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Manuscript title:

PERFORMANCE TESTING OF DOSIMETERS USED IN INTERVENTIONAL RADIOLOGY: RESULTS FROM THE VERIDIC PROJECT

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Abstract

Interventional procedures in radiology and cardiology are associated with high dose to the patient. Accurate dosimetry is essential and calibration of the equipment is a means to provide the necessary accuracy of dose assessment.

The objective of this work is to investigate the performance of dosimeters used in interventional procedures in different standard and non-standard X-ray radiation qualities, and to investigate potential uncertainties related to dose measurements, thus improving accuracy of patient dosimetry in interventional procedures.

Four new reference radiation qualities dedicated to interventional cardiology applications have been established, allowing calibration of dosimeters used in clinical conditions with appropriate traceability to primary standards. Testing of solid-state semiconductor detectors and thermoluminescent dosimeter properties, e.g. influence of photon energy, angle of incidence and dose rate, was performed in the standard and non-standard radiation qualities.

Both dosimeter types showed good performance in the non-standard beams during all performance tests. Solid-state dosimeters displayed weak dependence on energy, angle of incidence and dose rate, in the range defined by the manufacturer and requirements of the international standard. Thermoluminescent dosimeters displayed excellent linearity and angular dependence. The influence of energy dependence on measurement uncertainty can be reduced if appropriate radiation quality is selected for calibration.

Keywords

Diagnostic Radiology, *Dosimetry*, *Interventional Cardiology*, *Radiation Quality*, *X-rays*

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1. Introduction

Diagnostic radiology is a major contributor to the total population dose from artificial sources of radiation (UNSCEAR, 2011). Dosimetry is an important tool in diagnostic and interventional radiology to check equipment performance, for optimization of medical practice and risk assessment. An accurate measurement is ensured by calibration of the instrumentation in radiation qualities of well-defined properties. The range of clinically used radiation qualities is wide and depends on the type of X-ray equipment and protocol settings. Radiation quality influences the response of dosimeters (Hourdakis et al., 2010, Salomon et al., 2020).

Radiation qualities are usually specified in terms of the X-ray tube voltage, first and second half value layer (HVL) (IAEA, 2007). HVL is readily measurable and is related to the mean energy of the X-radiation, which is usually not known. Standard radiation qualities are defined in IEC (International Electrotechnic Commission) 61267 standard (IEC, 2005). The clinical beams might be significantly different from the reference qualities, especially on the side of the high energies (Järvinen et al., 2015, Salomon et al., 2020). Using the dosimeter outside of the range of radiation qualities in which it was calibrated introduces significant uncertainty in measurements (Roshau and Hintenlang, 2003).

Dosimeters commonly used in diagnostic and interventional radiology are solid-state dosimeters, ionisation chambers, thermoluminiscent dosimeters (TLD) and gafchromic films (Hourdakis et al., 2010, IAEA, 2007).

Ionisation chambers have been the standard instruments used for diagnostic radiology dosimetry and quality assurance assessment for many years. Dosimeters based on semiconductor technology are now becoming widely available, and as the semiconductor detectors are smaller in size, they are more convenient to use in many situations. Diagnostic dosimeters should be

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designed in compliance with IEC 61674 (IEC, 1997), which is a standard that pertains to dosimeters equipped with either ionisation chambers or semiconductor detectors. Traditionally, the main disadvantage of semiconductor-based devices is their pronounced energy dependence of response which differs considerably from the relatively constant response of ionisation chambers in the diagnostic X-ray energy range for measurement of air kerma. Multiple semiconductor elements are incorporated into the semiconductor detector used for X-ray dosimetry. Dose compensation is applied automatically and is derived based on radiation quality. The commercial semiconductor detectors are mounted on lead backing plates, to attenuate radiation incident from the rear, ensuring that the automatic energy compensation is applied correctly. As a result, these detectors measure the air kerma incident from the direction of the primary beam and, consequently, have pronounced angular dependence. The use of lead backing plates in solid-state dosimeters can also influence the behavior of the X-ray system's automatic exposure control. Nevertheless, these types of detectors have found many applications in routine clinical measurements in hospitals. Most of them are capable of determining the air kerma, tube voltage, half value layer (HVL), and exposure time, as well as the output waveform from a single irradiation (Martin et al., 2007).

According to the requirements of the international standard IEC 61674 (IEC, 1997), the Quality Control (QC) semiconductor solid-state dosimeters 'response variation must be within ±5% in the minimum rated range of photon energy, ±2% for the variation in air kerma rate and ±3% for different angles of incidence. When the dosimeters are used in clinical conditions outside of the rated range of the influence quantities, the response variation might increase. Photon energy (radiation quality) and air kerma rate are especially important (Hourdakis et al., 2010, IEC, 1997).

DOI: 10.1016/j.radmeas.2021.106515

Thermoluminescent dosimeters exhibit good dosimetric characteristics due to their tissue-equivalent composition in terms of interactions with photon radiation over a certain energy range. Thanks to this property they have been used for clinical studies of patient skin dose measurements in interventional procedures (Bogaert et al. 2009; Dabin et al., 2018). The most common types of TLDs contain round or square pellets made of LiF:Mg,Ti or LiF:Mg,Cu,P. The main sources of uncertainty associated with these dosimeters are the energy dependence, angular dependence, and linearity of the dosimeter response. In addition, thermal treatment and the reading process can considerably affect the dosimeter properties. Regarding energy dependence of the dosimeter response, several studies were conducted in the ISO 4037 (ISO, 1996) standard N-series radiation qualities and reference photon beams of ^{137}Cs and ^{60}Co isotopes (Saez-Vergara et al., 1999; Olko et al., 2002; Davis et al., 2003; Apostolakopoulos et al., 2019; Parisi et al., 2019), while one study examined the performance of TLDs in the RQR-series (Radiation Qualities in Radiation beams emerging from the X-ray source assembly) (Carinou et al., 2008). Two studies were based on irradiations in the quasi monoenergetic beams (Kron et al., 1998; Duggan et al., 2004), and one in the standard NIST radiation qualities (Nunn et al., 2008). The results of these different studies show that the relative response curves of LiF:Mg,Ti and LiF:Mg,Cu,P are fundamentally different. LiF:Mg,Cu,P TLDs usually display a similar shape of energy response in different studies, with a minimum relative response value in the 80-100 keV energy range. In case of the LiF:Mg,Ti results were more heterogeneous in different studies, but TLD energy dependence generally shows a maximum value in the 30-50 keV energy range. The cause of differences in TLD energy response may be due to the pellet material properties and not the reading and annealing procedures (Saez-Vergara et al., 1999). In the interventional procedures energy range from 15 keV up to 120 keV, the energy response deviates up to ±20% from unity, and up to +40% higher than unity, for LiF:Mg,Cu,P and LiF:Mg,Ti TLDs respectively. In order to properly investigate the behavior of these passive dosimetry systems irradiations in the non-standard radiation qualities is necessary.

High dose values delivered to the patient skin during an interventional procedure may cause supralinearity of the TLD response, depending on impurity content of the TLD material, thermal treatment of the dosimeters, reading process, glow peak temperature and the photon energy. This effect is more pronounced in LiF:Mg,Ti than in LiF:Mg,Cu,P material, which gives this material a significant advantage for use in interventional procedures (Moscovitch et al., 2007).

Radiochromic films (Gafchromic XR type T) are also used for measurements of maximum delivered skin dose in high dose and high dose rate IC procedures (Farah et al., 2015). The main consequence of ionising radiation interactions with the radiochromic films is the film color alteration, whereas the alteration intensity is proportionate to the dose value. The quantitative post-irradiation analysis and determination of skin dose is strongly dependent on various film properties and performance under clinical irradiation conditions (Greffier et al., 2017; Didier et al., 2019). Major factors contributing to the variation in the film response are the energy dependence and dose rate dependence. A group of authors found a difference of 9% between film readings in two different clinical beams for the same delivered dose. Clinical beams with medium (75 kV, 4 mm Al) and high (120 kV, 6 mm Al) beam energy were used. Irradiation conditions in interventional procedures involve backscattered radiation and high dose rate pulsed fields, in comparison with laboratory conditions where the fields are continuous and with low dose rate values. These differences cause the need for characterisation under clinical conditions, similarly as with thermoluminescent dosimeters. Film-to-film uniformity, film darkening over time and the impact of scanner used, represent additional influences on the quantification of dose, besides the before mentioned factors (Farah et al., 2015).

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In order to improve the accuracy of dose measurement for patients and medical staff in the interventional radiology and cardiology procedures, and due to the differences in irradiation conditions in the calibration laboratories and hospitals, dosimeters should be calibrated in the radiation qualities whose characteristics are as close as possible to the X-ray beams generated by the medical systems on-site.

VERIDIC project (Validation and Estimation of Radiation Skin Dose in Interventional Cardiology), focused on the validation of skin dose calculation (SDC) software products in interventional cardiology, which will optimize radiation protection of patients. One of the objectives of the VERIDIC project (under Work Package 2) (Dabin et al. 2020) was to develop a protocol for acceptance and QC tests of SDC software to be used by medical physicists in clinical practice. The adequate use of such protocol is highly related to the accuracy of dose measurement of commonly used field dosimeters.

Following this, the objective of this work is to investigate the performance of dosimeters used in interventional procedures in different standard and non-standard radiation qualities, relevant for clinical practice. Although gafchromic films were tested in the frame of the VERIDIC project for the sake of completeness, these results were not deemed novel enough to be reported in the present article. The results are in agreement with more extensive studies performed by Farah et al. (2015) and Greffier et al. (2017), and are available in an online report (Blideanu et al. 2020).

By providing traceability in these radiation qualities and minimizing the differences in calibration conditions compared to the radiation qualities used in hospitals and by investigating potential uncertainties related to dose measurements this work intends to improve accuracy of patient dosimetry in interventional procedures.

2. Materials and Methods

To address the issue stated in the objective of this work, four new reference beam qualities dedicated to interventional cardiology applications have been established, allowing calibration of dosimeters used in clinical conditions with appropriate traceability to primary standards. Testing of solid-state semiconductor detector and thermoluminescent dosimeter properties, e.g. influence of photon energy, angle of incidence and dose rate, was performed in the standard radiation quality and non-standard radiation qualities which correspond to irradiation conditions characteristic for fluoroscopically guided interventional procedures in interventional radiology (IR) and interventional cardiology (IC).

2.1. X-ray beam qualities

In order to investigate performance of the dosimeters under irradiation conditions which differ from those proposed in the standard RQR series (IEC, 2005), non-standard radiation qualities corresponding to those used in clinical conditions were established.

To investigate typical radiation qualities used in interventional procedures, an inventory of Radiation Dose Structured Reports (RDSRs) from different interventional procedures was collected. Six interventional X-ray units (one Canon (Canon Medical Systems, Japan), two GE (GE Healthcare, USA), one Philips (Philips, Netherlands) and two Siemens (Siemens Helathcare, Germany)) from hospitals in France, Italy, Ireland and Switzerland were used for the collection of RDSRs, with a sample of 30 RDSRs per interventional unit. The frequency of use of combinations of tube voltage and additional filtrations was analyzed, including both fluoroscopy and cine acquisition regimes. Despite the limited number of procedures and X-ray units, a wide range of X-ray tube voltages ranging from 57 kV to 125 kV and a range of added filtration in the primary beam from 0 mm Cu up to 1.0 mm Cu was observed in the collected procedure sample of

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total 180 RDSRs. The radiation qualities most commonly used included X-ray tube voltages in the range from 80 kV to 120 kV, and a range of additional filtration of 0, 0.1, 0.3 and 0.9 mm Cu. Although the X-ray tube voltage and additional filtration values were similar, notable differences among the interventional units exist (even in the case of the units produced by the same manufacturer). For instance, the vast majority of all irradiations (between 53% and 98%), whether using fluoroscopy or cine regime, were performed with additional filtration between 0.1 and 0.3 mm Cu on three systems (Canon, GE and Siemens). On the Philips unit, a similar trend was observed in cine regime, but fluoroscopy irradiations were performed with a slightly higher filtration (0.4 mmCu) in about 90% of the cases. On the remaining systems, however, more than 60% of the cine acquisitions were performed without additional filtration. Use of 0.9 mmCu was only significant (about 10%) in the two GE systems in fluoroscopy regime.

The X-ray spectra for selected X-ray tube voltage and filtration combinations were calculated by using the SpekCalc code, which is a commonly used and extensively validated tool for X-ray tube applications (Poludniowski et al., 2009). As a balance between accuracy and complexity, radiation qualities selected for testing of dosimeters included extreme values of the additional Cu filtration, e.g. 0 and 0.9 mm Cu, for two X-ray tube voltage values (80 kV and 120 kV) and inherent filtration of 2.5 mm Al.

The selected radiation qualities were generated by using a Seifert 320 X-Ray generator (Seifert, Radevormwald, Germany). For the purpose of validating the non-standard radiation qualities, X-ray spectra were measured by using a method based on CdTe semiconductor detector which has been developed by the French Alternative Energies and Atomic Energy Commission (CEA) (Plagnard, 2014). Measured spectra correspond well with the spectra calculated by SpekCalc. The measurement set-up used for spectrometry measurements is presented in Fig. 1.

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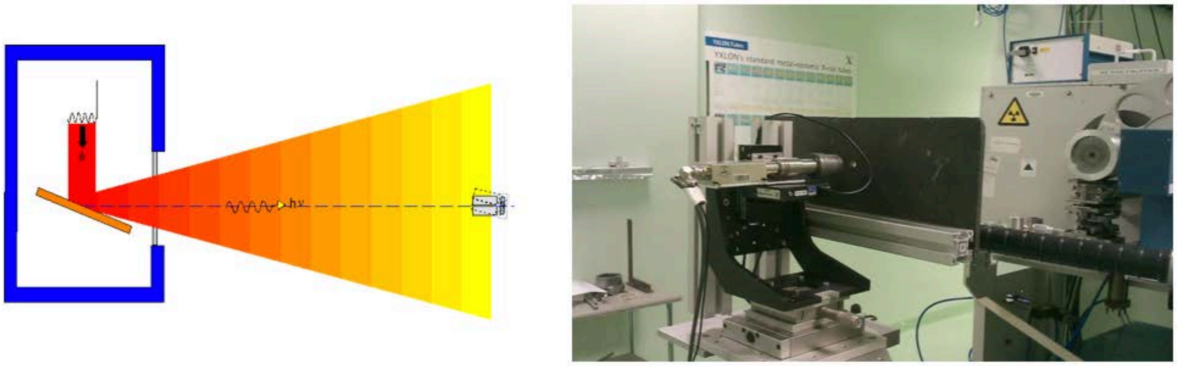

Figure 1. Schematic representation of the spectrometer positioning in the X-ray field (left), and the experimental set-up used for the X-ray spectra measurements, emitted by the CEA X-ray generator (right).

The four newly established radiation qualities were metrologically characterised in terms of air kerma rate by using the primary standard free-in-air ionisation chamber available at CEA Primary Standard Dosimetry Laboratory (PSDL). Besides the new non-standard radiation qualities, a standard radiation quality of similar properties in terms of X-ray spectra, RQR8, has been selected in order to compare the calibration results between laboratory and hospital irradiation conditions (IEC, 2005). The measured pulse-height energy spectra of the non-standard radiation qualities and the standard RQR8 radiation quality are presented in Fig. 2.

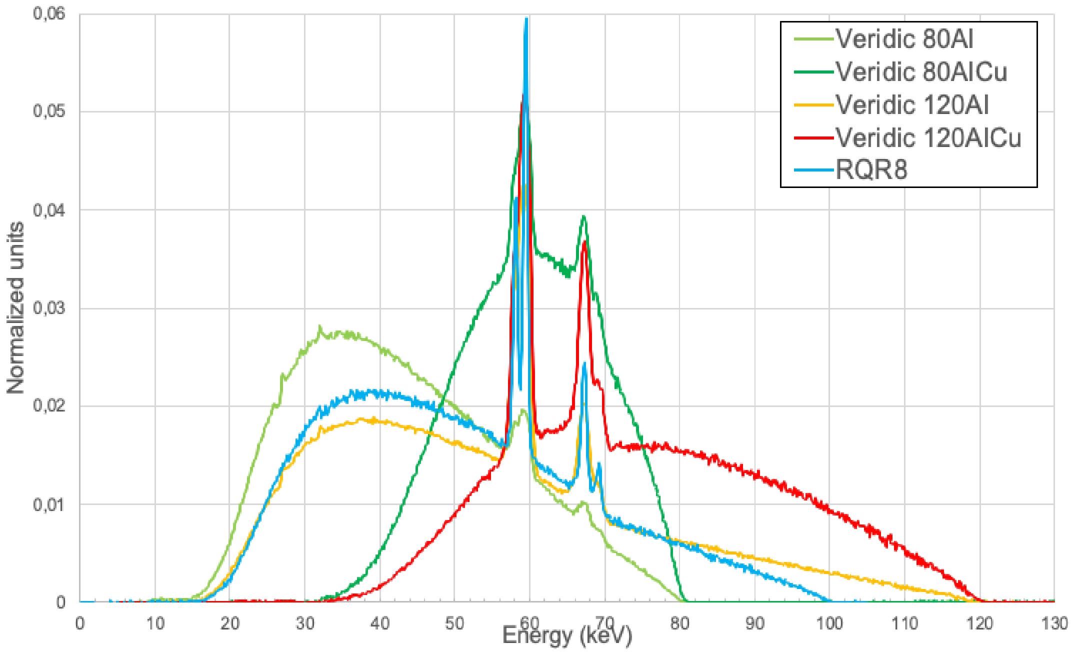

Figure 2. Energy spectra for the IC radiation qualities and the standard RQR8 radiation quality

The established standard and non-standard radiation qualities were further used to test solid-state and thermoluminescent dosimeters, in particular to investigate their response as a function of air kerma rate, photon energy and angle of incidence.

2.2. Solid-state quality control dosimeters

The commercial semiconductor diagnostic dosimeters that are tested in this paper are: MPD (Multi-Purpose Detector) and R100B, both used with the Barracuda electrometer module (RTI electronics, Molndal, Sweden), Black Piranha (RTI electronics, Molndal, Sweden), and Unfors Xi (RaySafe, Billdal, Sweden). The R100B dosimeter has a single detector element while MPD, Piranha and Unfors Xi contain multiple detector elements. These detector elements have thin metal layers, providing compensation of the derived detector response for different radiation qualities. The MPD and Piranha detectors use some of the detector elements to non-invasively determine tube voltage, while the rest of the detector elements are used for measurement of the incident air kerma with compensation for detector energy dependence. Technical specifications of these solid-state dosimeters in terms of applicable X-ray tube voltage range, dose and dose rate range are displayed in Table 1.

Table 1. Technical specifications of the tested QC solid-state dosimeters.

QC dosimeter	Manufacturer	X-ray tube voltage [kV]		Dose range [Gy]		Dose rate range [mGy·s^{-1}]	
		min	max	min	max	min	max
MPD	RTI Electronics	35	155	1.5×10^{-8}	$1\times10^{+3}$	1.5×10^{-6}	$4.5\times10^{+2}$
R100B	RTI Electronics	Not specified		1×10^{-10}	$1.5\times10^{+5}$	1×10^{-6}	$7.6\times10^{+1}$
Black Piranha	RTI Electronics	50	150	1×10^{-10}	$1.5\times10^{+3}$	1×10^{-6}	$3.2\times10^{+2}$
Xi R/F Classic	RaySafe	35	160	1×10^{-8}	$1\times10^{+4}$	1×10^{-5}	$1\times10^{+3}$

2.3. Thermoluminescent dosimeters

The passive dosimetry system that was tested in the reference radiation quality and the IC non-standard radiation fields was based on the MCP-N dosimeters. These LiF:Mg,Cu,P dosimeters are in form of 4.5 mm diameter circular pellets with 0.9 mm thickness. Sets of three dosimeters were prepared for each irradiation used for the performance testing. Prior to every exposure, the TLDs were annealed 10 minutes in an oven at 240°C, followed by fast cooling in a freezer down to -10°C. In order to monitor the accumulated dose during transportation and storage, two sets of four TLDs were used. Following the exposure to a certain radiation field, the dosimeters were heated at 120°C in an oven for a period of 30 minutes. The TLDs were read on a Harshaw 5500 system with a constant temperature increment rate of 10°C/s, in range from room temperature up to 240°C. The TLD signal output was corrected for the individual sensitivity of each dosimeter, which was determined by using a reference ^{137}Cs radionuclide source.

2.4. Irradiation set up at the SSDL

The performance testing of solid-state QC dosimeters used in diagnostic and interventional radiology was performed in the Secondary Standard Dosimetry Laboratory (SSDL) of Vinca Institute of Nuclear Sciences (IAEA, 2018). A vented ionisation chamber Magna (Standard Imaging Inc, Middleton, WI, USA) was used as a reference standard, whereas a dedicated metrological continuous radiation mode X-ray unit X80-225 kV-E (Hopewell Designs, Alpharetta, GA, USA) was used to generate standard and non-standard beam qualities.

Traceability to primary standard, for standard and non-standard radiation qualities was ensured by calibration of the reference standard in French PSDL in CEA. The reference air kerma rate values were measured by using a reference standard ionisation chamber Exradin A600 whose calibration coefficients are displayed in Table 2, for standard (RQR8) and non-standard radiation qualities.

Irradiation set up for all dosimeters was arranged in accordance with the International Atomic Energy Agency (IAEA) Code of Practice TRS 457 (IAEA, 2007), applying a substitution method, while using a monitor chamber in order to account for X-ray beam output variations. The reference air kerma rate measurements were corrected for the influence of ambient conditions, whereas the stability of the X-ray generator was monitored using a monitor chamber type PTW 34014 (PTW, Freiburg, Germany). Air-kerma rate was measured at the focus to detector distance of 100 cm.

The dosimeter performance tests for both standard and non-standard radiation qualities include energy dependence, angular dependence and the linearity test. The X-ray tube current was held constant at 10 mA for the energy dependence and angular dependence tests, while any variations in the X-ray generator output were accounted for and corrected with the PTW 34014 chamber measurements. In the case of linearity test, variation of air kerma rate was achieved by changing the X-ray tube current values in the range from 3 mA up to 25 mA.

The selected standard radiation quality routinely used for dosimeter calibration in the field of diagnostic radiology in laboratory conditions is the RQR8 (IAEA, 2007). The properties of standard radiation quality and non-standard radiation qualities (Section 2.1) used in this research are presented in Table 2. The inherent filtration for 80 kV and 120 kV non-standard radiation qualities was 2.5 mm Al, and 0.9 mm Cu was added to the inherent filtration to establish radiation qualities denoted as Veridic3 80AlCu and Veridic4 120AlCu, respectively, as presented in Table 2. Veridic1 80Al and Veridic2 120Al radiation qualities were established without any added copper filtration. The half-value layer of Veridic1 80Al beam (2.55 mm Al) is slightly less than the minimum permissible first HVL at 80 kV(2.9 mm Al) as per the current European guidelines (EC, 2012); however, this is deemed to be fairly representative of the low beam qualities used in practice.

During the angular dependence test in RQR8 and Veridic3 80AlCu beams, the range of angle of incidence was set from 0° to ±90°, with an increment of 15°. The dosimeters were positioned free in air, while the dosimeter holders used for positioning contain low Z materials (such as polymethyl methacrylate, PMMA) in order to reduce the contribution of scattered radiation to the primary beam measurements. The angle of incidence was defined between the primary beam axis and the front surface of the dosimeter, where the 0° angle of incidence is achieved by positioning the dosimeter front surface perpendicular to the primary beam axis direction. In order to vary the angle of incidence values the dosimeters with appropriate holders were positioned on a custom-made rotary table. On the X-ray tube focus-detector distance of 100 cm, the dosimeters were positioned within the 99% isodose area, which corresponds to the 8 cm beam diameter uniform X-ray field cross-section surface. Heel effect is negligible in the case of X-ray generators used in

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the calibration laboratories, as evidenced by the investigated field uniformity (Makarić et al., 2019).

Table 2. Properties of radiation qualities used for performance testing of solid-state and thermoluminescent dosimeters. Calibration coefficients of the Exradin A600 ionisation chamber used for reference air kerma values in the QC dosimeter tests are provided in the rightmost column.

Radiation quality	X-ray tube voltage [kV]	Half-value layer [mm Al]	Additional filtration [mm Cu]	Calibration coefficient of reference standard [mGy nC^{-1}]
RQR8	100	3.97	/	17.82
Veridic1 80Al	80	2.55	0	17.90
Veridic3 80AlCu	80	8.63	0.9	17.66
Veridic2 120Al	120	3.73	0	17.76
Veridic4 120AlCu	120	11.33	0.9	17.39

2.5. Solid-state quality control dosimeters performance tests

2.5.1. Energy dependence test

Energy dependence of the dosimeter response is an important characteristic that needs to be accounted for when performing measurements in various radiation fields that may greatly differ from the reference radiation quality, under which the instrument has been calibrated. In this work the influence of photon energy was tested for four solid-state detectors described in Section 2.2. The energy dependence test results are expressed in terms of relative response of the dosimeter, normalized to the response in RQR8 radiation quality. The relative response is determined by using the following equation (IAEA, 2007):

$$r = \frac{R}{R_0} = \frac{M/(Q \cdot N_K \cdot k_D \cdot k_M)}{R_0} \qquad (1)$$

where R and R_0 are the absolute response values for the non-standard radiation qualities and the standard (reference) radiation quality, respectively. The absolute dosimeter response is defined as

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the quotient of the value M indicated by the solid-state detector, and the reference value of air kerma rate defined by the term $Q \cdot N_K \cdot k_D \cdot k_M$, which includes collected charge in the active volume of the ionisation chamber, the ionisation chamber calibration coefficient, the air density correction factor and the monitor chamber correction factor for the X-ray generator output, respectively. The IEC standard 61674 (IEC, 1997) requires a variation in the dosimeter response within ±5% in the 50 kV - 150 kV X-ray tube voltage range, in standard radiation qualities.

2.5.2. Angular dependence test

Pronounced angular dependence of the solid-state dosimeters 'response mainly exists due to their design, e.g. placement of lead backing plates to attenuate the radiation that is incident from the rear of the detector, even though these detectors are potentially sensitive to incident radiation from all directions (Roshau and Hintenlang, 2003). The influence of angle of incidence on the indication of the solid-state detectors was tested in the standard RQR8 radiation quality, and the non-standard Veridic3 80AlCu beam. The relative angular dosimeter response was determined by normalizing the measured absolute response to the response acquired for the 0° angle of incidence, for each beam quality independently. IEC 61674 (IEC, 1997) standard imposes a ±3% upper limit of dosimeter response variation, but this limit is applicable in the angle of incidence range of ±5° from the reference orientation. This study covered much wider range of angles, so this limit is not applicable.

2.5.3. Dose rate dependence test

The linearity test was performed for the standard RQR8 and non-standard Veridic3 80AlCu radiation qualities in the X-ray tube current range from 3 mA up to 25 mA. Those values correspond to the tube current range available on the X-ray system for the selected irradiation settings. The linearity test results were expressed as the normalized dosimeter response to the reference air kerma rate value chosen for the tube current of 9 mA, for each of the radiation qualities separately. According to the IEC 61674 (IEC, 1997) the deviation criteria is ±2% from the calibration condition, over the whole air kerma rate range.

2.6. Thermoluminescent dosimeters performance tests

TLDs containing LiF:Mg,Cu,P pellet material were irradiated in the standard RQR8 radiation quality and non-standard radiation qualities. Previous to irradiation, the TLDs were annealed for ten minutes at 240°C, followed by fast cooling at -10°C. Two sets of four TLDs were used to monitor the accumulated dose during storage and transportation. Following exposure, the dosimeters were heated at 120°C for 30 minutes. Harshaw 5500 system was used for dosimeter readout, and the acquired data was corrected for individual sensitivity of the dosimeters, which was determined by using a reference ^{137}Cs source. Energy dependence, angular dependence and dose rate dependence of the dosimeter response were examined.

2.6.1. Dose rate dependence test

The influence of dose rate on TLD response was studied in the reference RQR8 radiation quality at CEA PSDL using X-ray tube current ranging from 0.9 mA to 24.1 mA, corresponding to air kerma rates between 5 mGy min^{-1} and 140 mGy min^{-1}. Those values correspond to the tube current range available on the X-ray system for the selected irradiation settings. For each of the irradiation conditions response was averaged for a sample of three dosimeters. The response was normalized to the value measured at 5 mGy min^{-1} dose rate.

2.6.2. Angular dependence test

Angle of incidence influence quantity was investigated in the RQR8 radiation quality and the non-standard Veridic3 80AlCu and Veridic2 120Al radiation qualities. Angle values ranged from 0° up to 90°, with a 15° increment, similarly to the angular dependence test of the solid-state

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dosimeters. The symmetry of angular response was tested in the CEA radiation fields for RQR8 and Veridic3 80AlCu qualities, while the response for Veridic2 120Al radiation quality was tested in the Vinca SSDL radiation field. The response was normalized to the value measured at 0° angle of incidence, when the TLD pellet surface is perpendicular to the incident beam.

2.6.3. Energy dependence test

The influence of radiation quality was tested by irradiating the TLD batches in the standard radiation quality RQR8 and the four non-standard qualities. The energy response was normalized to the value acquired for the reference ^{137}Cs radiation field. Variation of the dosimeter response depending on the radiation quality used for the passive dosimetry system calibration was tested by calibrating the system in all five radiation qualities respectively (standard and non-standard).

2.7. Uncertainty assessment

Measurement uncertainty was evaluated for each measurement of variation of QC solid-state detector response with investigated parameters (energy, angle of incidence and dose rate). In all cases, the expanded combined uncertainty (k = 2) was larger than 1/5 of the limit of variation and smaller than 1/2. According to IEC 61674, the limits of variation are expanded by adding the measurement uncertainty (IEC, 1997). Relative response for reference conditions was 1 by definition, and this value has no measurement uncertainty assigned. Expanded combined measurement uncertainty in case of energy dependence was between 2.2% and 2.4%, and most important contributions were calibration factors of reference chamber (for two radiation qualities), reference chamber stability and difference between radiation quality established in CEA PSDL and SSDL of Vinca Institute of Nuclear Sciences. In case of angular dependence and linearity tests, measurement uncertainty was 1.0%. Major contributions were repeatability of measurements by QC dosimeter, change in air density, i.e. temperature and pressure during the test, QC dosimeter positioning, and in case of linearity test – electrometer non-linearity (two electrometers were used for the test). Angle of incidence was measured with absolute measurement uncertainty of 2°.

Regarding dose estimation with TLDs a standard deviation of the energy response of 5% can be estimated taking into account maximum and minimum responses for different system calibrations. The contribution of angular dependence to the measurement uncertainty is a standard uncertainty of 4% ($k = 1$). An expanded uncertainty (with $k = 2$; 95% interval of confidence) of 16% can be estimated for skin dose measurements in interventional procedures with LiF:Mg,Cu,P TLDs, considering the contribution of energy response ($k = 1$, 5%), angular response ($k = 1$, 4%), and the uncertainties associated with the dosimetry system (fading 3%, individual dosimeter sensitivity 2%, repeatability 1%, calibration coefficients 1.4%, and calibration doses 2.2%). Additionally, in cases where the position of maximum skin dose is unknown, a correction factor up to 40% with additional uncertainty with standard deviation of 12% should be used to account for the probability that no dosimeter is in the region of the maximum skin dose (Dabin et al., 2015).

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3. Results

3.1. Solid-state quality control dosimeters

Solid-state dosimeter behavior in the non-standard X-ray beams was evaluated in terms of relative response normalized to the absolute response for the standard RQR8 radiation quality. Results are presented in Fig. 3. Relative response was within 5% for all tested radiation qualities which is in line with the requirements of the standard (IEC, 1997). In the whole HVL range (from 2.55 mm Al for Veridic1 80Al up to 11.33 mm Al for Veridic4 120AlCu), Unfors Xi dosimeter showed excellent performance with the relative response deviation of approximately up to ±1% from the reference value. Other detectors also demonstrated compliance with the requirements of IEC 61674 standard for all radiation qualities (IEC, 1997). The angular dependence of solid-state detector response was measured for standard RQR8 radiation quality (Fig. 4a) and non-standard highly filtered Veridic3 80AlCu radiation quality (Fig. 4b). Solid-state detectors R100B and Unfors Xi showed relatively small angular dependence. When the measurement uncertainty is taken into account, response for ±15° is within the limits of variation defined in IEC 61674 for both detectors in both radiation qualities. However, more robust multiple element detectors, MPD and Piranha, have a rapidly decreasing angular response with the increase of angle and all the results are outside of limits of variation in both radiation qualities. Dose rate dependence of the solid-state dosimeters was tested in the X-ray tube current range from 3 mA to 25 mA, by normalizing the response to the dose rate value at 9 mA. Results are presented in Fig. 5a and 5b for standard RQR8 radiation quality and non-standard highly filtered Veridic3 80AlCu radiation quality, respectively. All relative responses were between 0.99 and 1.01 for both standard RQR8 and non-standard Veridic3 80AlCu beam qualities. Considering the measurement uncertainty of 1%, these values are not significantly different from unity.

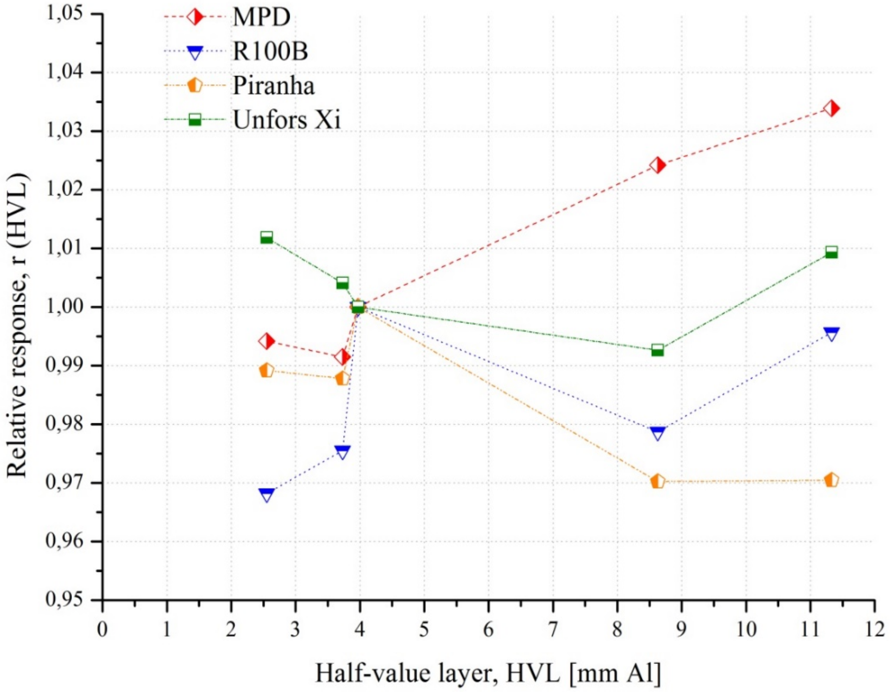

Figure 3. Relative response of four solid-state detectors measured for one standard (reference) radiation quality (RQR8) under laboratory conditions, and four non-standard radiation qualities which correspond to clinical conditions (Veridic1 80Al, Veridic2 120Al, Veridic3 80AlCu and Veridic4 120AlCu).

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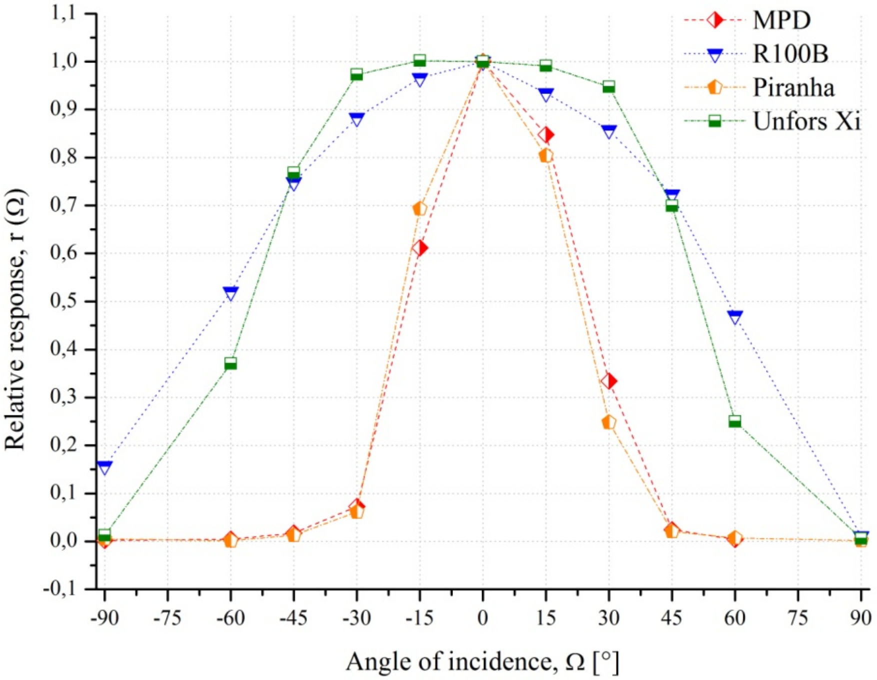

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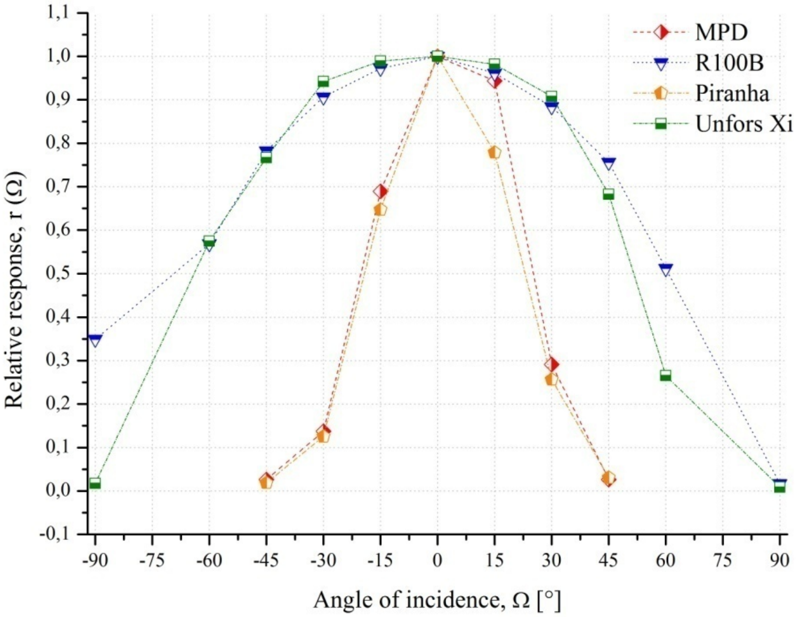

432

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Figure 4. The angular dependence test results of four solid-state detectors for: a) the reference standard RQR8 radiation quality; b) the non-standard Veridic3 80AlCu radiation quality - in the angle range from 0° to ±90°. The relative angular response was normalized to absolute response value for 0°.

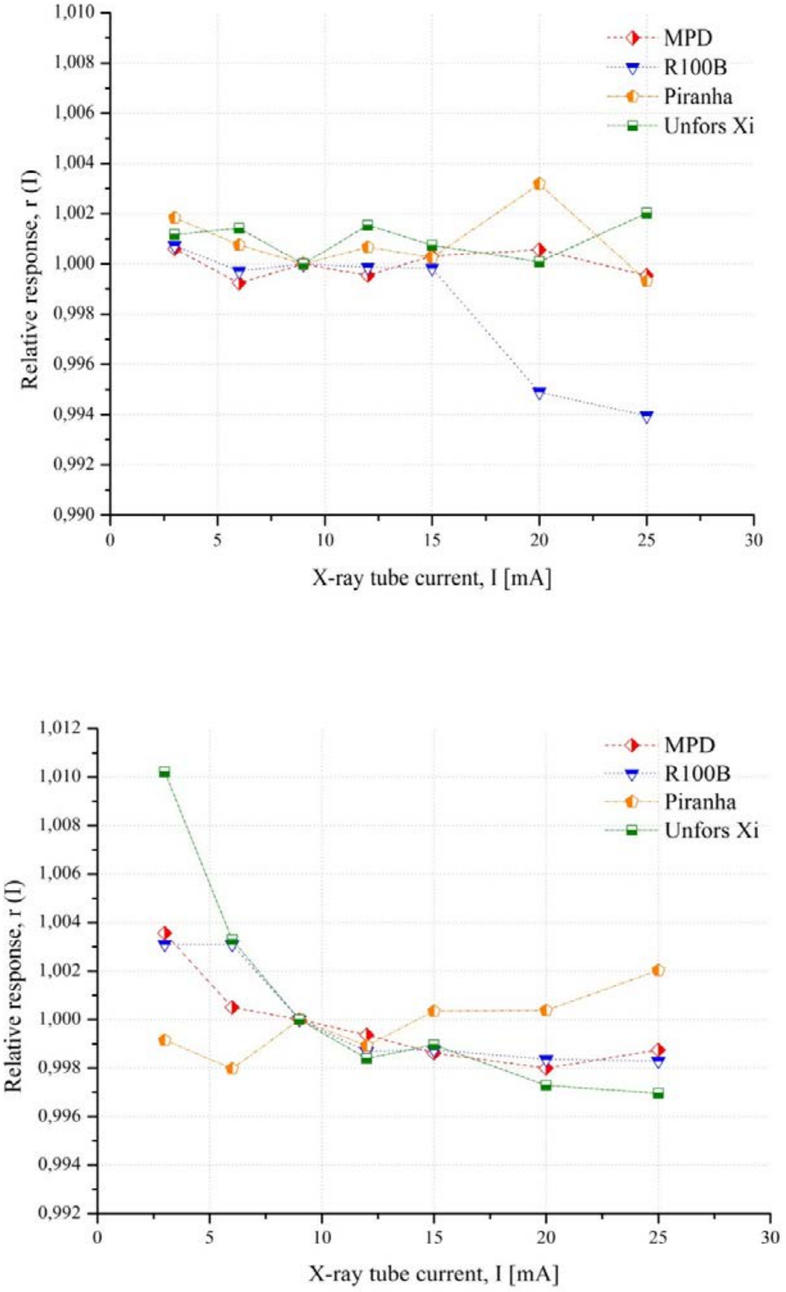

Figure 5. The linearity test results for four solid-state detectors in the air-kerma rate range determined by the X-ray tube current range from 3 mA to 25 mA, for: a) the reference standard RQR8 radiation quality;

b) the non-standard Veridic3 80AlCu radiation quality. The relative response was normalized to the absolute response value at 9 mA X-ray tube current.

3.2. Thermoluminescent dosimeters

TLD performance testing results are presented in Figs. 6-10. Dose rate dependence is shown in Fig. 6, where response was normalized to 5 mGy min^{-1}. Comparison of angular dependence in RQR8 and Veridic2 120Al radiation qualities normalized to 0° is presented in Fig. 7, while the comparison of angular dependence in RQR8 and Veridic3 80AlCu radiation qualities, including response symmetry evaluation is given in Fig. 8. The energy response of TLDs for all five radiation qualities (one standard, four non-standard) is normalized to ^{137}Cs and compared with other energy dependence studies of the LiF:Mg,Cu,P material in Fig. 9. Fig. 10 shows the influence of system calibration radiation quality on the relative energy response.

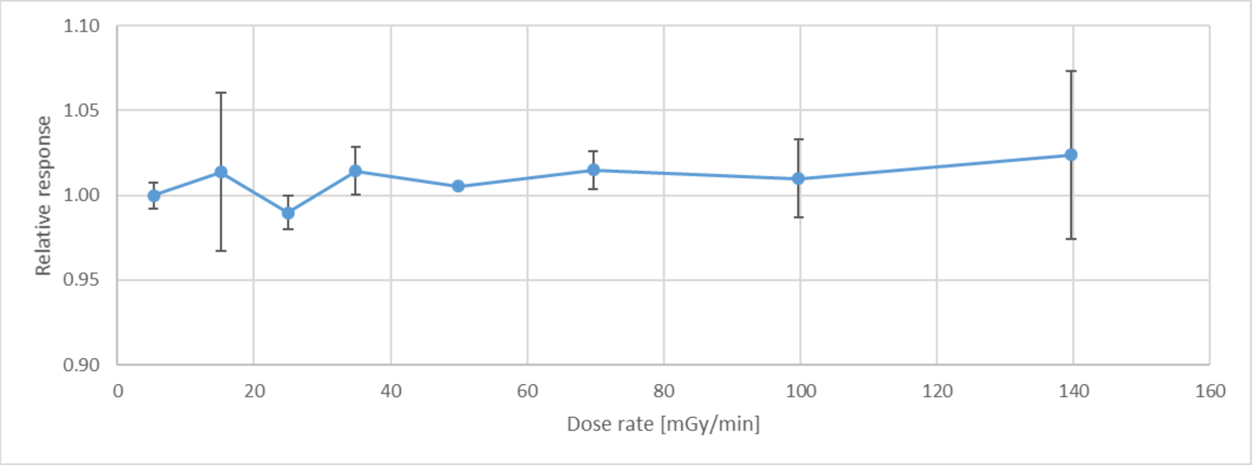

Figure 6. Dose rate dependence of the LiF:Mg,Cu,P response for the RQR8 radiation quality, normalized to the value measured at 5 mGy min^{-1}. Each data point represents average response of three dosimeters, and the error bars represent standard deviation of the average response.

The relative angular response has values within ±4% for angles of incidence between 0° and 60°, while the deviation is between -10% and +4% over the whole angle range.

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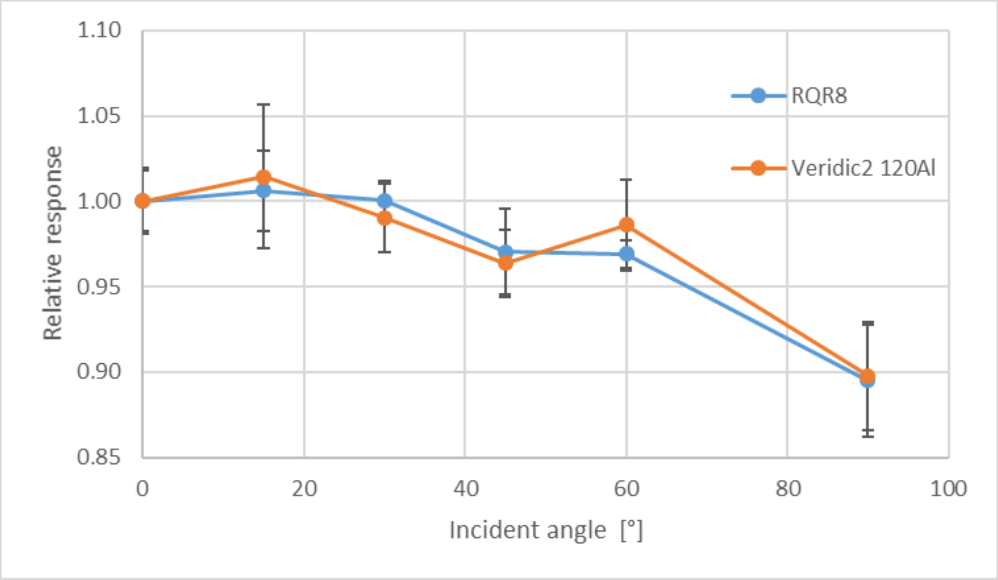

Figure 7. Angular dependence of LiF:Mg,Cu,P response normalized to the value at 0°. Combined energy and angular dependence was tested for RQR8 and Veridic2 120Al radiation qualities. Each data point represents average response of three dosimeters, and the error bars represent standard deviation of the average response.

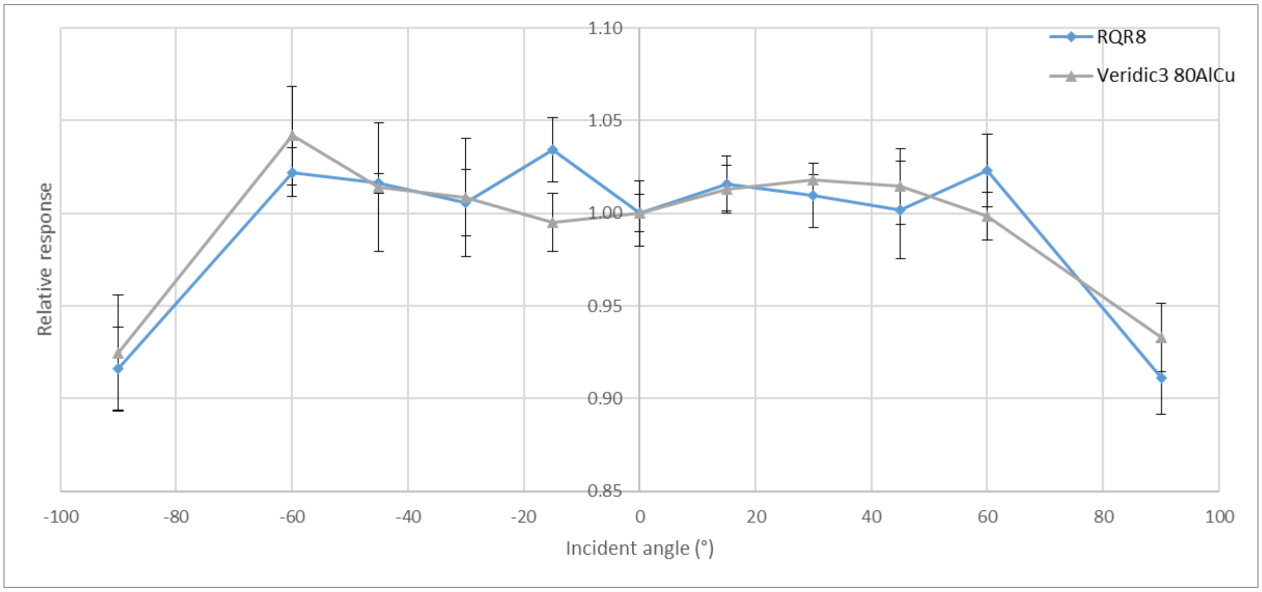

Figure 8. Angular dependence of LiF:Mg,Cu,P response normalized to the value at 0°. Combined energy and angular dependence was tested for RQR8 and Veridic3 80AlCu radiation qualities, including symmetry of the angular response. Each data point represents average response of three dosimeters, and the error bars represent standard deviation of the average response.

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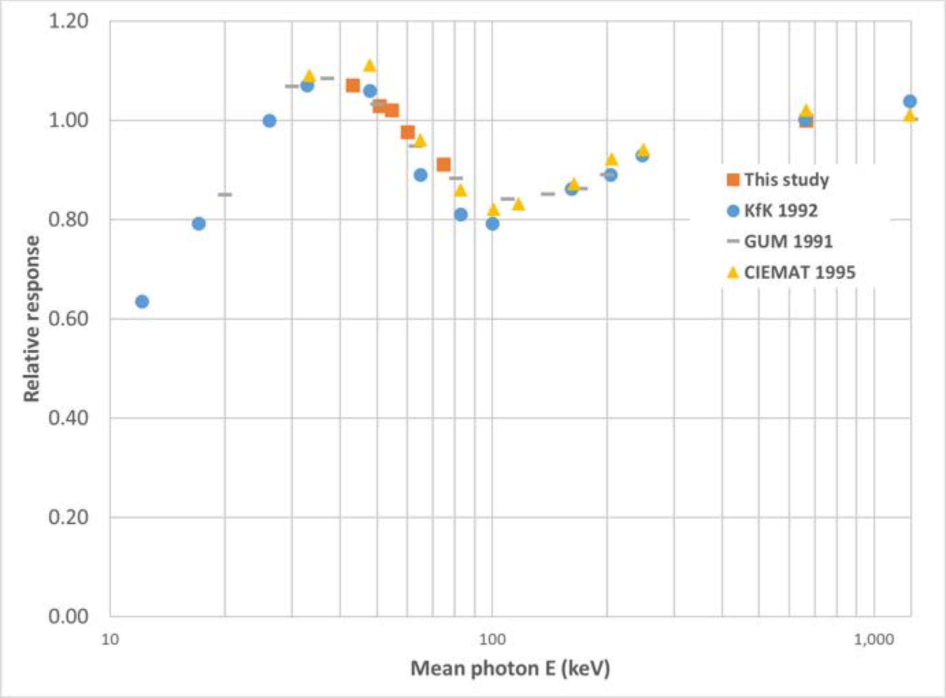

Figure 9. Energy dependence of the LiF:Mg,Cu,P response comparison from various studies (Olko et al., 2002).

To evaluate the impact of the TLD system calibration to the TLD energy response, the calibration of the TLDs was performed in each of the tested radiation qualities. As presented in Fig. 12, relative response of TLDs was calculated as a ratio of the TLD response in any radiation quality and TLD response in the radiation quality used for calibration.

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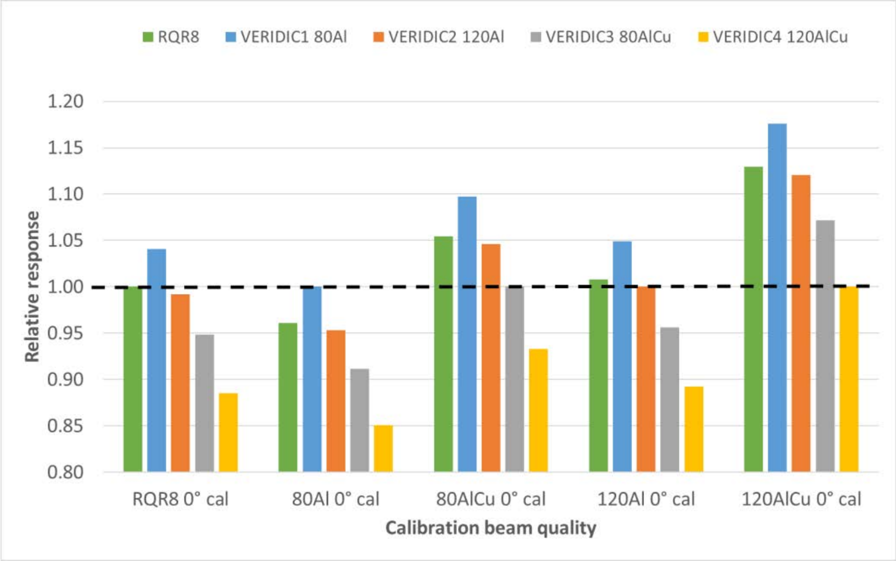

Figure 10. Energy dependence of the LiF:Mg,Cu,P response for the system calibrated for RQR8, Veridic1 80Al, Veridic3 80AlCu, Veridic2 120Al and Veridic4 120AlCu, respectively.

4.Discussion

Although it is generally believed that semiconductors have pronounced energy dependence (Roshau and Hintenlang, 2003), results of tests in this study demonstrated good performance in terms of energy dependence, i.e. relative response was within 5% for all tested radiation qualities which is in line with the requirements of the standard (IEC, 1997). In the whole HVL range Unfors Xi dosimeter showed excellent performance with the relative response deviation of approximately up to ±1% from the reference value. All the other detectors also conform to the requirements of IEC 61674 standard for all radiation qualities, even though the range of HVLs was wider than the minimum rated range. Seven out of 12 relative response values for these detectors were not significantly different from unity.

Tests performed to evaluate the influence of angle of incidence showed that some dosimeters behaved well even for angles of incidence up to ±30°. Solid-state dosimeters are very sensitive to the influence of angle of incidence, but R100B and Unfors Xi show relatively small angular dependence. When the measurement uncertainty is taken into account, response for ±15° is within the limits of variation defined in IEC 61674 for both detectors in both radiation qualities. On the other hand, more robust multiple element detectors, MPD and Piranha, have a rapidly decreasing angular response with the increase of angle and all the results are outside of limits of variation in both radiation qualities. It should be noted that all the tested angles were outside of the minimum rated range. All dosimeters show similar variation in response with increasing angle of incidence in both standard and non-standard radiation quality.

Performance testing of X-ray equipment often requires the assessment of doses and dose rates for X-ray beams with many different radiation qualities and in non-ideal conditions. Solid state dosimeters provide a viable alternative to ionization chambers and are configured to give measurements of air kerma independent of radiation quality. The solid state detectors are mounted on lead backing plates, affecting the variation in sensitivity with angle. Nevertheless, it is important to note that other factors, such as direction of incident radiation, extra focal radiation and scattered radiation could increase the overall uncertainty of the measurement and potentially push the dosimeters outside of the acceptable range, which can be expected with the effect of scattered radiation (IAEA, 2007; Martin et al., 2007, Hourdakis et al., 2010).

The effects of dose rate in the tested continuous fields produced by the X-ray generator in laboratory conditions were not significant, considering the IEC standard requirements of ±2% (IEC, 1997). All relative responses were between 0.99 and 1.01 for both standard RQR8 and non-standard Veridic3 80AlCu beam qualities. Considering the measurement uncertainty of 1%, these values are not significantly different from unity. However, it should be noted that tube current ranging only up to about 25 mA (continuous) were used, due to technical limitation of the X-ray generator, while values up to about 1000 mA (pulsed) can be encountered in practice (for instance, Farah et al., 2015).

The presented results are in good agreement with similar studies (Martin et al., 2007, Hourdakis et al., 2010) that confirmed that different irradiation conditions, acquisition modes (radiographic or fluoroscopic), air kerma rate values, as well as the dosimeter's operational mode (integrating or dose rate) did not affect the response of dosimeters significantly.

The energy dependence of the LiF:Mg,Cu,P is the dominant source of measurement uncertainty of skin dose measurements. Therefore, it is important to choose an appropriate highly filtered radiation quality, characteristic for interventional procedures, in order to calibrate the system. From the present work, an incorrect radiation quality can cause an under- or over-estimation of the dose by 15%. However, without specific knowledge of the radiation qualities used in interventional procedures assuming a uniform distribution covering the radiation quality energies used in this work, would result in 5% standard deviation of the energy response. The influence of the backscattered radiation in interventional procedures is not taken into account when estimating the before-mentioned standard deviation. However, the uncertainty component caused by backscattered radiation is limited, owing to a limited decrease in mean energy by 6-17% compared to the incident beam (Aoki and Koyama, 2002) and no more than 80% increase in the primary beam dose at the entrance surface (usually 30 to 40%) for various field sizes and photon energies encountered in interventional procedures (Benmakhlouf et al., 2013).

Besides the energy dependence, angular dependence of LiF:Mg,Cu,P response is a major contributor to the measurement uncertainty, with under-response up to 10% for perpendicular exposure of dosimeters. Owing to the various angulations of the X-ray source during interventional procedures, passive dosimeters can be irradiated from multiple directions, resulting in a uniform distribution of angle of incidence, and an expanded uncertainty of 4%.

In order to limit the uncertainty associated with the energy response of thermoluminescent dosimeters, calibration of the passive dosimetry system should be performed in a beam quality which results in the smallest extent of relative response. According to the data presented in Fig. 10, the use of Veridic1 80Al and Veridic4 120AlCu radiation qualities for system calibration would lead to systematic underestimation or overestimation of the dose, respectively. On the other hand, relative responses for calibration radiation qualities RQR8, Veridic2 120Al and Veridic3 80AlCu are spread around unity, i.e. these qualities appear to be more adequate for passive dosimetry system calibration.

The dose rate dependence of LiF:Mg,Cu,P variation is between -1% and +2% over the whole dose rate range, based on the average TLD response (calculated for a sample of three dosimeters for each dose rate value). Considering the inherent measurement uncertainty of the TLDs, these results are not significantly different from unity. Again, it should not be overlooked that tube current ranging only up to about 25 mA (continuous) were used, while values up to about 1000 mA (pulsed) can be encountered in practice.

This study is first to our knowledge, that investigated the performance of diagnostic dosimeters in radiation qualities typical for interventional procedures, following essential principle of metrological traceability. The results of this study revealed that modern solid-state dosimeters and TLDs have good performance in a range of irradiation conditions, including non-standard conditions typical for clinical environment.

5. Conclusion

The results of testing of two types of dosimeters commonly used in clinical practice in diagnostic and interventional radiology are presented in this work. The tests included investigation of the energy dependence, angular dependence and linearity of the dosimeter response. Solid-state dosimeters containing single or multiple detector elements showed excellent energy dependence and linearity. Relative response normalized to the standard RQR8 radiation quality was within

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±4% for all dosimeters. Deviations from linearity were not significant for any of the tested solid state dosimeters. Angular dependence tests have shown that the tested single element detector meets the standard requirements even outside of the minimum rated range, up to 30°. However, multiple element detectors have rapidly decreasing response with increasing angle of incidence and can be used only in perpendicular geometry. TLDs have shown satisfactory linearity in the range of ±3% from the reference dose rate value, and the relative angular response within ±4% over a wide range of angles of incidence up to 60°. Energy dependence of the TLD response was in good agreement with previous studies (Olko et al, 2002).

In order to minimize the measurement uncertainty, traceable dosimeter calibration and testing should be performed in the radiation beam qualities which correspond to the radiation beams used in fluoroscopically guided interventional procedures in clinical conditions, in addition to the standard radiation beam qualities used for regular calibration of the QC equipment (IEC, 2005). Selecting appropriate radiation quality for passive dosimetry system calibration performed in this work will contribute to the decrease of the measurement uncertainty.

By comparing the energy response of QC dosimeters in standard RQR8 and non-standard radiation fields it can be concluded that for some dosimeter types the deviation introduced by non-standard qualities can influence the dosimeter indication up to ±4%, in the range of beam qualities that can be generated during a single interventional procedure, due to its dynamic nature and rapid change of X-ray tube voltage and filtration. This effect is more pronounced for certain types of dosimeters. In addition, due to the generally lower air kerma rates with non-standard beam qualities, accuracy of dose measurement can also be affected by the dose rate dependence of certain types of dosimeters. Therefore, examination of dosimeter response and performance in non-standard beams is recommended. Furthermore, the user should be aware of the properties of

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the dosimeters used, in order to use the instrument correctly and control the measurement uncertainty.

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References

Aoki, K., Koyama, M., 2002. Measurement of backscattered X-ray spectra at the water surface in the energy range 60 kV to 120 kV. Phys Med Biol. 47(7):1205-17. doi: 10.1088/0031-9155/47/7/314

Apostolakopoulos, F.H., Kržanović, N., Stanković, K., Perazić, L., 2019. Response of TL and OSL passive personal dosimetry systems in poly-energetic and multi-directional photon radiation fields. Applied Radiation and Isotopes. 151:235-241. doi: 10.1016/j.apradiso.2019.06.023

Benmakhlouf, H., Fransson, A., Andreo, P., 2013. Influence of phantom thickness and material on the backscatter factors for diagnostic X-ray beam dosimetry. Phys Med Biol. 58(2):247-60. doi: 10.1088/0031-9155/58/2/247.

Blideanu, V, Plagnard, J., Dabin, J., Ciraj Bjelac, O., Feghali, J.A., 2020. D9.142 – Dosimeter calibration and measurement uncertainties in Interventional Cardiology. Available online at: https://concert-h2020.eu/en/Publications

Bogaert, E., Bacher, K., Lemmens, K., Carlier, M., Desmet, W., De Wagter, X., Dijan, D., Hanet, C., Heyndrickx, G., Legrand V., Taeymans Y., Thierens, H., 2009. A large-scale multicentre study of patient skin doses in interventional cardiology: dose-area product action levels and dose reference levels. Br J Radiol. 82(976):303-12. doi: 10.1259/bjr/29449648

Carinou, E., Boziari, A., Askounis, P., Mikulis, A., Kamenopolou, V., 2008. Energy dependence of TLD 100 and MCP-N detectors. Radiation Measurements. 43(2-6):599-602. doi: 10.1016/j.radmeas.2007.12.042

Dabin, J., Negri, A., Farah, J., Ciraj-Bjelac, O., Clairand, I., De Angelis, C., Domienik, J., Jarvinen, H., Kopec, R., Majer, M., Malchair, F., Novak, L., Siskonen, T., Vahnavere, F., Trianni, A., Knežević, Ž., 2015. Characterisation of grids of point detectors in maximum skin dose measurement in fluoroscopically-guided interventional procedures. Phys Med. 31(8):1112-1117. doi: 10.1016/j.ejmp.2015.08.006

Dabin, J., Maeremans, J., Berus, D., Schoonjans, W., Tamborino, G., Dens, J., Kayaert, P., 2018. Dosimetry during percutaneous coronary interventions of chronic total occlusions. Radiation Protection Dosimetry, Vol. 181 (2), pp. 120-128. doi: 10.1093/rpd/ncx303

Dabin, J., Bildeanu, V., Ciraj-Bjelac, O., Deleu, M., De Monte, F., Feghali, J.A., Gallagher, A., Knežević, Ž., Maccia, C., Malchair, F., Merce, M.S., Simantirakis, G., 2020. D9.143 - VERIDIC Acceptance and quality control protocols for skin dose calculating software solutions in interventional cardiology. Available online at: https://www.concert-h2020.eu/en/Publications.

Davis S.D., Ross, C.K., Mobit, P.N., Van der Zwan, L., Chase, W.J., Shortt, K.R., 2003. The response of LiF thermoluminescence dosimeters to photon beams in the energy range from 30 kV X rays to ^{60}Co gamma rays. Radiation Protection Dosimetry. 106(1):33-43. doi: 10.1093/oxfordjournals.rpd.a006332.

Didier, R., Bourhis, D., Oueslati, C., Nasr, B., Le Ven, F., Noel, A., Jobic, Y., Damien, P., Pene-Baverez, D., Mansourati, J., Nicol, P.P., Gilard, M., 2019. In vivo validation of Dosemap software use in interventional cardiology with dosimetrics indicatios and peak skin dose evalutaion. Catheter Cardiovasc Interv. 94(2):216-222. doi: 10.1002/ccd.28097

Duggan, L., Hood, C., Warren-Forward, H., Haque, M., Kron, T., 2004. Variations in dose response with X-ray energy of LiF:Mg,Cu,P thermoluminescence dosimeters: implications for clinical dosimetry. Phys Med Biol. 49(17):3831-45. doi: 10.1088/0031-9155/49/17/001

European Commision, 2012. Criteria for Acceptability of Medical Radiological Equipment used in Diagnostic Radiology, Nuclear Medicine and Radiotherapy. Radiation Protection n° 162.

Greffier, J., Van Ngoc Ty, C., Bonniaud, G., Moliner, G., Ledermann, B., Schmutz, L., Cornillet, L., Cayla, G., Beregi, J.P., Pereira, F., 2017. Assessment of peak skin dose in interventional

cardiology: A comparison between Gafchromic film and dosimetric software em.dose. Phys Med. 38:16-22.
doi: 10.1016/j.ejmp.2017.05.044

Farah, J., Trianni, A., Ciraj-Bjelac, O., Clairand, I., De Angelis, C., Delle Canne, S., Hadid, L., Huet, C., Jarvinen, H., Negri, A., Novak, L., Pinto, M., Siskonen, T., Waryn, M.J., Knežević, Ž., 2015. Characterization of XR-RV3 GafChromic films in standard laboratory and in clinical conditions and means to evaluate uncertainties and reduce errors. Med Phys. 42(7):4211-26. doi: 10.1118/1.4922132.

Hourdakis, C.J., Boziari, A., Manetou, A., 2010. Performance Evaluation of Diagnostic Radiology Dosimeters in Clinical and Calibration X-ray beams. Health Phys. 98(5):704-716. doi: 10.1097/HP.0b013e3181d18d45.

International Atomic Energy Agency, 2018. SSDL Network Charter, 2nd Edition; The IAEA/WHO Network of Secondary Standards Dosimetry Laboratories.

International Atomic Energy Agency, 2007. Dosimetry in Diagnostic Radiology: An International Code of Practice. Technical Report Series No. 457, IAEA TRS 457.

International Electrotechnic Commission, 2005. Medical diagnostic X-ray equipment - Radiation conditions for use in the determination of characteristics, IEC 61267.

International Electrotechnic Commision, 1997. Medical electrical equipment - Dosimeters with ionizaion chambers and/or semiconductor detectors as used in X-ray diagnostic imaging, IEC 61674.

Järvinen, H., Turak, O., Ginjaurme, M., Daures, J., Hourdakis, C., Ferrari, P., Mariotti, F., 2015. Technical aspects on DAP calibration and CT calibration. European Radiation Dosimetry e.V. EURADOS Report 2015-03, Braunschweig, Germany. ISBN: 978-3-943701-10-4.

Kron, T., Duggan, L., Smith, T., Rosenfield, A., Butson, M., Kaplan, G., Howlett, S., Hyodo, K., 1998. Dose response of various radiation detectors to synchrotron radiation. Phys Med Biol. 43(11):3235-59. doi: 10.1088/0031-9155/43/11/006

Martin, C.J., 2007. An evaluation of semiconductor and ionisation chamber detectors for diagnostic X-ray dosimetry measurements. Phys Med Biol. 52(15):4465-80. doi: 10.1088/0031-9155/52/15/007

Makarić, V., Živanović, M., Kržanović, N., Đaletić, M., 2019. Determination of uniformity and field size of reference X-ray beams. Proc. of XXX Symposium of Society for Radiation Protection of Serbia and Montenegro, 2nd-4th October, Divčibare, Serbia, 2019. ISBN: 978-86-7306-154-2.

Moscovitch, M., Horowitz, Y.S., 2006. Thermoluminescent materials for medical applications: LiF:Mg,Ti and LiF:Mg,Cu,P. Radiation Measurements. 41: S71-S77. doi: 10.1016/j.radmeas.2007.01.008

Nunn, A.A., Davis, S.D., Micka, J.A., DeWerd, L.A., 2008. Li:Mg,Ti TLD response as a function of photon energy for moderately filtered X-ray spectra in the range of 20-250 kV relative to ^{60}Co. Med Phys. 35(5):1859-69. doi: 10.1118/1.2898137

Olko, P., Bilski, P., Kim, J.L., 2002. Microdosimetric interpretation of the photon energy response of LiF:Mg,Ti detectors. Radiation Protection Dosimetry. 100(1-4):119-22. doi: 10.1093/oxfordjournals.rpd.a005826

Parisi, A., Dabin, J., Schoonjans, W., Van Hoey, O., Megret, P., Vanhavere, F., 2019. Photon energy response of LiF:Mg,Ti (MTS) and LiF:Mg,Cu,P (MCP) thermoluminescent detectors: Experimental measurements and microdosimetric modeling. Radiation Physics and Chemistry. 163:67-73.
doi: 10.1016/j.radphyschem.2019.05.021

Poludniowski, G., Landry, G., DeBlois, F., Evans, P.M., Verhaegen, F., 2009. SpekCalc: a program to calculate photon spectra from tungsten anode x-ray tubes. Phys Med Biol. 54(19):N433-8.
doi: 10.1088/0031-9155/54/19/N01

Plagnard, J., 2014. Comparison of measured and calculated spectra emitted by the X-ray tube used at the Gustave Roussy radiobiological service. X-Ray Spectrometry, Vol 43(5). doi: 10.1002/xrs.2554

Roshau J.R., Hintenlang D.E., 2003. Characterization of the angular response of an isotropic MOSFET dosemeter. Health Phys. 84 376-79. doi: 10.1097/00004032-200303000-00012

Saez-Vergara, J.C., Romero, A.M., Ginjaurme, M., Ortega, X., Miralles, H., 1999. Photon energy response matrix for environmental monitoring systems based on LiF:Mg,Ti and Hypersensitive phosphors (LiF:Mg,Cu,P and a-Al_2O_3:C). Radiation Protection Dosimetry. 85(1-4):207-211. doi: 10.1093/oxfordjournals.rpd.a032835

Salomon E, Homolka P, Csete I, Toroi P. Performance of semiconductor dosimeters with a range of radiation qualities used for mammography: A calibration laboratory study. Med Phys. 2020 Mar;47(3):1372-1378.

Tse, J., McLean, D., 2015. Investigation of the clinical performance of a novel solid-state diagnostic dosimeter. J Appl Clin Med Phys. 16(4): 244-253. doi: 10.1120/jacmp. v16i4.5439
United Nations Scientific Committee on the Effects of Atomic Radiation, 2011. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2010 - 57th session, includes scientific report: Summary of Low-dose Radiation Effects on Health.

Figure captions

Figure 1. Schematic representation of the spectrometer positioning in the X-ray field (left), and the experimental set-up used for the X-ray spectra measurements, emitted by the CEA X-ray generator (right).

Figure 2. Energy spectra for the IC radiation qualities and the standard RQR8 radiation quality

Figure 3. Relative response of four solid-state detectors measured for one standard (reference) radiation quality (RQR8) under laboratory conditions, and four non-standard radiation qualities which correspond to clinical conditions (Veridic1 80Al, Veridic2 120Al, Veridic3 80AlCu and Veridic4 120AlCu).

Figure 4. The angular dependence test results of four solid-state detectors for: a) the reference standard RQR8 radiation quality; b) the non-standard Veridic3 80AlCu radiation quality - in the angle range from 0° to ±90°. The relative angular response was normalized to absolute response value for 0°.

Figure 5. The linearity test results for four solid-state detectors in the air-kerma rate range determined by the X-ray tube current range from 3 mA to 25 mA, for: a) the reference standard RQR8 radiation quality; b) the non-standard Veridic3 80AlCu radiation quality. The relative response was normalized to the absolute response value at 9 mA X-ray tube current.

Figure 6. Dose rate dependence of the LiF:Mg,Cu,P response for the RQR8 radiation quality, normalized to the value measured at 5 mGy min^{-1}*. Each data point represents average response of three dosimeters, and the error bars represent standard deviation of the average response.*

Figure 7. Angular dependence of LiF:Mg,Cu,P response normalized to the value at 0°. Combined energy and angular dependence was tested for RQR8 and Veridic2 120Al radiation qualities. Each data point represents average response of three dosimeters, and the error bars represent standard deviation of the average response.

Figure 8. Angular dependence of LiF:Mg,Cu,P response normalized to the value at 0°. Combined energy and angular dependence was tested for RQR8 and Veridic3 80AlCu radiation qualities, including

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symmetry of the angular response. Each data point represents average response of three dosimeters, and the error bars represent standard deviation of the average response.

Figure 9. Energy dependence of the LiF:Mg,Cu,P response comparison from various studies (Olko et al., 2002).

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Tables

Table 1. Technical specifications of the tested QC solid-state dosimeters.

Table 2. Properties of radiation qualities used for performance testing of solid-state and thermoluminescent dosimeters. Calibration coefficients of the Exradin A600 ionisation chamber used for reference air kerma values in the QC dosimeter tests are provided in the rightmost column.

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