collection and storage, acquisition was done for a period of 4 h with integration periods of 1 min, resulting in lower measurement uncertainties. For some device models automatic data acquisition was not available, therefore a set of values was manually readout, increasing the uncertainty for these models.

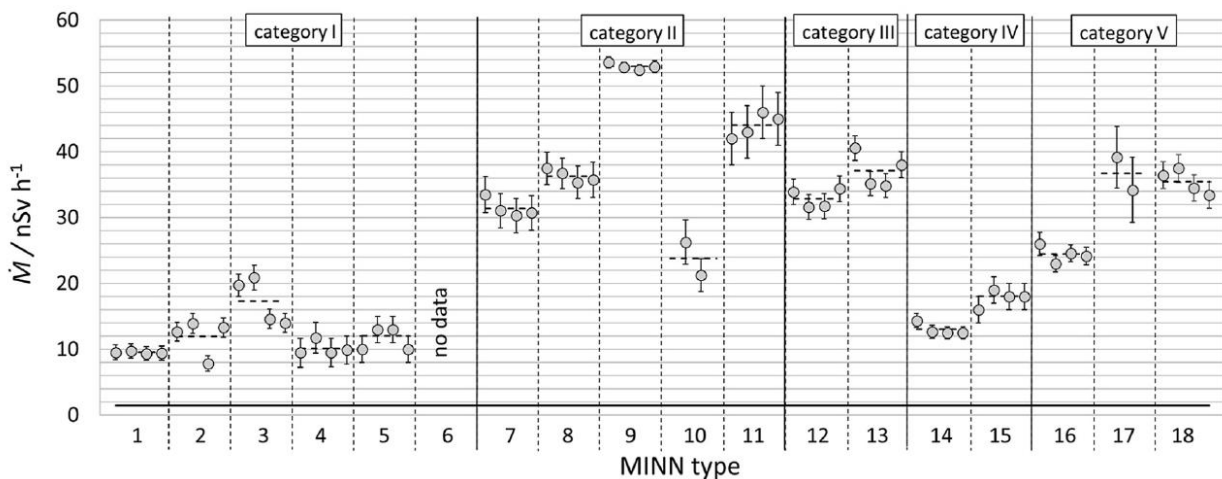


Figure 1-18. Inherent background MINN indication component determined at the low-background laboratory UDO-II (PTB). The dashed lines represent mean values for a certain MINN type. The solid horizontal line represents the reference dose rate level of 1.4 nSv/h (Morosh et al., 2021).

Influence of secondary cosmic radiation (SCR) on the MINN indication was evaluated by positioning the devices on a platform located on a lake of approximately 3 m depth. In this way terrestrial radiation component is well attenuated and may contribute to the indication with about 1 nSv/h. Secondary cosmic radiation was measured during a period of 1.5 h and by subtracting the previously determined inherent background. Almost all of the selected MINN models exhibit significant overresponse to SCR, compared to the reference dose rate of 29 nSv/h. In Fig. 1-19 response of MINNs to SCR is presented.

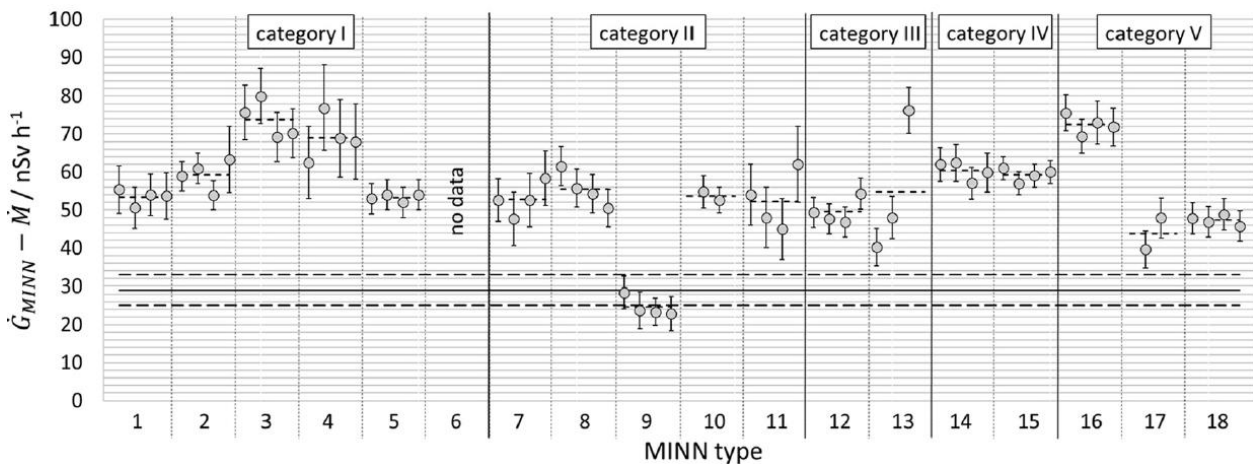


Figure 1-19. MINN indication due to secondary cosmic radiation (inherent background subtracted), compared to the reference value of 29 nSv/h determined by MUDOS: Muon Dosimetry system operated on PTB reference site (Morosh et al., 2021).

Radioactive plume simulation setup was used to estimate MINN response to the small changes in natural background radiation dose rate level due to artificial radionuclides in the environment. Radiation fields in the environment mostly contain Compton photons of various energies and angles of incidence. The setup was drafted in a way to simulate propagation of a radioactive cloud caused by artificial radioisotope release. Sources of Cs-137, Co-60 and Ra-226 with different shielding thicknesses were used to produce radiation fields of six different dose rates. Prior to and after exposure to the artificial radiation sources, background radiation was measured in a period of 30 min. Each of the exposures also lasted for a period of 30 min. All MINNs were positioned 1 m above the ground at the 5 m distance from the radiation source with 20 cm of gap between the detectors. Some of the MINNs had no indication whether their preferred orientation is horizontal or vertical, and for some models no difference in indication was observed. Dose rates used for the plume simulation were up to 381 nSv/h (for Ra-226), while the background radiation level was 75.8 nSv/h. The reference values were measured by the secondary standard Reuter-Stokes RS-131 ionization chamber. In Fig. 5 MINN indication variation during plume simulation is presented. Sources 1, 2 and 3 are Cs-137, 4 and 6 are Co-60 and Ra-226 is the source 5.

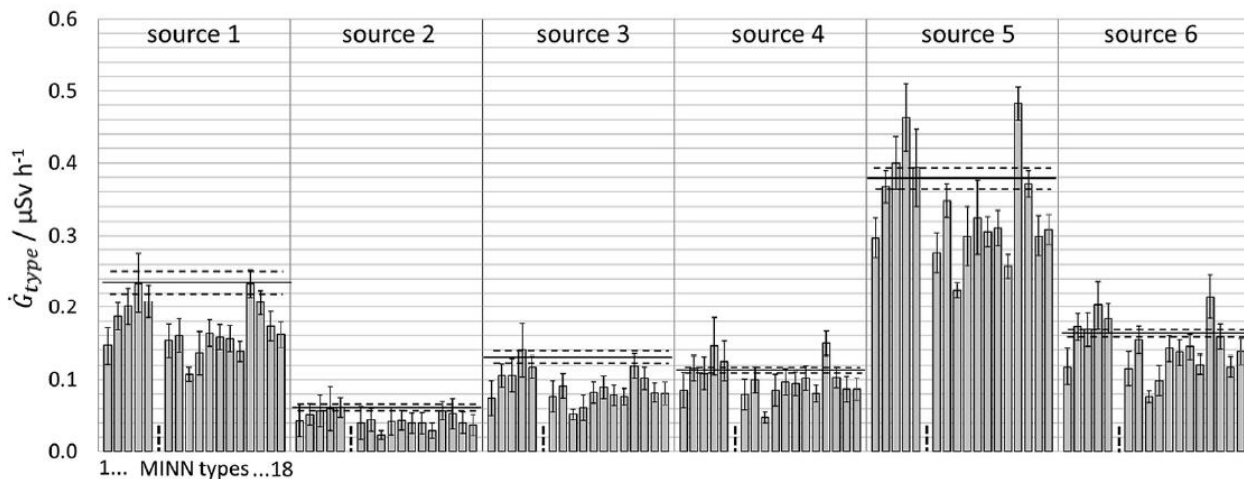


Figure 1-20. MINN indication variation during plume simulation. Six different dose rates were achieved by using Cs-137, Co-60, Ra-226 sources with different shielding thicknesses. The reference value determined by RS-131 chamber is presented with the solid line (with associated uncertainty in dashed lines) (Morosh et al., 2021).

It is observed that all of the MINN models have indications close to the reference value for Cs-137 (sources 1, 2, 3), while some exhibit energy dependence when exposed to Co-60 (sources 4, 6), even more pronounced in the radiation field of Ra-226 (source 5). Even though most of the MINNs are in line with the requirements on linearity and energy dependence given in IEC 60846-1:2009.

Tests of non-linearity and energy dependence of the response were tested in laboratory conditions in the dose rate range from 200 nSv/h up to 900 μSv/h, and in the ISO 4037 N-series X-ray radiation qualities and S-Am, S-Cs, S-Co. Most of the MINNs comply with the IEC 60846-1:2009 limits of variation from

-15 % to +22 % in a limited dose rate range. Some of the models completely comply with the standards, while some have under-response below the lower limit at around 500 $\mu\text{Sv/h}$, which is mainly because of dead-time of GM tube-based dosimeters. On the other hand, all 18 tested MINN models have a lack of adequate energy compensation filters, exhibiting very pronounced increase in relative energy response for low-energy photons, and not complying with the IEC 60846-1:2009 limits of variation from -29 % to +67 %. Angular dependence of the MINNs should also be evaluated, which is a limitation of this study, not taking into account the observed over-response of these devices.

In research by Morosh et al., 2021 a systematic comprehensive analysis of MINN performance was done. Followed by this, in a paper by Krzanovic et al., 2022 evaluation of IEC type testing requirements and test methods for active area dosimeters which are used for environmental monitoring was done. It is pointed out that clear distinction between active dosimeters for area workplace monitoring and area environmental monitoring is necessary, specifically due to the different irradiation conditions in these two monitoring approaches. Important difference in test methods and limits of variation are related to radiation-based and environment-based influence quantities. In terms of radiation-based influence quantities extension of the photon energy range down to N-40, N-60 and N-80 and up to R-C ISO 4037-1:2019 radiation qualities would provide better insight into energy dependence of the detector response. Additionally, due to the measurement ranges of environmental area monitors, low-dose rate reference radiation fields would be needed, besides the widely used N-series radiation qualities. Radiation beams from the ISO 4037-1:2019 L-series radiation qualities would be possibly better suited since they are as highly filtered X-ray beams as are the N-series radiation qualities and provide comparably lower dose rates. Non-linearity tests for environmental area monitors should cover very-low dose rates (possibly even 100 nSv/h). Angle of incidence is a very important influence quantity for environmental monitoring, since ideally, a dosimeter fit for this purpose would have a satisfactory energy and angular response in a 4π geometry. This is very hardly achievable due to the incorporated dosimeter electronics, associated probes, active volume position in the detector, preferred detector orientation etc. As for environmental-based radiation conditions a wider range of ambient temperature covering harsher operative conditions such as (-20 °C; 50 °C) and (10 %; 90 %). In this paper methods of test, rated ranges, and limits of variation of different IEC standards which are related to active area monitoring dosimeters were examined. A comparison was made with the IEC 62387:2020 which covers passive dosimetry systems, for individual monitoring, area monitoring (with distinction between area workplace and area environmental monitoring). Followed by this, a measurement programme regarding environmental area monitoring was developed, and tests were done on four area dosimeters. Three devices were MINNs also used in the research by Morosh et al., 2021, and one device is a novel spectro-dosimeter based on CeBr_3 scintillation probe. The MINNs were based on GM tubes of different geometries (being, cylindrical GM tube with an entrance window, two cylindrical GM tubes and a pancake GM tube).

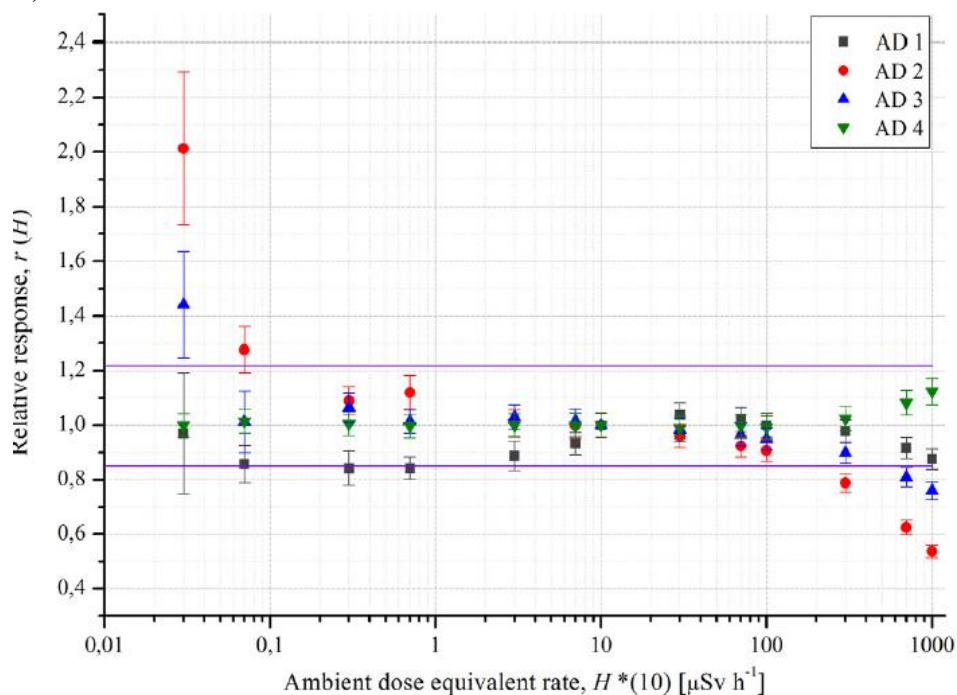


Figure 1-21. Non-linearity of in the range from 30 nSv/h up to 1 mSv/h with displayed (-15 %; +22 %) limits of variation. AD 1, 2, 3 represent selected MINN models from Morosh et al., 2021, and AD 4 is a spectro-dosimeter (Krzanovic et al., 2022).

Limits of variation for the non-linearity test were from -15 % up to +22 %, with the test range from 30 nSv/h up to 1 mSv/h. The reference dose rate used for determining the relative response was 10 μ Sv/h. The upper limit of test range was selected according to the measurement ranges as per manufacturer specifications of selected MINN types. Two regions of non-linearity are observed, being the range below 1 μ Sv/h and above 100 μ Sv/h. Certain MINN types have had an increase in response for the lowest dose rates (with the expected increase in measurement uncertainty due to low-counting statistics), as well as decrease in response for the highest dose rates (because of GM tube dead time). One of the MINNs and the spectro-dosimeter show remarkable performance being within the non-linearity requirement for the whole dose rate range (Fig. 6). Energy dependence was tested in the energy range from N-30 (24.6 keV mean energy) up to S-Co (1.25 MeV mean energy). Even though the spectro-dosimeter would comply with the IEC 60846-1:2009 standard since its energy response is within the limits (-29 %; +67 %) in the mandatory energy range (80 keV; 1.25 MeV), none of the detectors fulfil the criteria for the extended energy range, with the spectro-dosimeter detection efficiency falling off at low-energies, and MINNs exhibiting the over-response at low-energies (despite one MINN having less pronounced over-response, its also exhibiting under-response at N-30 and N-40 radiation beams) (Fig. 7).

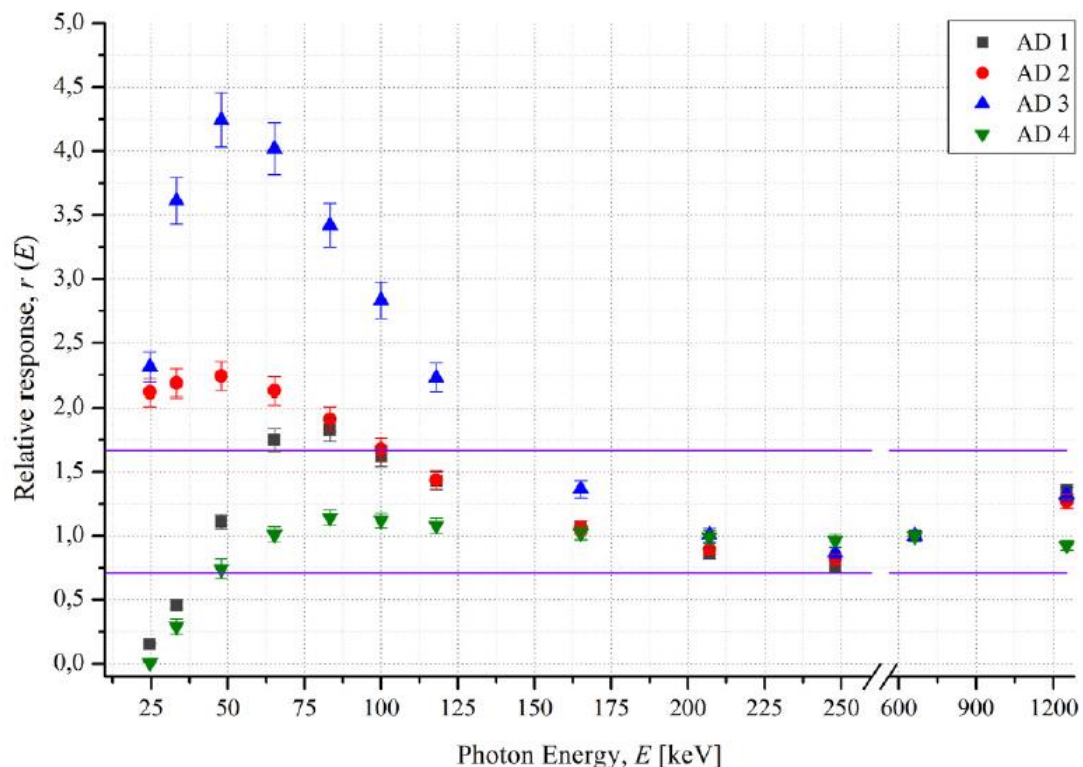


Figure 1-22. Energy dependence response in the N-series (N-30 - N-300) and S-Cs, S-Co ISO 4037 radiation qualities. Spectro-dosimeter under-response may be caused due to the drop in detection efficiency, and MINN over-response is caused due to inappropriate energy compensation of the active volume (Krzanovic et al., 2022).

Following the recommendations of the test methodology for angular dependence of active area dosimeters, angular dependence is tested for the lowest photon energy where the energy dependence criteria is met. Common radiation quality for all the tested area environmental dosimeters is the N-200 radiation quality with 165 keV mean energy. Angular dependence of MINNs was tested in two orientations, while spectro-dosimeter was tested only in vertical orientation, since its geometry is symmetrical for horizontal axis (due to the scintillation probe being cylindrical). Mandatory range in IEC 60846-1 for this influence quantity covers angles up to $\pm 45^\circ$, which is sufficient for area workplace dosimeters. The range was expanded to (0° ; 360°). Limits of variation for the angular dependence of the response (-29 %; +67 %, or -0.71; 1.67) could be relaxed for the larger angles of incidence as is the case with the criterion set for passive dosimetry systems under these conditions (0.67; 2.00), or the limit for external probes in emergency monitoring (0.62; 2.50) in IEC 60846-2:2015. In Fig. 8 angular dependence for active area dosimeters is presented for the N-200 radiation quality. It can be observed that two of the tested MINN models do not comply with the non-modified criterion for angular dependence even for the high energy N-200 radiation beam. The spectro-dosimeter has expected under-response near the dead angle of 180° , while one MINN (AD3) has negligible angular dependence (with variation from the 0° value of less than 20 %

for all angles of incidence except for 90°). Angular response results were normalized to the reference conditions (S-Cs and 0°).

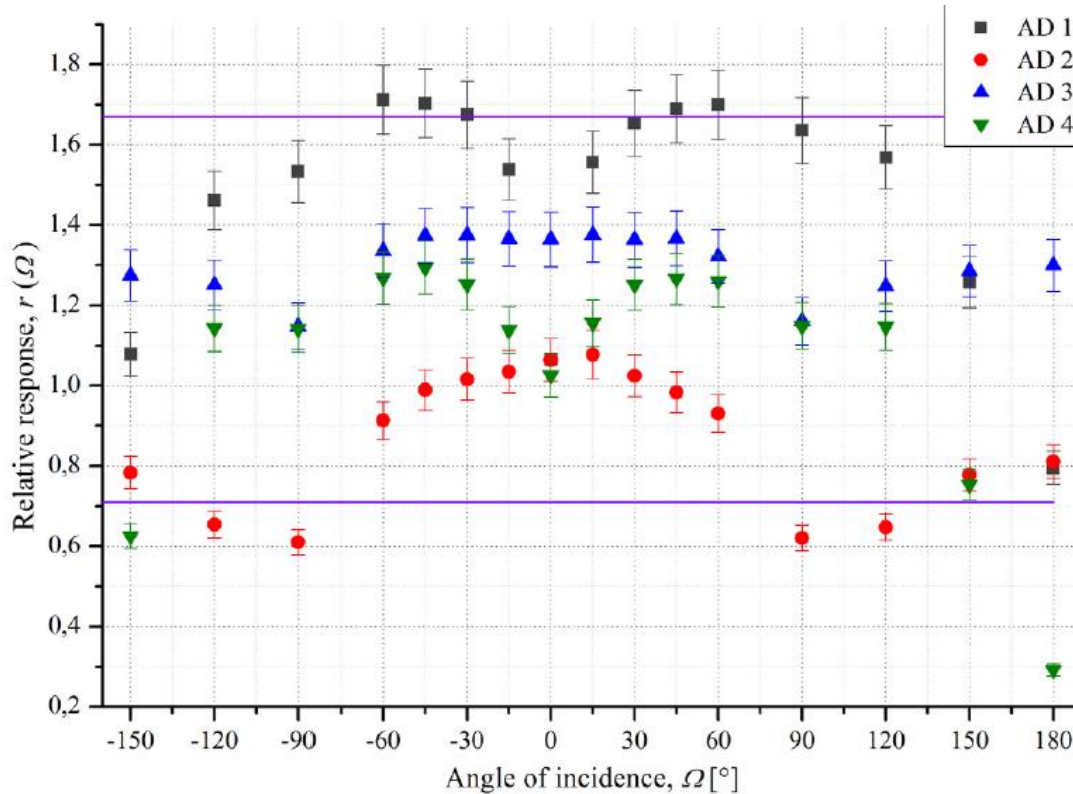


Figure 1-23. Angular dependence of active area environmental area dosimeters in the 2π geometry respective to the vertical axis of rotation. AD 1, 2 and 3 represent selected MINN models and AD 4 is a spectro-dosimeter (Krzanovic et al., 2022).

In papers by Coletti et al., 2017 and Cervone and Hultquist, 2018, Safecast non-governmental environmental area monitoring network dosimeters and data were evaluated. Following the Fukushima accident in 2011, Safecast project with the focus on collection and distribution of radiation monitoring data had started. The citizens started collecting data one month after the accident with hand-made radiation detectors. The project itself is crowdfunded and crowdsourced with more than 650 handheld active radiation detectors in 2016. The bGeigie Nano is an active area dosimeter based on a pancake GM tube (type LND 7317), which uses a gas mixture of neon and a halogen in its active volume. The device itself displays the count rate (in counts per minute, cpm) or in terms of ambient dose equivalent rate, $\mu\text{Sv/h}$. This MINN type was also included in the research by Morosh et al., 2021. Accuracy of data acquired by the detectors may strongly depend on the end-user due to assembly errors, which can happen despite the guidelines for use of bGeigie Nano dosimeter (Colletti et al., 2017). In paper by Colletti et al., 2017 it was shown that the Safecast MINNs can be used to detect radioactivity, improving the disaster response to radiation producing events, with data from Safecast network being correlated to the official data of U.S. Department of Energy (DOE) and the U.S. National Nuclear Security Administration (NNSA). In research by Cervone and Hultquist, 2018 methodology of calibration the Safecast dose rate meters was presented. The bGeigie Nano detector is preset to monitor Cs-137 radiation with a defined sensitivity to convert from cpm to the ambient dose equivalent rate in $\mu\text{Sv/h}$. A set of time-dependent calibration coefficients which consider decay correction for Cs-137, and the different ratios of isotopes Cs-134 and Cs-137 in the environment were presented. These coefficients allow for use of Safecast data with necessary corrections approximating the collected data to the DOE airborne measurements.

Papers by Wissmann and Saez Vergara, 2006, Neumaier and Dombrowski, 2014, and Dombrowski et al., 2017 have discussed the topic of environmental area monitoring with active area dosimeters in early warning networks. In the study by Wissmann and Saez Vergara, 2006, similar intercomparisons were performed by the EURADOS WG3 as to Morosh et al., 2021. In terms of photon energy influence quantity, instruments used in environmental monitoring may not be suitable due to the wide energy range of the background radiation components. It is explained that regular area monitoring instrumentation for radiation protection may not be suitable for measurements of secondary cosmic radiation since the source of these particles are the nuclear reactions of the primary cosmic radiation (protons and alpha particles of mean energies in the order of GeV), while in the case of the terrestrial radiation component, the energy range is well covered

by the test facilities. Inherent background test and calibration and low-dose rate levels, comparable to environmental radiation were done with the linearity test in the 10 nSv/h – 400 nSv/h dose rate range. Also, investigation of the response to secondary cosmic radiation and the simulation of the radioactive plume were done. The devices used in these intercomparisons were ionization chambers, GM tube-based detectors, proportional counters, and plastic scintillators. Neumaier and Dombrowski, 2014, have also discussed an EURADOS intercomparison in environmental monitoring, evaluating the performance of dose rate monitoring systems in official early warning networks across Europe, with the goal of harmonizing environmental area monitoring. The European Commission Joint Research Centre (EC JRC) coordinates and maintains the EURDEP system (European Radiological Data Exchange Platform). EURDEP database contains data on radiological air concentration and dose rate on an hourly basis. As explained in Morosh et al., 2021 as well, determination of the ambient dose equivalent rate originating from artificial radionuclides in the environment it is necessary to determine and subtract all other background radiation components (including inherent background, secondary cosmic radiation, and terrestrial radiation). Response to solely terrestrial radiation can be determined by performing calibration with the sealed Ra-226 in the controlled low-background environment (as is the case with UDO-II laboratory), while determination of inherent background and response to SCR was also discussed by Morosh et al., 2021. In general, over-response to SCR was recorded for different detector types (as also recorded in previous EURADOS comparisons, Wissmann and Saez Vergara, 2006), while most of the devices have good response to the terrestrial radiation component measured at the PTB free-field site (used for radioactive plume simulations). In Figs. 9 and 10 results of detector response to SCR and terrestrial radiation are presented, respectively. Like in the previous comparisons, the devices used were based on ionization chambers (IC), GM tubes (GM), proportional counters (PC), plastic scintillators (PSc) and spectro-dosimeters (SM). Besides the significant over-response of many tested devices to SCR, the spectro-dosimeter has a very pronounced under-response. Electronics of the spectro-dosimeter suppress most of the signals produced by muons, and these devices are in general unable to detect cosmic radiation.

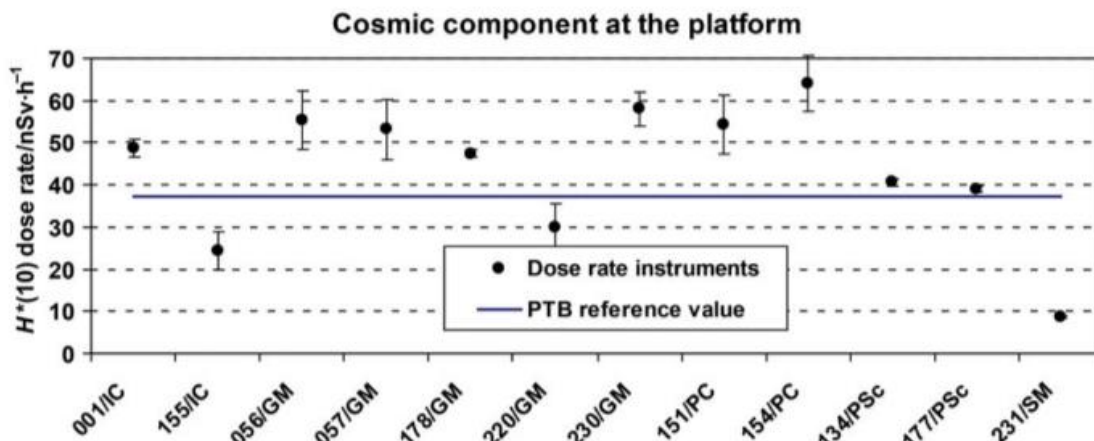


Figure 1-24. Secondary cosmic radiation response of different detector types used in official early warning environmental monitoring networks. The compared devices are based on ionization chambers (IC), Geiger-Muller tubes (GM), proportional counters (PC), plastic scintillators (PSc) and spectro-dosimeters (SM) (Neumaier and Dombrowski, 2014).

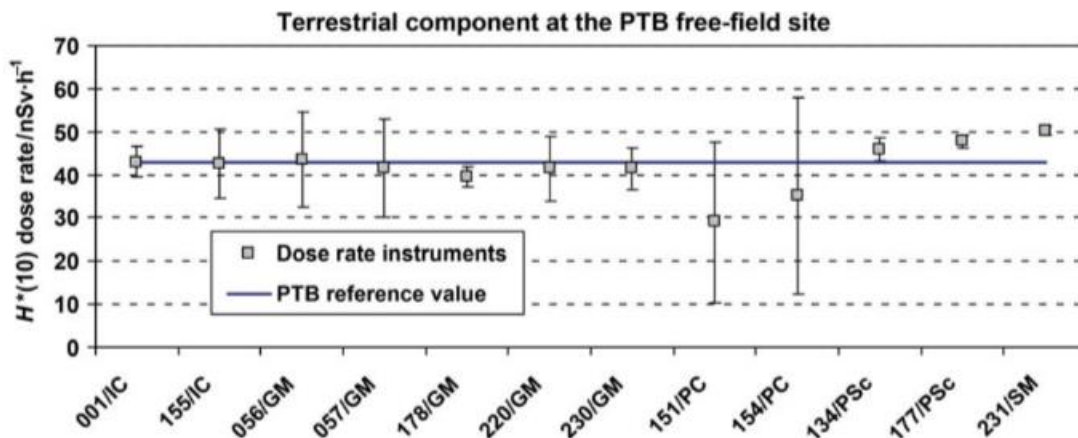


Figure 1-25. Terrestrial radiation response of different detector types used in official early warning environmental monitoring networks. The compared devices are based on ionization chambers (IC), Geiger-Muller tubes (GM), proportional counters (PC), plastic scintillators (PSc) and spectro-dosimeters (SM) (Neumaier and Dombrowski, 2014).

In environmental monitoring low-dose rates are of great interest but since very high dose rates (greater than 1 Sv/h) can be expected in the vicinity of nuclear facilities in case of emergency and high-activity radionuclides, which is why instrumentation of high sensitivity is suitable for such monitoring activities. Calibration of dosimetry systems intended for environmental monitoring with the Ra-226 source would yield most reliable results, due to its mean photon energy of approximately 1130 keV which corresponds to the environmental terrestrial radiation component (Neumaier and Dombrowski, 2014).

GM tubes are the most common instruments for early warning networks primarily due to their inexpensiveness, and a simple robust design which allows long operation times. In comparison, proportional counters, scintillation probes and ionization chambers produce more reliable dosimetry data with less pronounced energy dependence of the response but are more expensive and require more maintenance. Also, pressurized ionization chambers and scintillation counters have superior sensitivity, which is directly related to better measurement precision, compared to GM tube detectors which have relatively low counting statistics (Dombrowski et al., 2017). Recent developments in spectrometers which can measure dose rate in terms of ambient dose equivalent have led to more precise spectro-dosimeters with ideal sensitivity for environmental monitoring. Some of the commercially available spectro-dosimeters only give a rough estimate of the ambient dose equivalent derived from the recorded pulse-height spectra since they may use oversimplified algorithms for the conversion to $H^*(10)$. To achieve harmonization in early warning network monitoring instruments, certain dosimetric properties and requirements of standards need to be met. By using IEC 60846-1 requirements and test methods as the starting point, Dombrowski et al., 2017, have proposed recommendations on harmonization of environmental monitoring instruments. The requirements contain technical requirements for dose rate detectors, specific requirements for spectrometers which are to be used as dosimeters, early warning network distribution, data handling, as well as quality assurance (including calibration, intercomparisons, stability checks). Among other requirements on dose rate detector properties, influence quantities included in the recommendations are the dose rate measuring range, energy range of photon radiation, angular response, inherent background, temperature range and relative humidity and atmospheric pressure. Dose rate range which an environmental area monitor should cover should be at least from 10 nSv/h up to 10 mSv/h, except for monitoring in the vicinity of a nuclear reactor where the range should extend up to 10 Sv/h. Energy response in the photon energy range from 80 keV up to 3 MeV should be within (0.75; 1.54). If the detector is not near the radiation source in the environment low-energy photons would not have a significant contribution to the dose rate. Preferred active volume geometry in terms of angular response would be cylindrical or spherical, due to symmetry of the angular response which is important for environmental monitoring. Proposed relative response limits of variation are (0.95; 1.05) for the 2π plane around the vertical axis. For other directions the response should not exceed 1.54. The inherent background of the detector, in the absence of external radiation (to be estimated in a low-radiation environment, such as underground laboratory) would need to be less than 10 nSv/h.

Research by Friedrich and Hupe 2015, and Friedrich and Hupe 2018 is focused on examining performance of active area dosimeters used for area workplace monitoring in diagnostic radiology applications, specifically when exposed to pulsed X-ray radiation beams. Authorised radiation protection and quality control experts are required to measure ambient dose equivalent rate in the areas near the X-ray facility to determine supervised and controlled areas within the scope of a legal regulatory procedure. For this purpose, they must use area dosimeters which produce reliable dosimetry data. In Germany these instruments are nationally type-approved by the PTB according to the German measurement and verification act. To date, all available type-approved area dosimeters are only tested in continuous radiation fields, and therefore the

technical data of the measuring instruments are valid only for continuous radiation. In practice, however, most facilities use pulsed radiation X-rays. Ankerhold et al. 2009, published measurement results which show that nearly all active electronic area dosimeters do not measure reliably in pulsed photon radiation fields. Since becoming aware of this problem, the PTB has started research work in this field. The IEC/TS 63050 technical specification defines the tolerable variation limit of the response of the dosimeter in pulsed fields. Due to the pulsation of the radiation field the response shall not change by more than $\pm 20\%$. And the lowest acceptable value of the measurement range upper limit of a dosimeter shall be at least 1 Sv/h. To verify these requirements, tests should be performed by using at least for two dose rates: 20 % above the lower limit and 80% of the upper limit of the dose rate range stated by the manufacturer for pulsed radiation. For each dose rate, measurements should be performed with different pulse durations and should be repeated at least three times per measuring point. Four different $H^*(10)$ detectors were tested in the paper by Friedrich and Hupe, 2018. OD-2 is based on an ionization chamber, 6150 AD 6/E utilizes a GM tube and a 6150 AD-b/E probe which is an organic scintillator, FHZ 672 E-10 is a organic scintillator used with FH 40G-L10 main unit, and LB 1236-H10 is a proportional counter tube used with UMo LB 123 main unit. Detectors were tested both in diagnostic and radiation protection reference fields at 100 kV (being N-100 and RQR8). All of area dosimeters tested in this paper can be used for measurements in pulsed radiation fields in principle. But the parameters of the radiation field (especially the pulse duration and the dose rate per pulse) and the stated measurement ranges by the manufacturer must be considered.

Dose measurements in pulsed radiation fields with dosimeters using the counting technique are known to be inappropriate. Therefore, there is a demand for a portable device able to measure the dose in pulsed radiation fields. In research by Friedrich and Hupe, 2015, alternative devices for measurements in pulsed fields were explored. Using a designated secondary standard $H^*(10)$ ionisation chamber in combination with a reliable charge-measuring system could be a good alternative. Measurements were done using the HS01 chamber and UNIDOS electrometer, which show very good energy dependence for $H^*(10)$ (in a wide energy range from 12 keV up to 1.2 MeV). In addition, measurements have been performed with commercially available area dosimeters, Mini SmartION which is a digital survey meter based on a vented ionization chamber, and a Szintomat 6134 A/H with an organic scintillator with a photomultiplier. Detectors were tested at the pulsed X-ray facility of PTB using RQR8 and RQR9 radiation qualities. The response of the secondary standard remains within $\pm 1\%$ independent of the pulse duration. Decrease of the response is observed when doses per pulse are increased because of the volume saturation effects inside the ionisation chamber. Both area detectors exhibited good response, with operating ranges compared to the tests according to the ISO/TS 18090-1 technical specifications. These detectors have different limiting parameters based on their principle of operation. One is limited by the saturation (ion collection time), and other by the instantaneous dose rate (scintillation counts).

In the research by Zutz and Hupe, 2013, active area monitor performance was examined in the vicinity of linear accelerators (LINAC) used for radiotherapy. At high primary beam energies in the 10 MeV range, used for radiation therapy, the leakage dose of the accelerator head and the backscatter from the room walls, the air and the patient become significant. Therefore, radiation protection measurements of photon dose rates in the treatment room and in the maze are performed to quantify the radiation field. Since the radiation of the LINACs is usually pulsed with short radiation pulse durations in the μs range, active electronic dosimeters encounter issues in operating and in acquiring the dose rate data. The focus of this study is solely on the dose of photon radiation because the evaluation of the neutron and electron components requires additional considerations. The primary beam energy was set to 15 MeV, the field size of 40 cm \times 40 cm was used, with a pulse repetition frequency of 196 Hz (which is the maximum value). A water phantom was positioned in the iso-centre to simulate the influence of the presence of a patient. The ambient dose equivalent rate $H^*(10)$ was determined at various positions in the accelerator room which is built similarly to a medical treatment room. The accelerator delivers radiation pulses with a fixed pulse duration of 3 μs and a fixed dose per pulse of ~ 0.3 mGy. The results of the electronic dose rate meters demonstrate the inability of the tested devices (and probably all devices based on the pulse counting technique) to measure correct dose rates in this pulsed radiation field. The cause of failure is based on the measurement principle of these dosimeters. If the radiation pulse duration becomes close or smaller than the measurement cycle time of the dosimeter, the internal dead-time correction fails, and the device starts displaying wrong results. The active area dosimeters measured dose rates of approximately 0.4 mSv/h, while the $H^*(10)$ ionization chamber measured the dose rate of 15 mSv/h.

1.7 Spectro-dosimeters for ambient monitoring

In environmental monitoring and in early-warning networks knowledge on the type of radionuclide detected as well as the ambient dose equivalent rate is increasingly used in official data. Spectrometers which are characterized for area monitoring in the environment are increasingly used, besides regular active area dosimeters which are used for area monitoring either in the workplace or in the environment. These devices are also incorporated in official environmental area radiation monitoring networks. Devices which are inherently intended for spectrometry are also used for ambient dose equivalent rate measurements by developing conversion coefficients from the pulse height spectra to the operational dosimetry quantity, without utilizing physical filtration as in the usual detector design technology.

To examine potential use of spectro-dosimeters in the official radiation monitoring networks, Kessler et al., 2018 have evaluated the performance of scintillation probes based on LaBr_3 , CeBr_3 and SrI_2 by comparing their indication with well-characterized reference instruments for ambient dose rate measurements. This advancement of here mentioned scintillation detectors as spectro-dosimeters was done through the ENV57 MetroERM EMRP joint research project which also dealt with the topic of radiological early warning networks. These spectrometry systems exhibit acceptable energy resolution at Cs-137 of approximately 3 – 4 % (as opposed to 10 % resolution of NaI based spectrometers). Due to their smaller size, these detectors are also suitable for use together with unmanned airborne vehicles (UAVs) for airborne radionuclide and dose rate mapping (which is the subject of another EMRP joint research project, 16ENV04 Preparedness). Long-term outdoor measurement campaign was conducted to assess the effects of environmental influence quantities on spectro-dosimeter performance. Stability of these devices is mainly affected by the temperature dependence of associated photomultiplier. This dependence must be accounted for and corrected to achieve stable dose rate readings. Due to high efficiency of these detectors, they can well quantify the background radiation level, and to register changes in the dose rate less than 10 nSv/h. A part of angular dependence of the response is eliminated by having cylindrical detectors.

The ambient dose equivalent rate from a spectro-dosimeter is determined by obtaining the scalar product of the pulse height spectrum vector, \vec{n} , with the detector response vector, \vec{v} , i.e., $H^*(10) = \vec{v} \cdot \vec{n}$. A method proposed by Dombrowski, 2014, “Conversion of complete spectra without deconvolution” to determine the detector-specific conversion factors from the pulse height spectra to ambient dose equivalent, converts the counts of the recorded spectra directly into dose rate values. The spectrum is divided into several energy regions, where for each of the regions the coefficients are determined experimentally and by using Monte Carlo simulations. The energy regions should be selected having in mind general properties of radiation detectors, where the response curve usually drops significantly at energies below 80 keV and has a local maximum in the range from 80 keV to 100 keV, with the response curve being relatively flat above 1 MeV (Dombrowski, 2014). Experimentally determined conversion coefficients are estimated by using mono-energetic radiation sources such as Am-241, Co-57, Cs-137 and Co-60. The EGSnrc MC simulations were used to determine conversion coefficients for photon energies which are not practically achievable (e.g., 30 keV, 2015 keV, 3215 keV, etc.). Conversion coefficients are derived from the matrix equation $\vec{H} = \mathbf{N} \cdot \vec{v}$, where \vec{H} represents the vector with dose rate values from each of the monoenergetic radiation sources and \mathbf{N} represents the lower-triangular square matrix with the count rates of the spectra, where each row corresponds to a spectrum. The conversion curve can be determined by using a cubic smoothing spline fit from the *SciPy* package (Fig. 1) on the determined conversion coefficient values. Finally, the dose is calculated as the sum of the counts from each channel, n_j , of the multi-channel analyser (MCA) multiplied by the conversion coefficient, v_j , for each channel j individually, i.e., $H^*(10) = \sum_j v_j(E) n_j(E)$ (Kessler et al., 2017).

Similar methodology was used by Casanovas et al., 2016 to characterize a $\text{LaBr}_3(\text{Ce})$ scintillator to measure ambient dose equivalent rate. Comparison of $H^*(10)$ measured with spectro-dosimeter and a GM tube dosimeter in long-term environmental monitoring was done. The conversion coefficients from fluence to the operational quantity were estimated through Monte Carlo simulations with EGS5 code. Similar conversion coefficients were estimated as presented in Fig. 1 by Kessler et al., 2017.

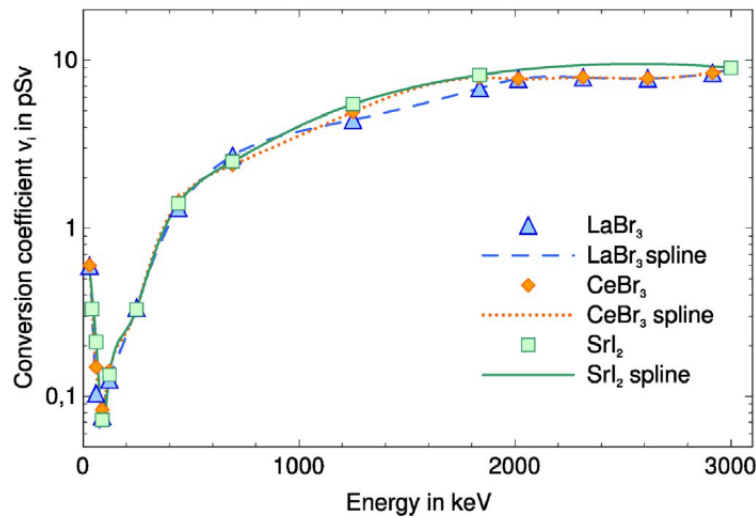


Figure 1-26. Conversion coefficients from recorded pulse-height spectra to the ambient dose equivalent for three spectro-dosimeters, based on LaBr_3 , CeBr_3 and SrI_2 (Kessler et al., 2017). The conversion curves are estimated for each spectro-dosimeter by performing a SciPy cubic smoothing spline fit.

The performance tests done by Kessler et al., 2018 include background radiation level measurements at the underground laboratory UDO-II, response to the secondary cosmic radiation at the platform on a lake and the free-field measurements with radioactive sources. All these facilities are operated and maintained by PTB. Inherent background was determined at UDO-II underground and in a lead castle above the ground. The values obtained in these two environments are comparable for each of the detectors, with differences of approximately 1 nSv/h. These detectors display a very low response to SCR with indication of approximately 3 nSv/h, while the reference dose rate of SCR background component is 32.2 nSv/h. In the free-field setup the dose rate values measured with spectro-dosimeters were compared to the Reuter-Stokes high pressure ionization chamber RSS-131. The results of this comparison are displayed in Fig. 2.

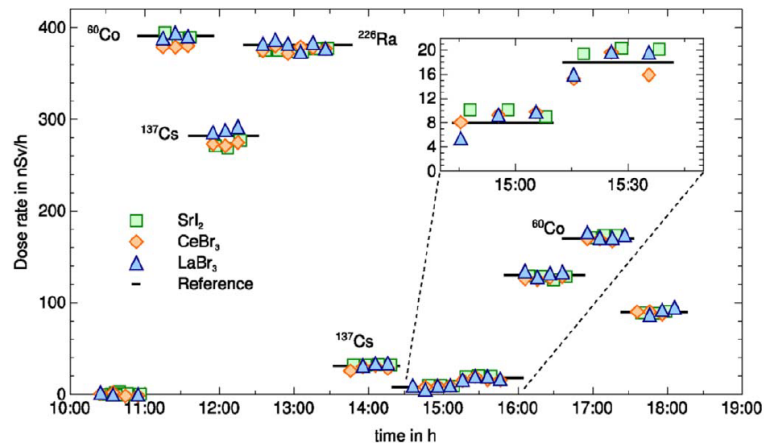


Figure 1-27. Results of the ambient dose equivalent measurements with three spectro-dosimeters compared to the reference Reuter-Stokes RS-131 high pressure ionization chamber (Kessler et al., 2018).

In research by Kessler et al., 2017 and Kessler et al., 2016, three scintillation-based spectro-dosimeters (LaBr_3 , CeBr_3 and SrI_2) and a semiconductor based CdZnTe spectro-dosimeter were characterized. The CdZnTe spectrometer is of cubical geometry and has a smaller volume compared to the scintillation detectors. Radioactive sources which were used to characterize the spectro-dosimeters with their respective photon energies were Am-241 (60 keV), Cd-109 (88 keV), Co-57 (122 keV), N-300 (247 keV), Ir-192 (296 keV, 308 keV, 316 keV, 468 keV, 604 keV), Cs-137 (662 keV), Co-60 (1173 keV and 1333 keV) and Y-88 (898 keV and 1836 keV). For each of these radiation sources an energy region was determined in a way that the peak energy (or the mean energy in the case of N-300 X-ray radiation quality), was set approximately in the median of the energy range (e.g., 96 – 148 keV for Co-57). Angular dependence of the spectro-dosimeters was evaluated in the Am-241 and the Cs-137 radiation fields. In the high energy radiation field, the angular dependence is less pronounced, and for the Am-241 radiation field the radiation absorption in the metal shielding of the

photomultiplier causes pronounced angular dependence. This dependence is more pronounced for CeBr₃ compared to LaBr₃. The angular dependence is displayed in Fig. 3.

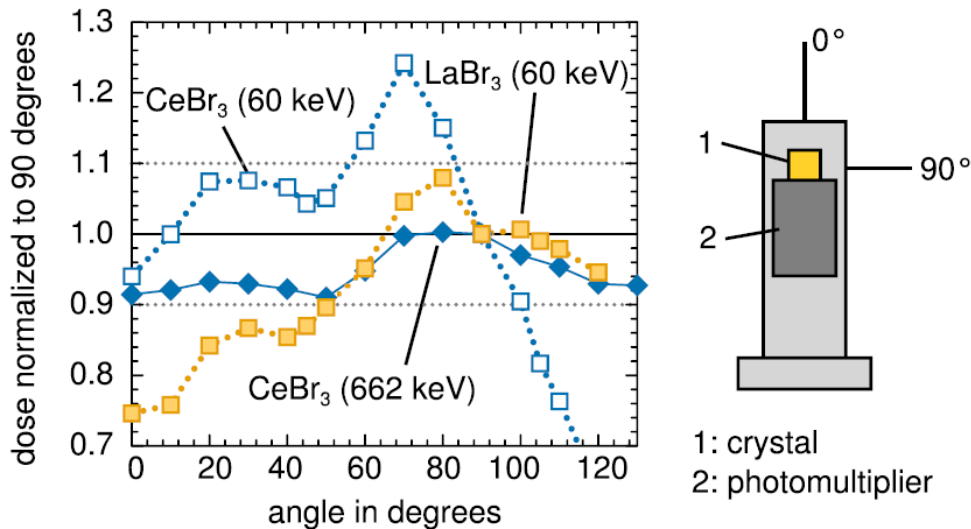


Figure 1-28. Angular dependence of spectro-dosimeters for high energy Cs-137 (662 keV) and low energy (Am-241) radiation fields. Angular dependence is more significant at low photon energies mainly due to the shielding of the PM (Kessler et al, 2017).

Dividing the spectra of spectro-dosimeters to 8 energy regions is sufficient to calculate the ambient dose rate from the recorded pulse height spectra (Kessler et al., 2017). CeBr₃ system is advantageous compared to other spectro-dosimeters since it has low inherent background, a sufficient energy resolution (especially at high photon energies). For the higher dose rates use of CdZnTe could be better since it has lower response. LaBr₃ system has better energy resolution than other systems but is difficult to be used at low photon energies and at low dose rates due to its high inherent background. SrI₂ has limited maximum dose rate that can be measured, therefore requiring use of advanced multichannel analyser. In Fig. 4 inherent background of these four detectors is presented (Kessler et al., 2016). For a detector to be suitable for early warning networks it should have a good energy resolution in the order of 3 % (or better) to successfully identify typical radionuclides released into the environment following a nuclear accident. Spectrometers should also have high sensitivity being able to measure increased radionuclide activity in the soil. Also, the detectors should be less robust, which excludes conventional high purity germanium detectors (HPGe).

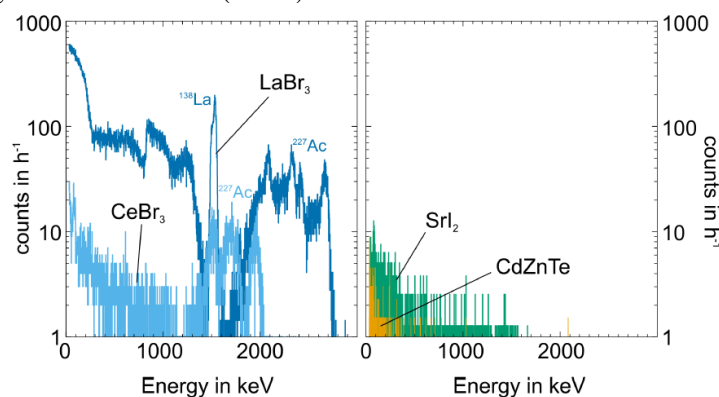


Figure 1-29. Inherent background of four spectro-dosimeters measured at UDO-II. LaBr₃ and CeBr₃ detectors have more pronounced inherent background due to radioactive contamination with La-138, Ac-227 and Ac-227 respectively. SrI₂ and CdZnTe display lower values of inherent background (Kessler et al., 2016).

Röttger and Kessler, 2019, have presented characteristic limits and uncertainties for low dose rate measurements with CeBr₃ spectro-dosimetry system compared to the HPIC (high-pressure ionization chamber) which is used a reference standard instrument. It was observed that the uncertainty of CeBr₃ spectro-dosimeter is on par with the HPIC, being very close to the uncertainty of the reference values. In addition, if special data evaluation is done the spectro-dosimeter may even be qualified as a modern secondary standard for low dose rate measurements, providing both ambient dose equivalent rate and radionuclide information. If the ambient dose equivalent rate from pulse height spectrum is determined

as a scalar product of two vectors (i.e., $H^*(10) = \sum_j v_j(E) n_j(E)$) (Kessler et al., 2017), the measurement uncertainty of $H^*(10)$ can be presented as $u(H^*(10)) = \sqrt{\sum_j (v_j \cdot u(n_j))^2 + (n_j \cdot u(v_j))^2}$. The uncertainty of number of counts at channel $u(n_j)$ is estimated with Poisson distribution, while $u(v_j)$ is estimated by analysing the conversion function uncertainties. The conversion function for the CeBr₃ detector is a sum of two exponential functions out of which one is related to the lower energy region and the other to the high energy photons, $v(E) = a \cdot e^{-b \cdot E} + c \cdot (1 - e^{-d \cdot E})$. Besides these two functions, two saturation functions are used to achieve a better fit of the curve (Fig. 5).

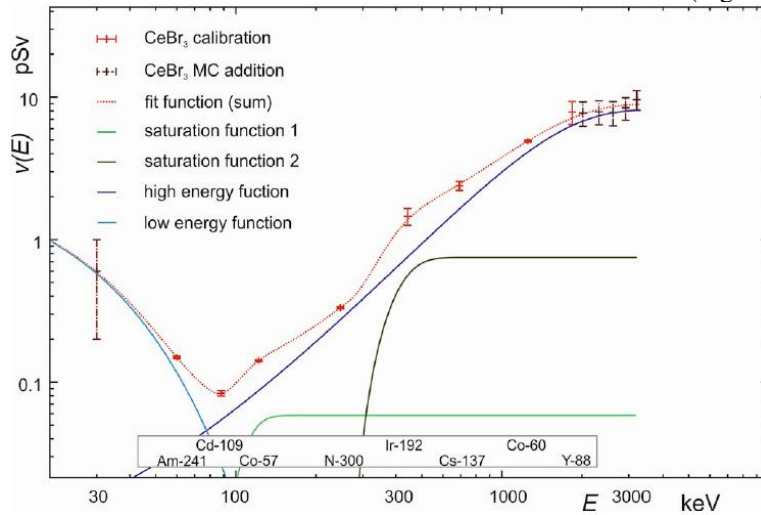


Figure 1-30. Energy dependent conversion function of the CeBr₃ spectro-dosimeter (Röttger and Kessler, 2019).

1.8 Passive dosimetry systems for ambient monitoring

Besides being widely used in individual monitoring at different ionizing radiation applications, use of passive dosimetry for area environmental monitoring was also explored in several papers. In the IEC 62387:2020 standard this need is recognised and specific response limits of variation for environmental area monitoring are defined. The research done by Knezevic et al., 2021 and Stankovic Petrovic et al., 2021 was done within the scope of I6ENV04 Preparedness project.

In paper by Stankovic Petrovic et al., 2021 a comprehensive review on the use of TL dosimetry methods for monitoring radiation dose in the environment was done with intention to harmonize procedures used by dosimetry services, relevant authorities, and Institutes across Europe. Differences in performing specific steps such as preheating, reading, annealing, minimizing fading, and others, are analysed. The conclusion of this work is that TL-based dosimetry measurement system must be type-tested even though the testing procedure is complicated. In addition to this, control dosimeters should be introduced, ISO protocols should be followed during system calibration, and finally, parameters influencing the measurement uncertainty must be identified and well understood in order to produce accurate dose measurement results. Various passive dosimeters, mainly TLD, are used for environmental monitoring in Europe. Other dosimeters such as optically stimulated dosimeters (OSLD), photographic film, radio photoluminescent dosimeters (RPLD) or electret ion chambers are also used. The published surveys and available data represent the main sources of information about different measurement systems that are in use, as well as the statistics of the applied dose correction methods. The monitoring process is very complex due to many influence quantities, some of which are the intrinsic properties of the system, and the others are consequences of the chosen monitoring procedures and steps. In order to overcome the complexity of problems related to environmental monitoring, several actions can be implemented, namely: (1) select/use dosimetry systems with proven intrinsic properties and with detection limits appropriate for the intended use, (2) conduct type tests for dosimetry systems that ensure that the requirements set by environmental monitoring international standards such as IEC 62387:2020 are met, (3) irradiations should be done in irradiation conditions compliant with ISO 4037:2019 standard series, (4) appropriate monitoring period should be defined for control dosimeters (to correct for fading and additional transit exposures), (5) use more than two dosimeters at each measurement site, (6) keep transit dose to a minimum, by reducing transit time, storage time before use and storage time before evaluation, (7) identify and assess all significant contributions to measurement uncertainty. Wide dose range can be measured, including those relevant for environmental radiation dosimetry, where low doses are of interest. Good understanding of the influence factors on the accuracy of dose measurements is required to optimize and harmonize TLD environmental monitoring procedures.

It should be noted that, specifically if passive dosimetry systems are used for area workplace monitoring, it can happen that the calibration conditions (which are performed free in air), can differ from the conditions under which dosimeters are used (where dosimeters are mounted on a wall). This discrepancy is not always regulated by the holder design.

Duch et al., 2017, have evaluated the status of passive dosimetry systems used in Europe by conducting a survey throughout which information on the main radiological characteristics of these systems was collected (including the measuring quantity, radiation type, type of detectors used, number of issued dosimeters for the monitoring period, rated ranges in terms of dose and energy, and the preferred term for such dosimeters). In environmental monitoring the transport dose can be a major contributor to the overall measured dose (if the transit period is high compared to the respective monitoring period, it can account for up to 35 %). Monitoring services which utilize passive dosimeters participate in intercomparisons as a means of quality assurance. Data on participation in such intercomparisons, traceability to national standards, national type approval and compatibility with relevant IEC 62387 and ISO/IEC 17025 standards was gathered. A total of 47 institutions from 24 countries took part in the survey. Out of all the passive detectors for environmental monitoring, TLDs are used in 83 % of surveyed monitoring services, while OSLDs and RPLDs are used in 3 % and 7 %, respectively. DIS hybrid dosimeters are used by 3 % monitoring services. Most used TLD materials are LiF:Mg,Ti (40 %) and LiF:Mg,Cu,P (34 %). The average lower energy limit of detection was 29 keV for all dosimetry services, with some of the services reporting energy of 5 keV and some 100 keV.

In paper by Knezevic et al., 2021, several types of passive dosimetry systems were tested for the effects of radiation-based influence quantities (photon energy, angle of incidence and non-linearity) to evaluate their performance in omnidirectional poly-energetic fields which soundly represent real radiation fields encountered in environmental monitoring. Different detectors, as well as different detector holders, passive dosimetry system calibrations, measurement procedures and uncertainties can lead to difference in measured data, therefore requiring harmonization of passive dosimetry systems. Even though TLDs are prevalently used in environmental monitoring, OSLDs, RPLDs and Film dosimeters are also employed for these applications. In this study 9 out of 12 systems used different types of TLDs, while the remaining 3 systems utilize OSL, RPL and film dosimeters. Even though the IEC 62387 standard defines the criteria and limits of acceptability for passive dosimetry systems, there are no general guidance and recommendation documents for routine measurement procedures in environmental monitoring, and the most data in literature on this topic originates from intercomparison exercises between different monitoring systems. The passive dosimetry detectors are usually allocated in a suitable holder with plastic and metallic filters to provide adequate filtrations for measured quantity, and which also

serves as a protection from environmental ambient conditions. Response to the radiation-based influence quantities can be influenced by dosimeter design, especially by energy compensation filter in the holder. Response non-linearity was checked in the dose range from 0.18 mSv to 1.2 Sv. Statistical uncertainty of the passive dosimetry systems' response was under 10 % for most of the systems, while some of them exhibited higher uncertainty (even up to 24 % for one system). Non-linearity of the response is presented in Fig. 1.

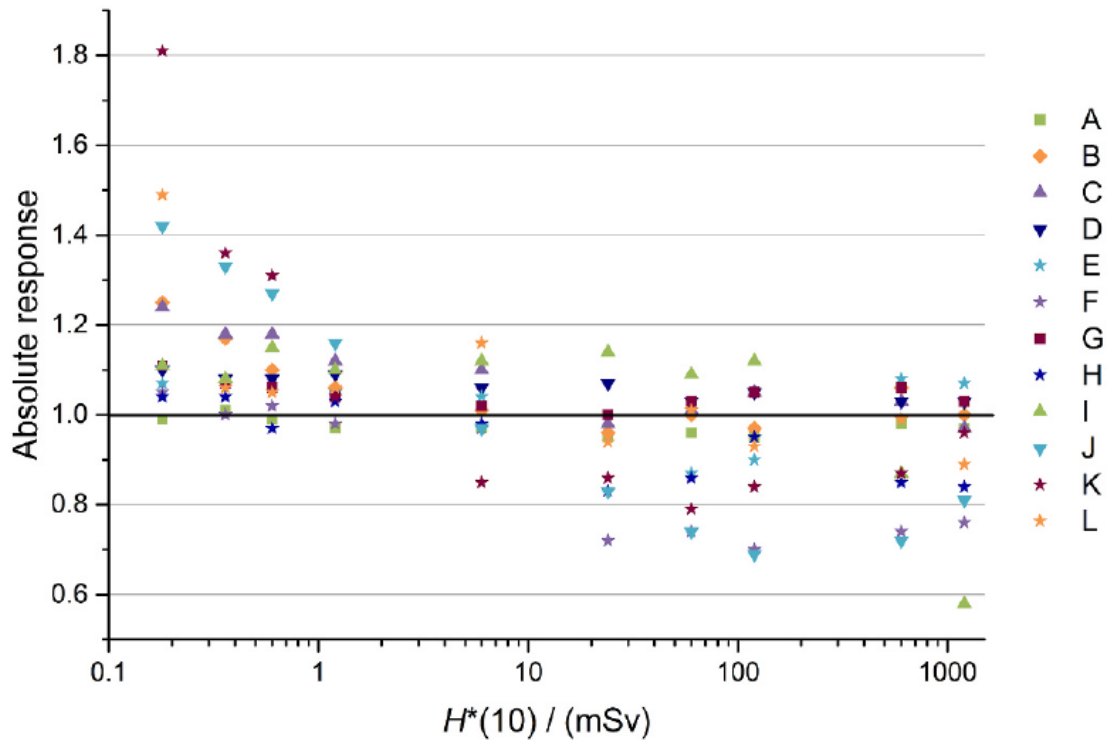


Figure 1-31. Non-linearity of passive dosimetry systems response in a wide range of dose rates encompassing low-dose values characteristic for environmental area monitoring for 12 different systems (TLD, OSLD, RPLD, Film) (Knezevic et al., 2021).

Angular response was tested for 0°, 30°, 60°, 90° and 180° angle values, and energy response in the photon energy range N60 - N300 with S-Cs, S-Co. Besides the IEC defined influence quantity tests, response of passive dosimetry systems to natural background radiation spectrum was evaluated. The angular response was evaluated at the S-Cs radiation quality where the largest deviation of response was observed for 90°. This deviation was not very pronounced since Cs-137 photons are of high energy and do not induce significant angular dependence of the response. While angular response deviation between 0.8 % and -4.5 % is an excellent result, its limitation is that only evaluation in the high energy radiation field was done. Three dosimetry systems comply with the standard in the whole test range of photon energies and have statistical uncertainties from 1 % up to 10 %. Four systems comply with the standard limits of variation if the measurement uncertainty of the reference values is used to expand the limits. These systems had higher statistical uncertainty compared to the previous three. Two systems had pronounced under-response at low-photon energies and two systems (one based on film dosimeters and the other based on TLDs with CaF₂:Mn and LiF:Mg,Cu,P) had a very pronounced over-response (even up to +118 %). Response to environmental radiation was evaluated by using a sealed Ra-226 source. Most systems exhibited under-response within 20 % (Fig. 2).

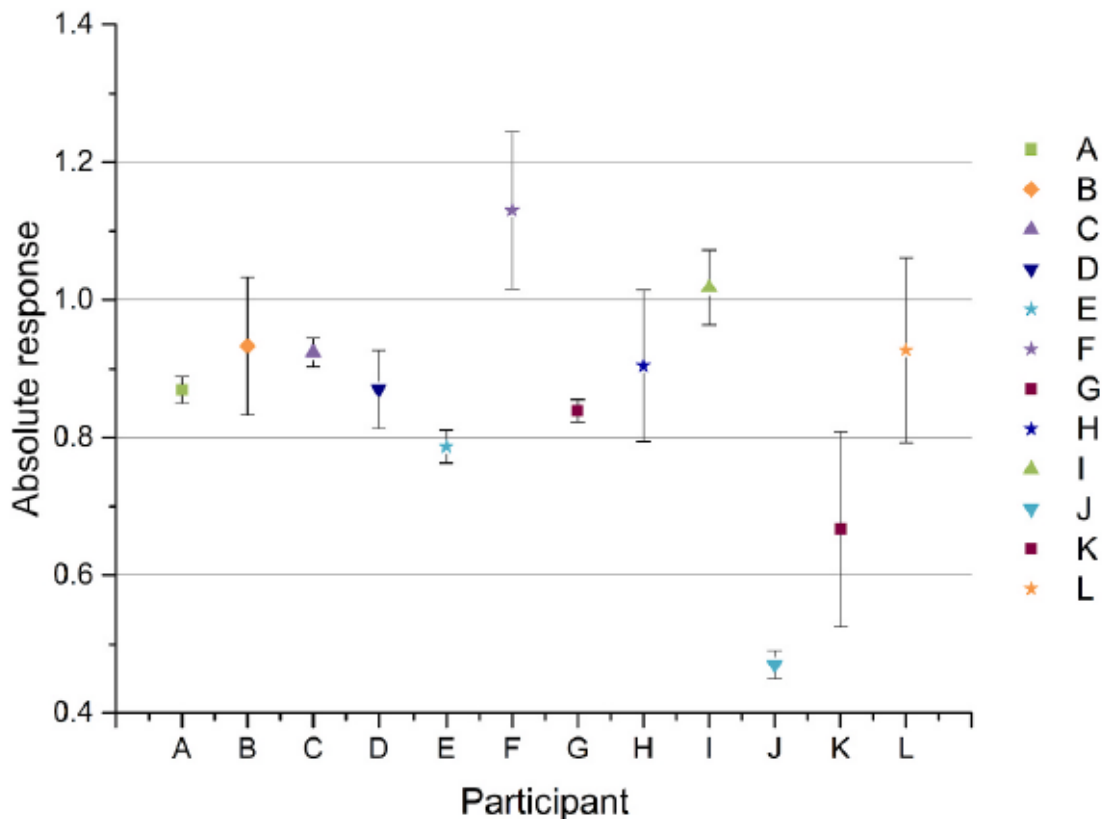


Figure 1-32. Response of passive dosimetry systems to environmental spectrum with Ra-226 source (Knezevic et al., 2021).

Overall passive dosimetry systems are suitable for environmental monitoring as well as following a nuclear accident. Out of 12 tested systems OSL and RPL based systems had excellent performance in all tests. Influence of detector holder on the response was also mentioned by Knezevic et al., 2021, and that since the holder itself is not classified as an influence quantity, detector assembly which consists of the detector and associated holder should be tested, and variation in holder may significantly affect the response of the detector within. This result is also presented in research paper by Krzanovic et al., 2023.

In papers by Dombrowski and Neumaier, 2013, and Dombrowski et al., 2017 results of intercomparisons of passive dosimetry systems for $H^*(10)$ measurements are presented. Dombrowski and Neumaier, 2013, have discussed the performance of passive dosimetry systems for long-term environmental monitoring under real environmental conditions in complex natural radiation fields. The dosimeters were exposed to environmental radiation long-term (periods of typically six months) at three reference sites operated by National Metrology Institute of Germany (PTB), the free-field measuring site, platform on a lake and the underground laboratory. These facilities were used to evaluate response to different background radiation components. The long-term intercomparison revealed the fact that, above all, the instability of passive measuring systems could lead to an insufficient reproducibility of the results. In practice, this might lead to the problem that a decision is not possible as to whether permissible limits are met at a special nuclear facility or not. Even though passive dosimetry systems had good agreement with the reference values (with deviations being less than 20 % in most cases), the fluctuations in the response lead to the conclusion that time periods longer than 3 months are not recommended for area environmental monitoring. The discrepancy in measurement results between some systems under the same irradiation conditions should be addressed by regular intercomparisons to harmonize the calibration factors of passive dosimetry systems.

In research by Dombrowski et al., 2017, the EURADOS intercomparison study of 32 passive dosimetry systems for area monitoring revealed several key findings. This intercomparison was conducted due to broad use of environmental area dosimeters for monitoring in vicinity of nuclear facilities and accelerators. The same facilities were utilized for this comparison as in Morosh et al., 2021 for active area monitors used in non-governmental networks. Sets of dosimeters were exposed to environmental radiation with joint effect of terrestrial (TR) and secondary cosmic radiation (SCR) for an extended period (either 3-month or 6-month period), to solely cosmic radiation, to a Cs-137 radiation field. The transport dose was determined by placing a batch of dosimeters in the UDO-II underground laboratory, where the

background radiation level is very low. Results of long-time exposure of passive dosimeters to environmental radiation (SCR + TR) are displayed in Fig. 3 for the irradiation period of 3 months (left) and 6 months (right).

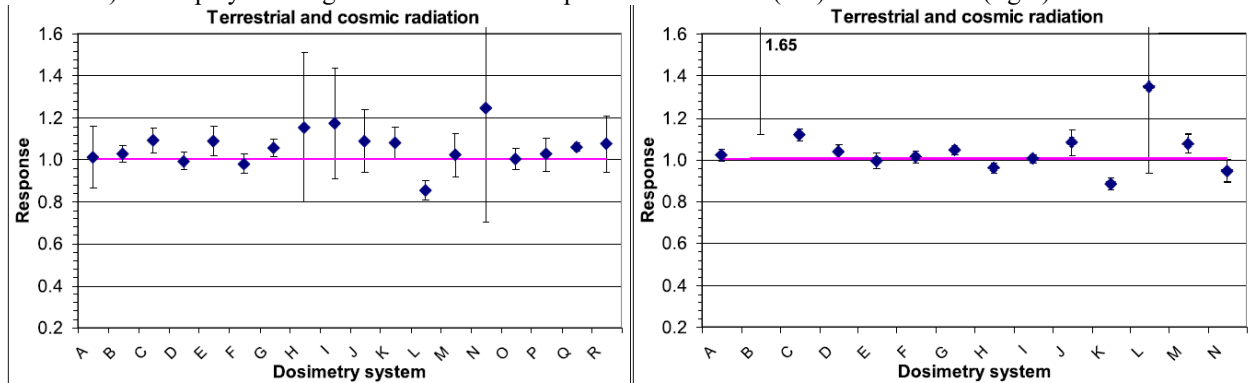


Figure 1-33. Response of passive dosimetry systems to long-term exposure to terrestrial and secondary cosmic radiation background components: 3-month exposure (left) and 6-month exposure (right) (Dombrowski et al., 2017).

Calibration of the passive dosimetry systems, their response to terrestrial radiation and response to cosmic radiation emerged as major influencing parameters on reported results in the intercomparison. Quantitatively, response assessments to Cs-137 photon beam irradiation indicated a slight tendency towards under-response, with most calibration factors being within $\pm 20\%$ around the reference value. Similarly, responses to combined terrestrial and cosmic radiation predominantly fell within $\pm 20\%$ around the reference value, suggesting over-response to environmental radiation (Fig. 3). Tested passive dosimetry systems exhibited a notable over-response to secondary cosmic radiation while tending to underestimate terrestrial radiation. Transport doses, while relatively lower than doses measured on reference sites, still varied notably. Estimated detection limits for uncovering additional artificial radiation in the natural environment ranged from approximately $22\ \mu\text{Sv}$ for 3-month measurements (corresponding to 20 % precision) to $11\ \mu\text{Sv}$ for 6-month measurements (corresponding to 10 % precision). Based on these data the passive dosimetry systems are not suitable for detection of excess dose rate (due to artificial radiation sources in the environment) of $0.1\ \text{mSv/a}$. This dose rate is 10 % of the permissible effective dose limit of $1\ \text{mSv/a}$ for the public as per 2013/59/Euratom directive (Dombrowski et al., 2017).

Assenmacher et al., 2020 have evaluated radiation-based characteristics of a passive dosimetry system for environmental monitoring based on radio photoluminescence dosimeters (RPLDs). The tested detectors utilize silver doped phosphate glass, $\text{P}_4\text{O}_{10}:\text{Ag}^+$. This material is commercially used for individual monitoring and measurement of personal dose equivalent. Energy dependence of these dosimeters was tested in a range of photon energies between 12 keV (which is the mean energy of N-15 radiation beam) and 1250 keV (mean energy of S-Co, Co-60 radiation quality). The energy dependence for measurement of both personal and ambient dose equivalent is presented in Fig. 4. Data on $H_p(10)$ measurements from Assenmacher et al., 2017 are shown for comparison. Relative response of the dosimeter satisfies legal requirement in Switzerland, being deviation of response less than 30 % for ambient dose equivalent in the energy range from 50 keV up to 5000 keV (at least up to 1250 keV). Having in mind the IEC 62387 requirement for energy response (-29 %; +67 %), the dosimeter complies with this standard as well.

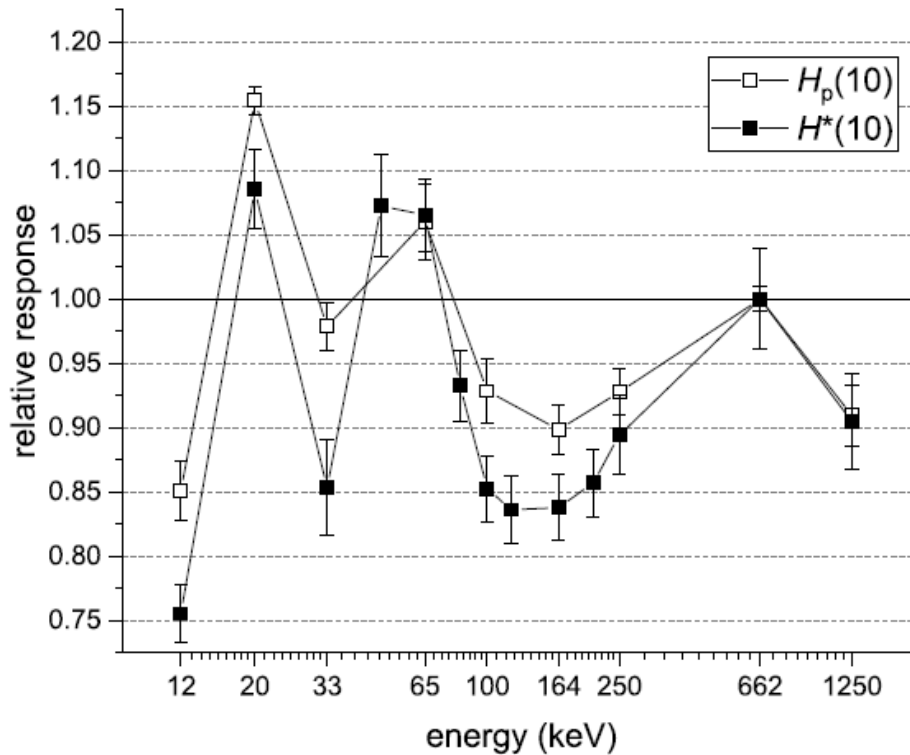


Figure 1-34. Energy dependence of the $P_4O_{10}: Ag^+$ based RPLD in a wide photon energy range including N-15 - N-300 and S-Cs, S-Co radiation qualities. Values of energy dependence in terms of personal dose equivalent are displayed for comparison (Assenmacher et al., 2020).

Angular dependence of the response was determined for the Cs-137 (reference) radiation quality and the low-energy X-ray N-80 radiation quality. The angular dependence was evaluated for both dosimeter orientations (horizontal and vertical). Angular dependence of the response for N-80 radiation quality is presented in Fig. 5. It should be noted that the angular response was normalized to the 0° value determined for the N-80 radiation quality, which is not in line with the test methodology of IEC 62387, where the reference conditions are the S-Cs radiation quality and 0° angle of incidence. Besides horizontal and vertical orientation angular dependence measurements, a „full rotation“ response evaluation was done. This test considers rotation of the dosimeter around its reference direction starting from 90° while being irradiated in eight fractions (with the angle of incidence steps of 45°).

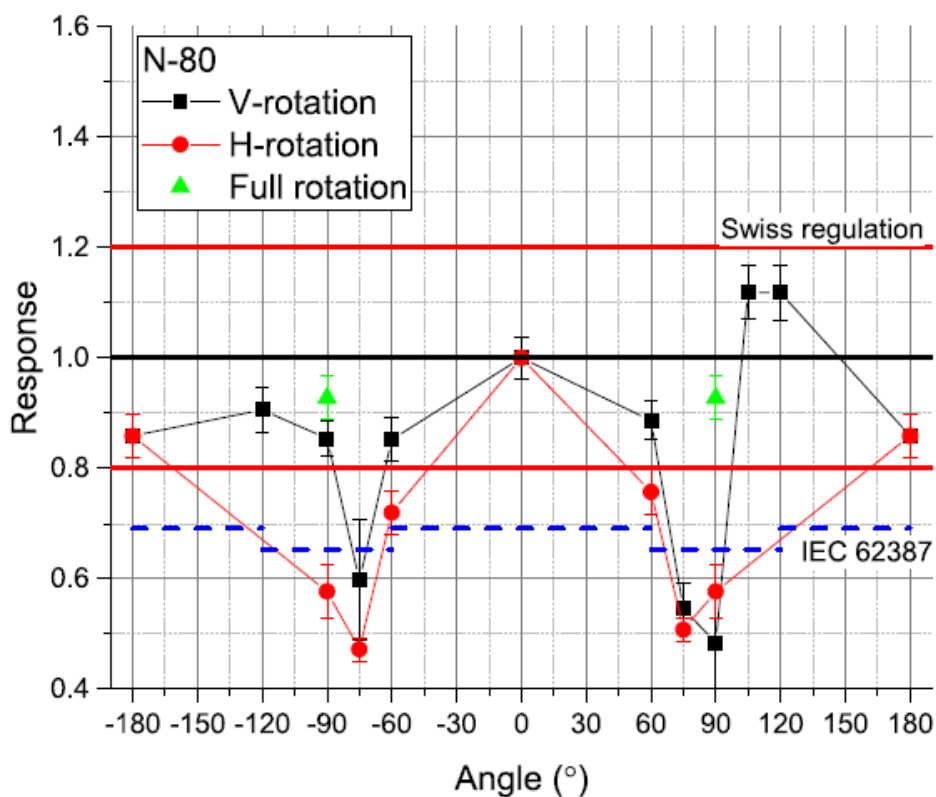


Figure 1-35. Angular dependence of the P_4O_{10} : Ag^+ based RPLD for the N-80 radiation quality. The test was done for horizontal and vertical dosimeter orientation, as well as for “full rotation” (Assenmacher et al., 2020).

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2 Analysis of Aggregated Calibration Data on Energy and Dose Rate Dependence of Radiation Protection Dosimeter Response

Most used radiation protection dosimeters were identified for individual and area workplace monitoring. Five of the most used active dosimeter models (AADs and APDs) in a total of 13 different countries were identified based on the aggregated data from dosimetry calibration laboratories. By far, EPD G/Mk (Thermo Fisher Scientific, USA) and DMC 3000 (Mirion, USA) are the most common APD models, being among the most used in 9 and 8 countries, respectively. Somewhat less common are the PM1610 (Polimaster, Lithuania) and DMC 2000 (Mirion, USA), which are among the most common in 5 countries each, and EPD TruDose (Thermo Fisher Scientific, USA) and RAD-60S (Mirion, USA), being among the most common in 4 countries. In the case of AADs, the most common area workplace dosimeter is FH40 (Thermo Fisher Scientific, USA), which was on the list in 8 countries. Radiagem 2000 (Gammadata, Sweden) and RadEye G10 (Thermo Fisher Scientific, USA) are also quite common dosimeter models, being among the most used in 5 countries each, followed by AT6130 (Atomtex, Belarus), 6150 AD (Automess GmbH, Germany), AT1121/AT1123 (Atomtex, Belarus) and RadEye B20 (Thermo Fisher Scientific, USA), all being among the most common in 4 countries. Other notable models which are among the most common in some of the surveyed countries include PM1703 (Polimaster, Lithuania), identiFINDER (FLIR, USA) and AT1117M (Atomtex, Belarus). Dosimeter models for workplace monitoring are portable devices, out of which some can be used with different probes based on the end-user needs and some are designed as pocket devices, which in design might resemble APDs, but measure ambient dose equivalent instead. Based on the data presented in the survey, a larger number of different dosimeter models is used in the case of workplace monitoring compared to individual monitoring. Moreover, EPD TruDose and DMC 3000 represent successor dosimeter models of EPD G/Mk and DMC 2000, respectively.

A paper focused on the analysis of aggregated calibration data was drafted and submitted to a peer-reviewed journal. The paper presented the calibration data which was interpreted as the non-linearity test and the energy dependence test. As this manuscript has not been published at the time of the publication of the Deliverable, it is not presented as its part.

3 Identification of missing data about current state of the art and performance of commonly used dosimeters

Research papers included in the conducted literature review (**A3.2.1**) related to radiation protection dosimetry with active and passive dosimetry systems, can be categorized into individual and area monitoring topics. In the case of individual monitoring most of the research papers, for both active electronic personal dosimeters and passive dosimetry systems, were focused on radiation protection of professionally exposed workers in medical applications of ionizing radiation. Besides discussing the performance issues at low-photon energies characteristic for diagnostic radiology procedures, the evaluation of performance under clinical conditions, involving pulsed radiation fields, was also highlighted. Calibration of radiation protection dosimeters (both active dosimeters and associated readers of passive dosimeters) is typically performed by utilizing the radionuclide reference radiation fields (Cs-137 and Co-60), realized according to ISO 4037:2019 and as such abbreviated as S-Cs and S-Co. Dosimeter performance in the reference radiation fields which have clearly defined photon energies can be quite different if a dosimeter has a pronounced dependence of response to variation of photon energy. Along with this influence quantity, angle of incidence also plays an important role at lower photon energies. These two quantities can be used to describe different irradiation conditions in real radiation fields and can be used to test the dosimeter performance under laboratory conditions. Such tests are defined in the relevant IEC standards and some of the research papers have focused on evaluation of the dosimeter performance according to the defined criteria. Non-linearity also becomes an important influence quantity at very high dose rates specific for medical procedures and pulsed radiation fields. In the section on individual monitoring the performance of different hybrid dosimeters was also researched, since these dosimeters present a novel approach in individual monitoring, utilizing the advantages of both active and passive dosimeters, while having satisfactory response to radiation-based influence quantities. Papers on area monitoring were more focused on the active and passive dosimeters which are used for environmental area monitoring, in the light of post-accidental situations and the detection of artificial radioactive material released into the environment. Performance analysis of different types of instruments utilized in non-official radiation monitoring networks was done. Issues with their performance were identified, in terms of energy dependence of the response, reflected in insufficient energy compensation of the detection volume. Besides evident performance issues, different test methods were explored, adapted to the specific irradiation conditions encountered in environmental monitoring, along with different limits of variation which are not properly addressed in the standards, whereas the present area workplace monitoring test methods and limits are not applicable. With the focus on environmental area monitoring, the possibility of use of well-characterized spectro-dosimeters was also evaluated, where these devices would significantly improve the quality of acquired dosimetry data throughout the monitoring networks. Possible missing data from the literature review may be insufficient data on the performance of hybrid dosimeters and spectro-dosimeters, being novel technologies in radiation protection, in terms of radiation-based influence quantities. Also, evaluation of new data on performance of various models of active electronic dosimeters in area and individual monitoring would further improve and confirm the present findings.

Identification of most commonly used active dosimeters for individual and area monitoring in the region of Europe was done (**A3.2.2**). For some of the identified dosimeters models the data on their calibration from different Secondary Standard Dosimetry Laboratories (SSDLs) was collected. The analysis of aggregated calibration data has shown that in most laboratories which perform calibration of radiation protection dosimeters, the data on non-linearity could be gathered, since as previously mentioned the dosimeter calibration on the radiation protection level is usually performed in S-Cs or S-Co radiation fields. On the other hand, data on energy dependence of dosimeters cannot be collected for many dosimeter models. The collected data could sometimes be interpreted as unreliable, due to the small sample size. Also, not many laboratories provide calibration of dosimeters at various photon energies. In calibration the effect of angle of incidence is not considered, as calibrations are regularly performed at the 0° angle of incidence. Based on the aggregated calibration data, additional measurements should involve collection of data on energy and angular dependence of the radiation protection dosimeters' response at different photon energies and angles of incidence.

To further assess the current state of the art, several models of both individual and area IEC compliant radiation protection dosimeters from different renowned manufacturers were identified (**A3.2.3**). Acquisition of the data on their performance in terms of response to radiation-based influence quantities is in general not obtainable. The data is often confidential and unavailable as it is the part of the type approval procedure. Information on compliance with relevant type testing standard proves that these dosimeters are in line with the performance requirements, but do not provide additional insights into the performance itself. In the discussion with the manufacturers it was concluded that the information presented can differ between the manufacturers and that often the relevant standards are not cited. Throughout the communication it has proven difficult to obtain more detailed information on performance.

The measurement programme executed in **A3.2.5** will be used to acquire data on the performance of radiation protection dosimeters in terms of their response to radiation-based influence quantities. The performance regarding energy

dependence, angular dependence at defined energies, and non-linearity will be evaluated. The measurement protocol will cover a wide range of photon energies, including the ISO 4037:2019 N-series X-ray radiation qualities (e.g., N-40, N-60, N-80, N-100, N-120, N-150, N-200) and the S-Cs, S-Co radionuclide radiation qualities. Angular dependence will be evaluated at three lowest energies where the dosimeter fulfils the IEC defined criteria, and at the reference radiation quality (S-Cs). Non-linearity will be evaluated in a wide range of dose rates, compared to the pre-defined reference dose rate, considering the limits of variation defined in the standards. The measurement programme should be conducted in line with the measurement capabilities and the available irradiation facilities.

4 Proposed measurement programme

The performance tests of active dosimeters for individual (personal) monitoring and area (ambient) monitoring used for radiation protection include evaluation of dosimeter response to photon energy, angle of incidence, non-linearity, overload and stability. Reference value is established by using own calibrated equipment with stated traceability. Calibration factors and dosimeter responses should be reported with measurement uncertainty. Evaluation of the dosimeter performance for each of the radiation-based influence quantities will be done in terms of relative response.

Relative response, as per the relevant IEC standards (IEC 61526:2010 for active electronic dosimeters for personal monitoring, and IEC 60846-1:2009 for active area dosimeters for area monitoring), is defined as the normalized value of absolute response, where the normalization is done to the value obtained for the reference conditions. For these tests, reference conditions are defined as S-Cs radiation quality at 0° angle of incidence, at the dose rate of 100 $\mu\text{Sv h}^{-1}$. If dose is investigated instead, the reference dose to be used is 100 μSv . For the angular dependence of the response, the relative response is calculated by normalizing to the response at 0° in the S-Cs radiation field (not at 0° for each radiation quality separately!). During an influence quantity test, only the values of the quantity under test should be varied, while other parameters should be kept constant.

The results should be reported in terms of (absolute) response and the relative response for each radiation-based influence quantity separately. Clearly indicate the results with associated estimated measurement uncertainty of the response for each test. Take into account the correlations that arise for the relative response.

Non-linearity should be tested at **2 dose (rate) values per order** of magnitude, in line with the dosimeter measurement range.

Recommended dose values for a dosimeter which has a measurement range from 1 $\mu\text{Sv/h}$ to 1 Sv/h:

- ❖ 3 $\mu\text{Sv/h}$, 7 $\mu\text{Sv/h}$, 30 $\mu\text{Sv/h}$, 70 $\mu\text{Sv/h}$, **100 $\mu\text{Sv/h}$** , 300 $\mu\text{Sv/h}$, 700 $\mu\text{Sv/h}$,
3 mSv/h, 7 mSv/h, 30 mSv/h, 70 mSv/h, 300 mSv/h, 700 mSv/h

The dose (rate) values can be selected differently if the recommended values can't be achieved.

Stability of the dosimeter indication can be evaluated in five consecutive days by performing measurements under the reference conditions (100 $\mu\text{Sv/h}$ at S-Cs).

Overload of the dosimeter is tested by irradiation of the dosimeter with a dose rate which is out of the instrument measurement range (10 times above the upper limit of the measurement range, if such a dose rate is available). After this exposure, measurement under the reference conditions (100 $\mu\text{Sv/h}$ at S-Cs) should be done, and the absolute response is recorded.

Energy dependence should be evaluated in the following ISO 4037:2019 radiation qualities:

- ❖ N-series (all available radiation qualities that are in the measurement range, e.g., N-40 – N-200), and S-Cs, S-Co

If the N-series is not available, or appropriate dose rates can't be achieved, another series of radiation qualities can be used. S-Am can also be used if available. The dose rate chosen for the energy dependence test should be held constant for all radiation qualities. Since 100 $\mu\text{Sv/h}$ is hardly achievable in the N-series radiation qualities, use of a higher dose rate is recommended.

Angular dependence should be evaluated for the three lowest energy radiation qualities for which the energy dependence of the response is in line with the IEC criteria (0.71 – 1.67 for relative energy response) (e.g., if a dosimeter does not comply with the criteria for energy dependence below N-80, then the angular dependence is tested for N-80, N-100 and N-120). Angular dependence should be tested in both rotations of the dosimeter (with associated ISO slab phantom for personal dosimeters), for both dosimeter orientations (vertical and horizontal). Angular dependence should also be done for the S-Cs radiation quality.

For personal dosimeters the following angles of incidence are to be used:

- ❖ $0^\circ, \pm 30^\circ, \pm 45^\circ, \pm 60^\circ, \pm 75^\circ$

For area dosimeters the following angles of incidence are to be used:

- ❖ $0^\circ, \pm 45^\circ, \pm 60^\circ, \pm 90^\circ, \pm 120^\circ, 180^\circ$

0° at S-Cs represents the reference condition for the angular dependence test.

5 Results of the performance tests on radiation protection dosimeters according to the Measurement programme

The measurement programme included tests on dosimeter response non-linearity, energy dependence and angular dependence. The tests were performed by several dosimetry calibration laboratories, where each of the participants selected and tested several dosimeters (at least five). In total 28 AADs (active area dosimeters) and 6 APDs (active personal dosimeters) were included in the study. The evaluation of the performance was done against the relevant IEC standards (IEC 61526:2024 for APDs, and IEC 60846-1:2009 for AADs). Dosimeter non-linearity was tested in a wide range of dose rates depending on the capabilities of the calibration laboratory and respective to the dosimeter measurement range. Relative response to the reference dose rate was determined. Energy dependence was done in a wide range of photon energies for most of the dosimeters, covering standard radionuclide-based radiation fields (S-Cs and S-Co), as well as the N-series radiation qualities from N-40 to N-200, all established in line with the requirements set by ISO 4037:2019. Angular dependence of the dosimeters was done in two perpendicular dosimeter orientations for the reference radiation quality S-Cs, as well as for the three lowest energy radiation qualities for which the energy dependence criteria were fulfilled. The paper, which shows cases the performance of APDs and AADs, and proposes possibilities to update the current relevant type testing standards was drafted and submitted to a scientific journal. It has been accepted and published in the Journal of Radiation Research and Applied Sciences, <https://doi.org/10.1016/j.jrras.2026.102159>. In the following, the scientific publication which is the result of research undertaken within WP3 is provided.

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 $\mu\text{Sv h}^{-1}$ – 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.

Keywords

active area dosimeters, active personal dosimeters, dosimeter performance, individual monitoring, workplace monitoring

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 and Van Hoey, 2022). Accurate and reliable dosimetry data can be acquired by using dosimeters which comply with relevant international standards (Yasar et al., 2017; Calvacante et al., 2025).

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 and 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 (Ciraj-Bjelac et al., 2018; Abuelhia and Alghamdi, 2020; 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; Kržanović et al., 2017; Yasar et al., 2017; Hupe et al., 2019; Cui et al., 2024; Li et al., 2025). 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 (Pavelić et al., 2019; Alomairy, 2023). 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 overresponse 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 (Ćeklić et al, 2014; Kržanović et al, 2019; Morosh et al., 2021; 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.

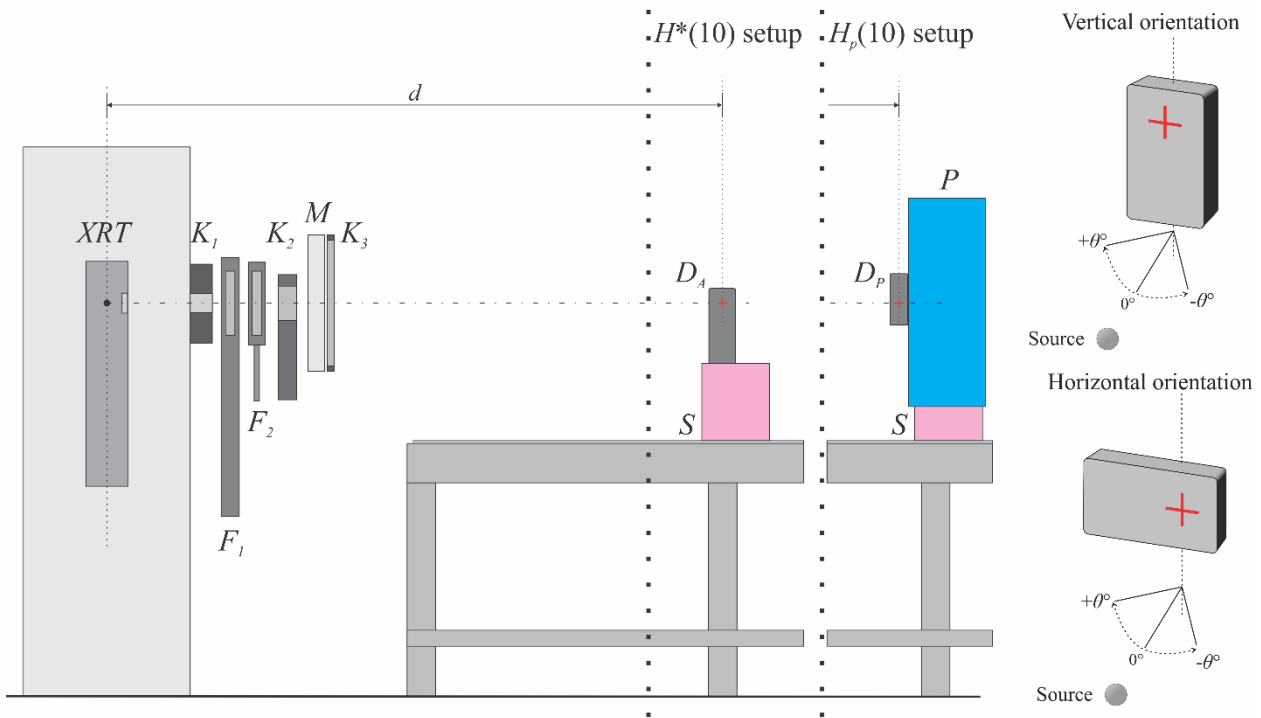


Figure 36. Schematic representation of the experimental setup. (left): XRT - X-ray tube; K1, K2 and K3 - apertures; F1 and F2 - additional filtration; M - monitor ionization chamber; d - source-to-detector distance; P - ISO slab phantom (used with PDs); S - positioning support (low Z material); DA - AD; DP - PD. (right): Dosimeter orientation and rotation for the angular dependence test.

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 Table 1 and Table 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).

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 [$\mu\text{Sv h}^{-1}$]	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 Si – diode	0 20	0.02 1000	20 20	1 5	AD15 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	● ● ●
VINS DMRZ-M15	G-M tube	0.1	1	59	1.3	AD25 AD26	■ ■

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. 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 [$\mu\text{Sv h}^{-1}$]	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	■

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:

$$R = \frac{M}{H_r} \quad (1)$$

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:

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

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:

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

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 (Ćeklić et al., 2014; Kržanović et al. 2017). 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 $\pm 45^\circ$ from the reference direction. This range is defined with respect to the area workplace monitors. For area dosimeters, the following angles were used, 0° , $\pm 45^\circ$, $\pm 60^\circ$, $\pm 90^\circ$, $\pm 120^\circ$, 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 $\pm 60^\circ$. For personal dosimeters the angular dependence test was performed in both directions of rotation for the angles 0° , $\pm 30^\circ$, $\pm 45^\circ$, $\pm 60^\circ$, and $\pm 75^\circ$. 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 (relative 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 $3 \mu\text{Sv h}^{-1}$ to 7Sv h^{-1} , whereas

in the case of PDs the dose rate range spanned from $3 \mu\text{Sv h}^{-1}$ to 2Sv 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 $100 \mu\text{Sv h}^{-1}$, 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 ($100 \mu\text{Sv h}^{-1}$ 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 Fig. 2 and Fig. 3 the energy dependence of ADs and PDs is displayed, respectively. Fig. 4 and Fig. 5 show the angular dependence of ADs in N-40 and N-100

radiation qualities, respectively. Fig. 6 and Fig. 7 display the angular dependence of PDs in radiation qualities N-40 and N-60, and N-100 and N-120, respectively. Fig. 8 and Fig. 9 present the non-linearity response of ADs and PDs, respectively. Figs. A1 – A7 are provided in the 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 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).

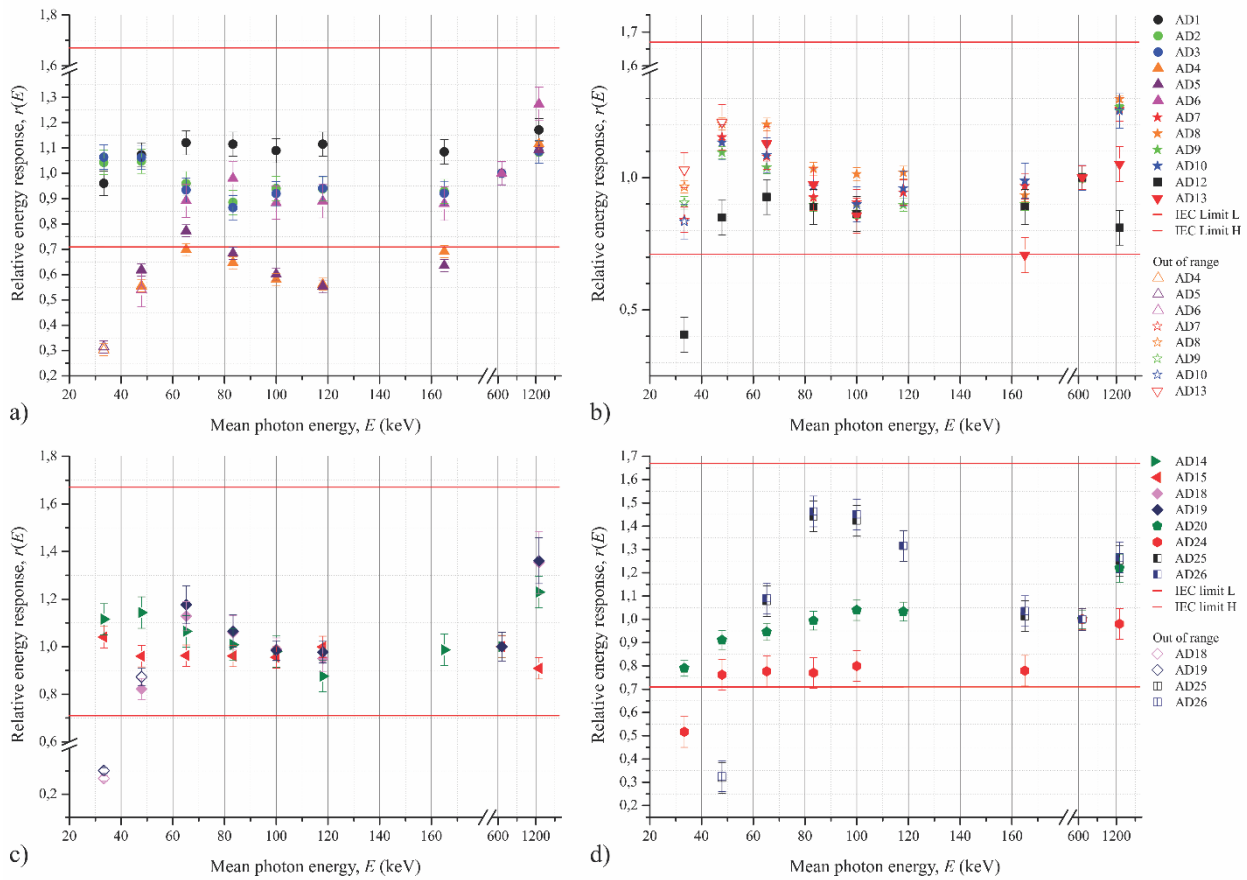


Figure 2. Energy dependence of active area dosimeter (AD) response in the range from 33 keV (N-40) to 1.25 MeV (S-Co): a) AD1-AD6; b) AD7-AD13; c) AD14-AD19; d) AD20-AD26. The limits of variation (-29%; +67%) in terms of relative energy response are displayed (IEC, 2009).

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.

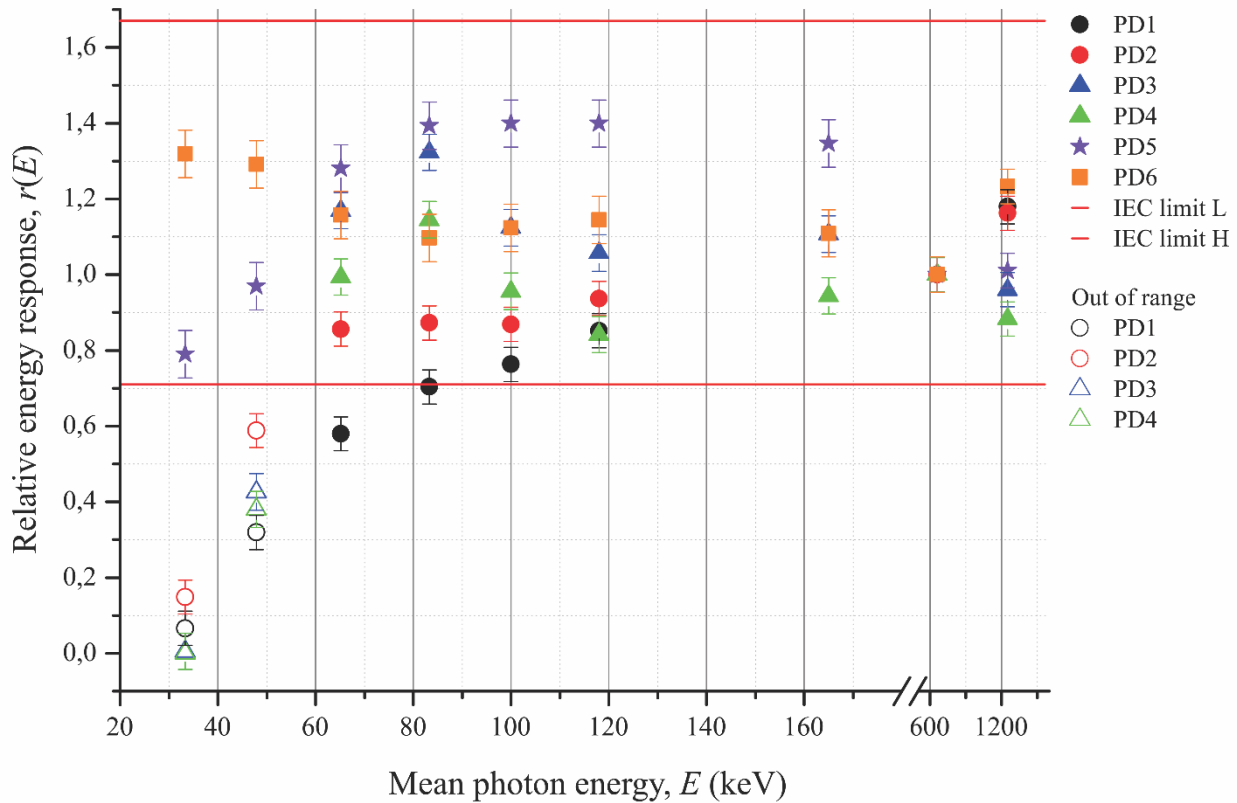


Figure 3. Energy dependence of active personal dosimeter (PD) response in the range from 33 keV (N-40) to 1.25 MeV (S-Co). The limits of variation (-29 %; +67 %) in terms of relative energy response are displayed (IEC, 2024).

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 (Lee et al., 2016; Kržanović et al., 2017). 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 $\pm 45^\circ$. 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 Fig. 4 and Fig. 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).

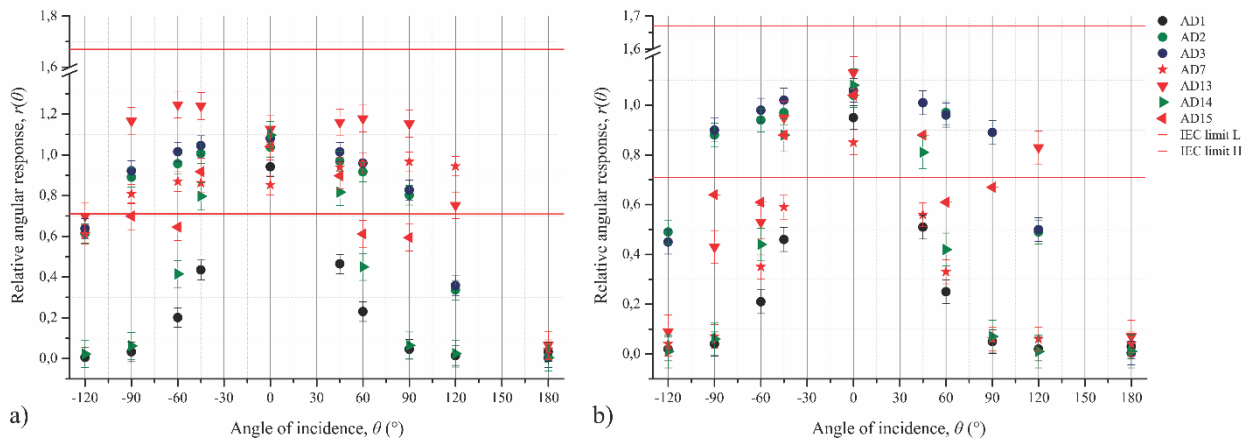


Figure 4. Angular dependence of active area dosimeter (AD) response in the N-40 (mean photon energy 33.3 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed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

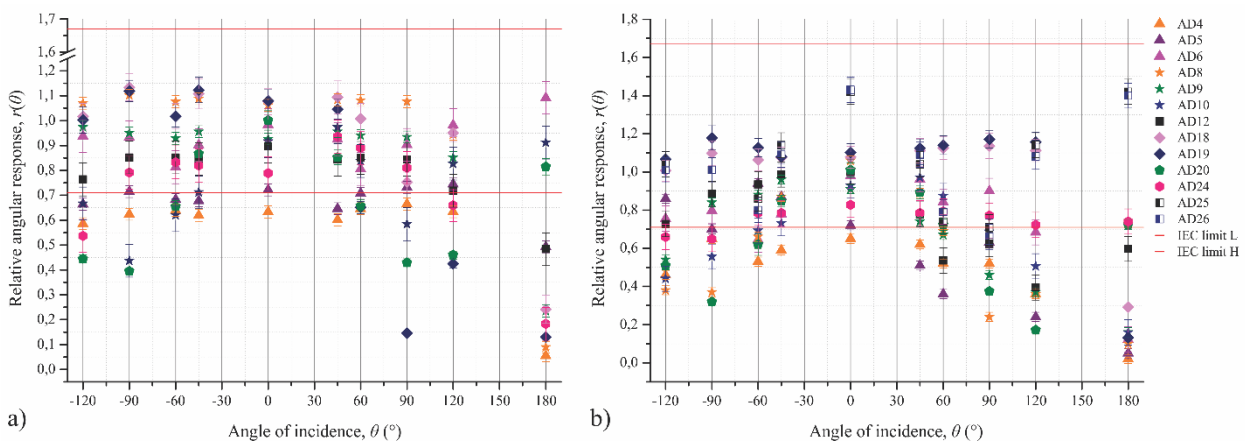


Figure 5. Angular dependence of active area dosimeter (AD) response in the N-100 (mean photon energy 83.3 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed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

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° , $\pm 45^\circ$, $\pm 60^\circ$, $\pm 90^\circ$, $\pm 120^\circ$, 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 $\pm 45^\circ$ 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 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 $\pm 45^\circ$. It 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 Fig. 6 and Fig. 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).

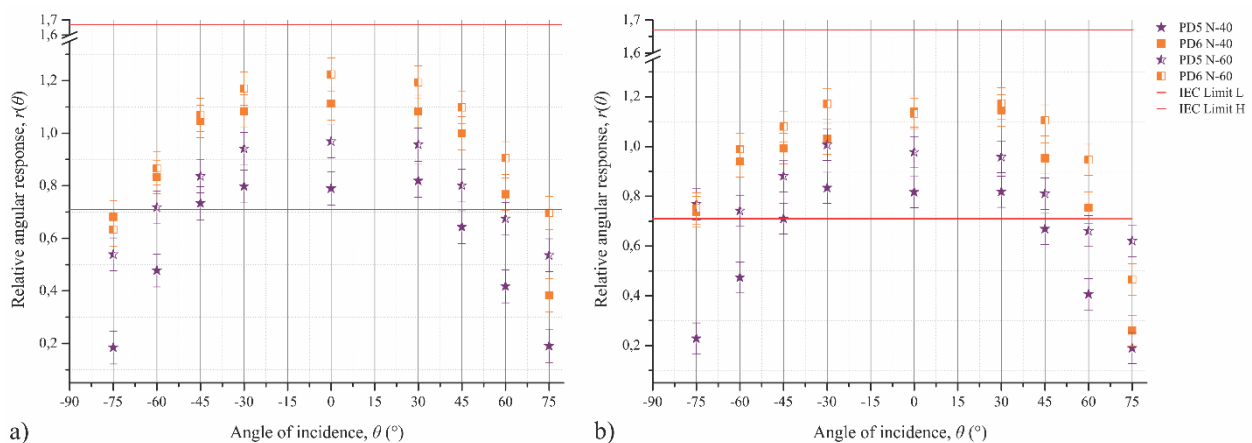


Figure 6. Angular dependence of active personal dosimeter (PD) response in the N-40 and N-60 (mean photon energies 33.3 keV and 47.9 keV) radiation qualities. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (-29%; +67%) in terms of relative energy and angular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

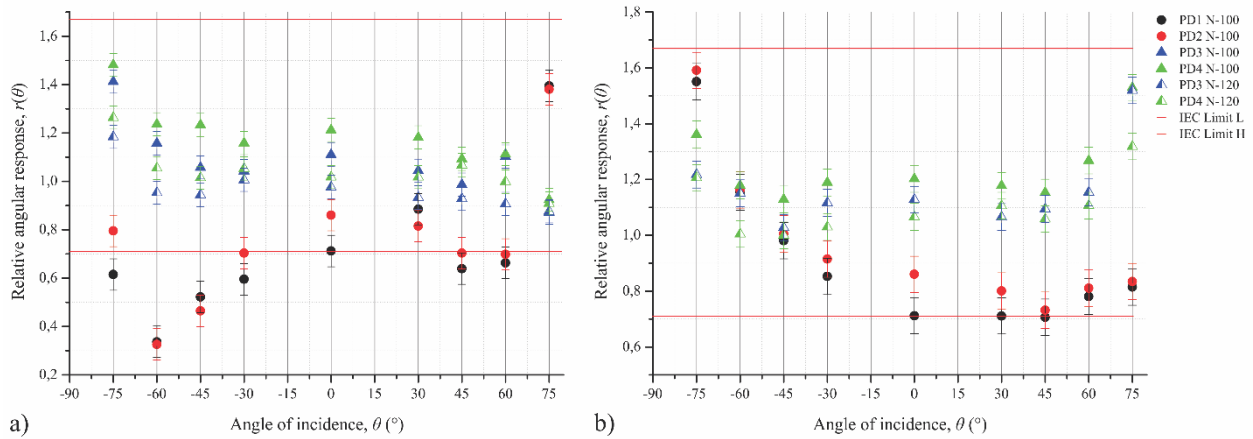


Figure 7. Angular dependence of active personal dosimeter (PD) response in the N-100 and N-120 (mean photon energies 83.3 keV and 100 keV) radiation qualities. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (-29%; +67%) in terms of relative energy and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

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 $\pm 10\%$ 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 ($3 \mu\text{Sv h}^{-1}$), which may be attributed to the resolution of the instrument reading. Non-linearity of ADs is presented in Fig. 8.

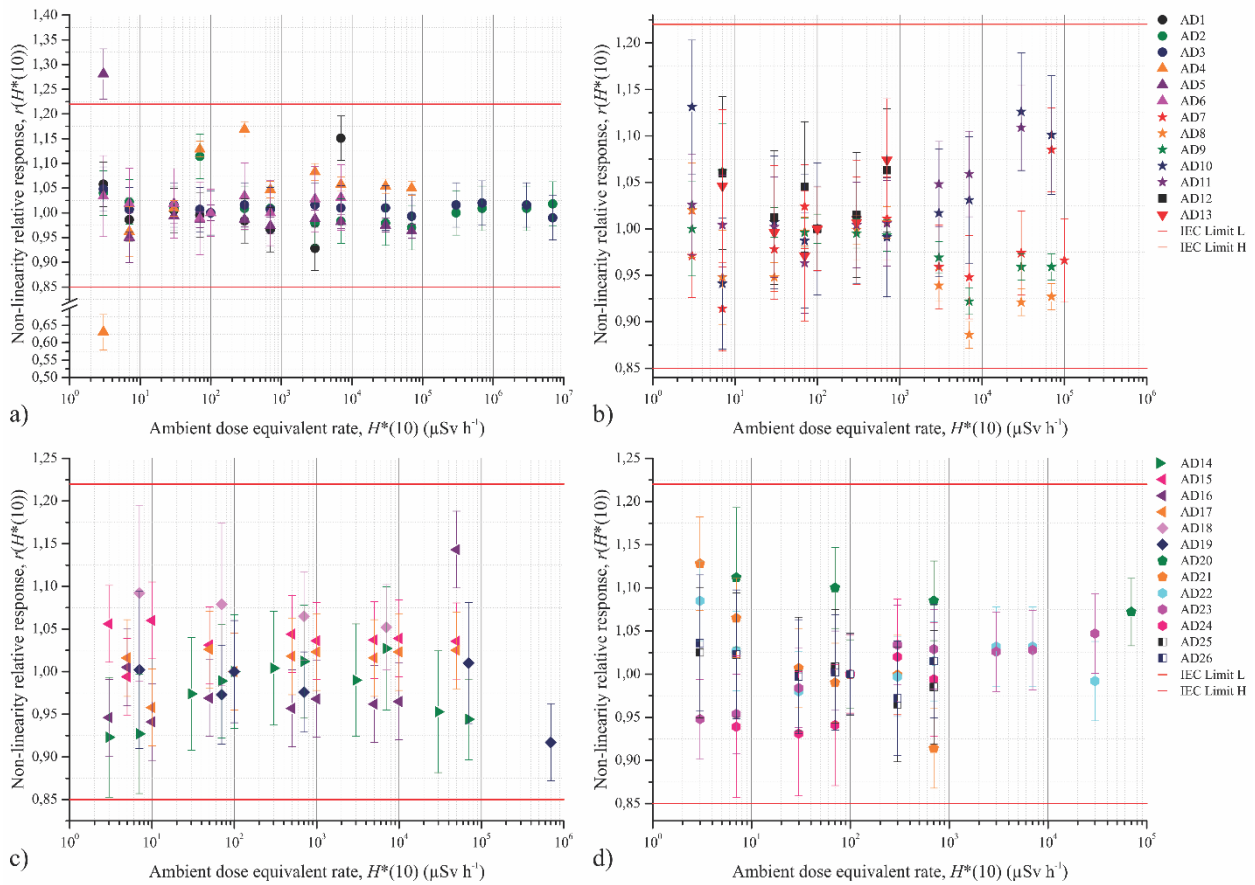


Figure 8. Non-linearity of active area dosimeter (AD) response in the dose rate range from $3 \mu\text{Sv h}^{-1}$ to 7Sv h^{-1} : a) AD1-AD6; b) AD7-AD13; c) AD14-AD19; d) AD20-AD26. The limits of variation (-15%; +22%) in terms of relative response are displayed (IEC, 2009).

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 $3 \mu\text{Sv h}^{-1}$ and $7 \mu\text{Sv h}^{-1}$, 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.

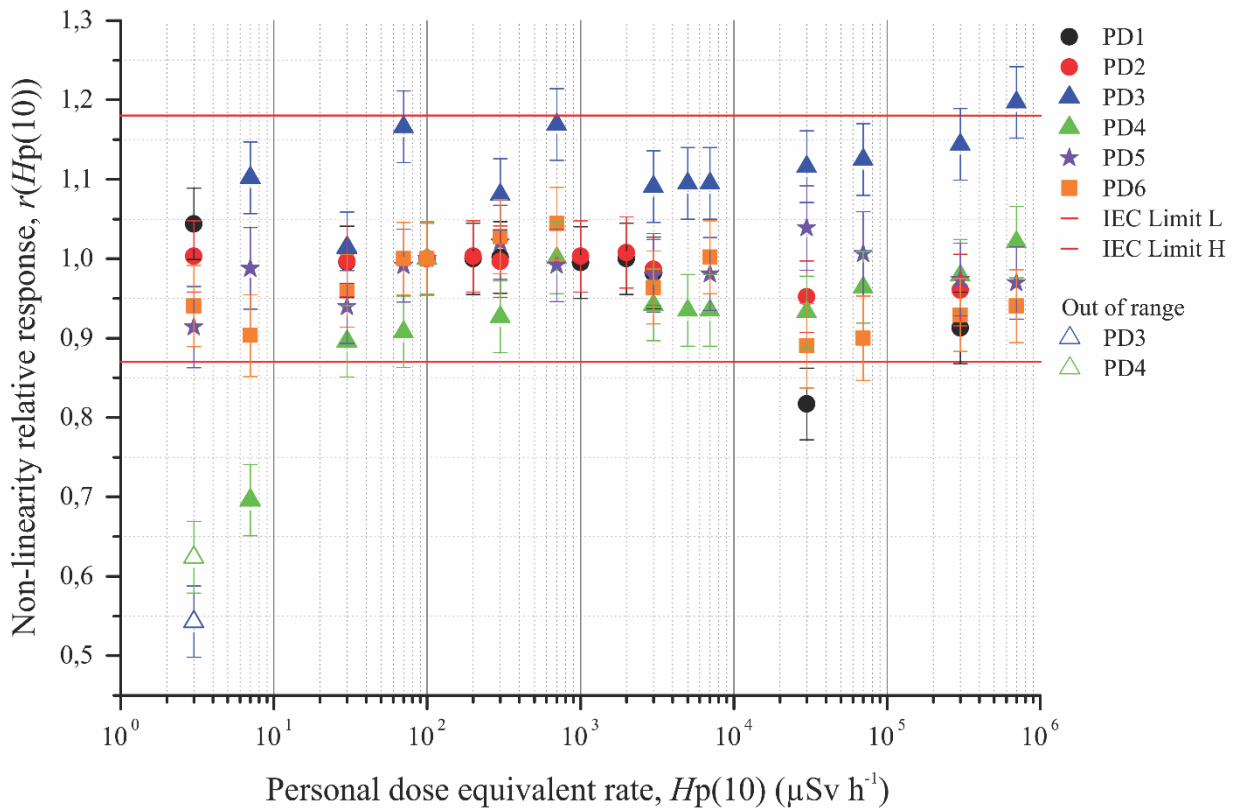


Figure 9. Non-linearity of active personal dosimeter (PD) response in the dose rate range from 3 $\mu\text{Sv h}^{-1}$ to 2 Sv h^{-1} . The limits of variation (-13 %; +18 %) in terms of relative response are displayed (IEC, 2024).

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.

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		

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.

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

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 $\pm 40\%$ (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. In the case of the energy and angular dependence test, limits 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° ; $\pm 60^\circ$) (IEC, 2024), and for ADs (0° ; $\pm 45^\circ$) (IEC, 2009). Proposed class A dosimeters would comply with more strict limits of variation, 0.83 – 1.25, which correspond to the $\pm 20\%$ 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 $< \pm 10\%$, 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 $\pm 10\%$ 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).

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 - $\pm 45^\circ$	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 Sv h^{-1}	0.91 – 1.11	0.83 – 1.25

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 $\pm 75^\circ$ for PDs, or $\pm 90^\circ/\pm 180^\circ$ 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.

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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.

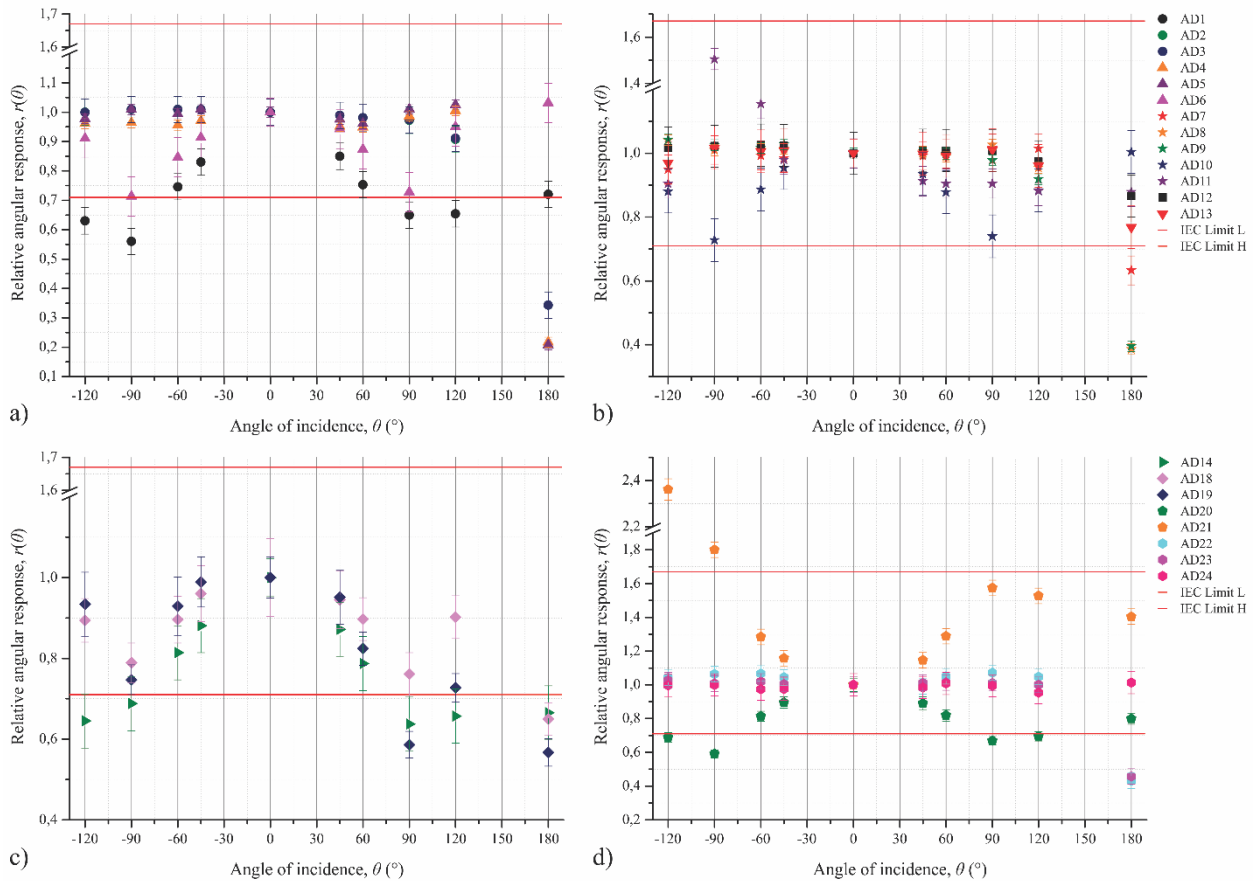


Figure A1. Angular dependence of active area dosimeter (AD) response in the S-Cs (mean photon energy 662 keV) radiation quality in vertical dosimeter orientation. a) AD1-AD6; b) AD7-AD13; c) AD14-AD19; d) AD20-AD26. The limits of variation (-29%; +67%) in terms of relative energy and angular response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

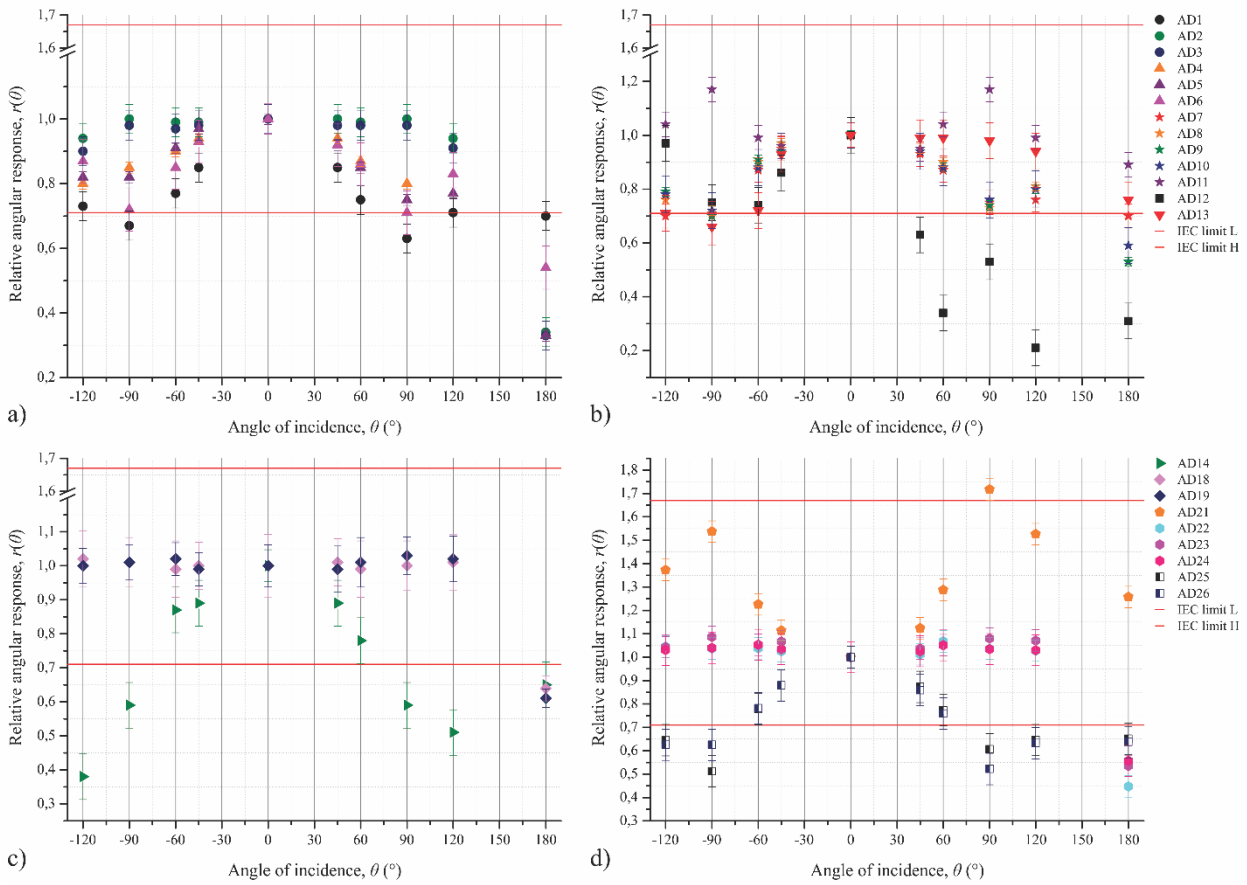


Figure A2. Angular dependence of active area dosimeter (AD) response in the $S\text{-Cs}$ (mean photon energy 662 keV) radiation quality in horizontal dosimeter orientation. a) AD1-AD6; b) AD7-AD13; c) AD14-AD19; d) AD20-AD26. The limits of variation (-29 %; +67 %) in terms of relative energy and angular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

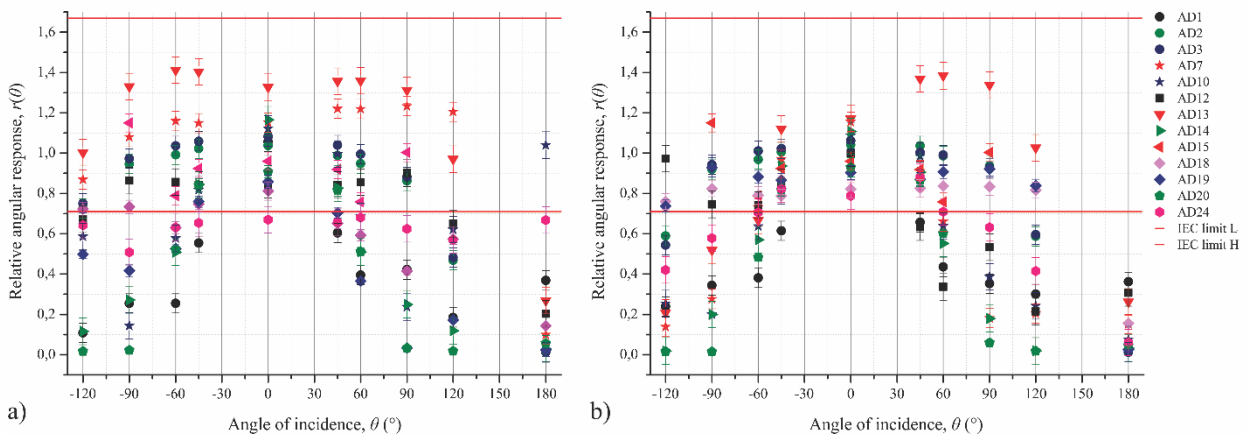


Figure A3. Angular dependence of active area dosimeter (AD) response in the $N\text{-60}$ (mean photon energy 47.9 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are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

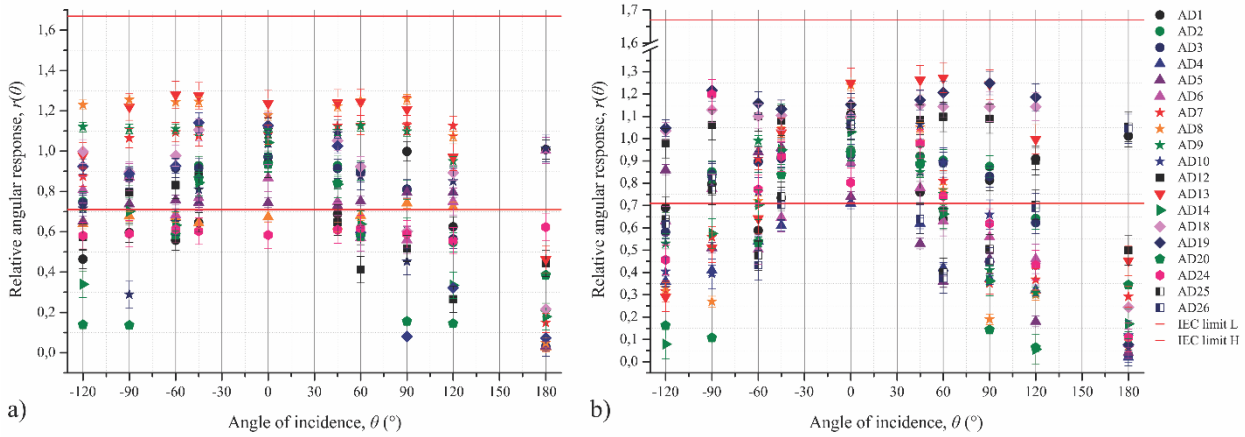


Figure A4. Angular dependence of active area dosimeter (AD) response in the N-80 (mean photon energy 65.2 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed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

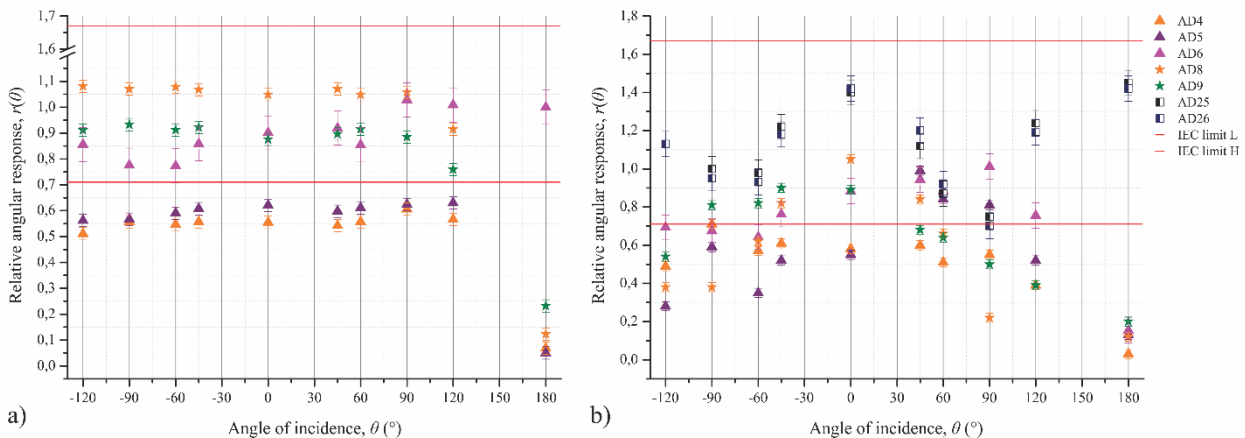


Figure A5. Angular dependence of active area dosimeter (AD) response in the N-120 (mean photon energy 100 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed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

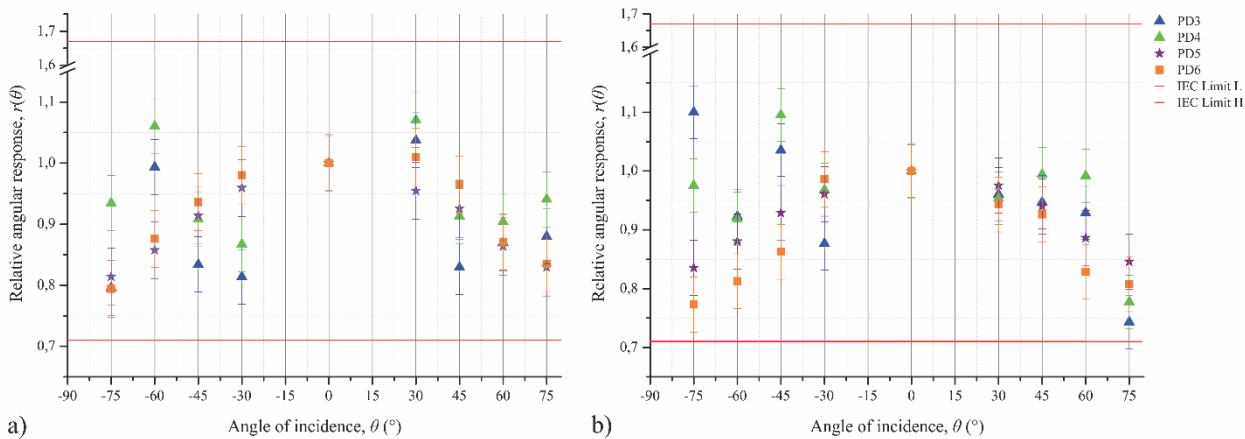


Figure A6. Angular dependence of active personal dosimeter (PD) response in the S-Cs (mean photon energy 662 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed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

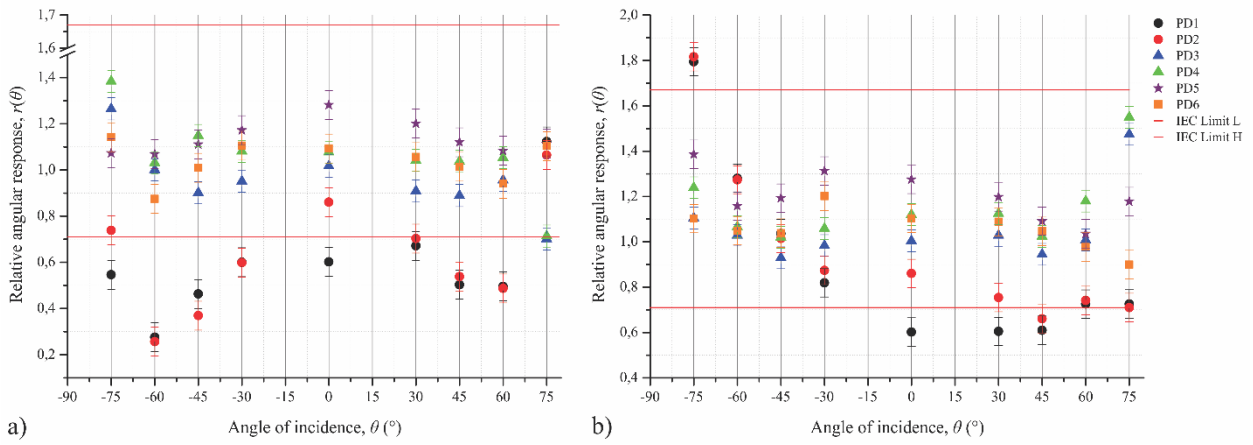


Figure A7. Angular dependence of active personal dosimeter (PD) response in the N-80 (mean photon energy 65.2 keV) radiation quality. a) vertical dosimeter orientation; b) horizontal dosimeter orientation. The limits of variation (-29 %; +67 %) in terms of relative energy and angular response are displayed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