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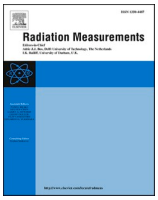

Influence of anode/filtration setup on X-ray multimeter energy response in mammography applications

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ABSTRACT

Quality control and assurance of mammography X-ray generators include the use of solid-state detectors and/or ionization chambers calibrated in standard reference radiation fields. The IEC 61267:2005 standard defines reference mammography radiation fields for Mo/Mo anode/filtration, while various anode/filtration combinations are encountered in clinical mammography X-ray units. Not all Secondary Standard Dosimetry Laboratories have an X-ray generator with Mo/Mo radiation setup. Thus, traceability can be established only for the available anode/filter combinations, commonly limited to W/Al. In this study, W/Al radiation fields were established under laboratory conditions by performing half-value layer measurements. Then, four solid-state detectors were characterized. X-ray multimeter performance was evaluated in terms of energy response in the W/Al radiation fields. In the laboratory conditions, the energy response of the dosimeters had a large deviation from unity for dosimeters without appropriate anode/filter combination selected in the software settings, even though most of the dosimeters had a uniform relative response. The discrepancy in the response was further investigated by examining its variation induced by available detector software settings, and it was determined that the dosimeter response can vary up to 20 %. In a clinical setup, the half-value layer was determined, and detector performance was examined. Dosimeters were tested in clinical fields with Mo/Mo, Mo/Rh, W/Rh, W/Ag anode/filter combinations in the X-ray tube voltage range from 25 kV to 35 kV. For most clinical radiation fields, multi-element detectors had energy response deviation within ±5 %. The single-element detector had one software setting available and exhibited strong energy dependence. Extensive testing of detector response, such as presented in this paper. allows for correction factor interpolation based on the half-value layer.

1. Introduction

One of the leading health problems in the world is breast cancer in women. If discovered in the early stages breast cancer is highly treatable, and regular mammography screening examinations for women are recommended as a diagnostic procedure used for the detection of microscale changes in breasts. Screening and diagnostic mammography procedures provide an X-ray image of the breast tissue. Depending on the size and composition of the breast tissue, different exposure parameters and anode/filter combinations are used. Patient risk assessment for mammography medical imaging procedures is expressed by estimating the mean glandular dose (MGD) delivered to the breast tissue (Dance et al., 2000). DICOM data provided by digital mammography systems include data on incident air kerma (recorded as entrance dose, ED) and MGD (recorded as organ dose, OD). The entrance dose recorded value can differ from the true value due to changes in the X-ray tube voltage output, and the organ dose is always an approximation since it is assumed that every breast tissue has the same composition (Gennaro et al., 2020). In research by Gennaro et al., it was estimated that the patient-specific calculated MGD can differ from the

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mammography-unit-reported OD up to 10 %. Automatic exposure control (AEC) systems, present as an integral part of mammography units, are used for optimisation of image quality produced during mammography screening, with respect to minimizing the MGD. Testing of the AEC is part of the quality control (QC) procedure for conventional and digital mammography. Quality control in mammography is necessary to ensure that X-ray generators are functioning properly, thus performing medical imaging of satisfying quality while minimizing the dose delivered to the patient during these procedures.

The most common measurement devices used for mammography QC are ionization chambers (ICs) and solid-state detectors (SSDs) used as stand-alone dosimeters or incorporated into X-ray multimeters (XMMs) (with associated electrometer modules). XMMs are based on (one or more) silicon solid-state detectors. Due to the availability of different software correction factors and built-in detector filtrations, these devices are suitable for QC in various diagnostic radiology modalities (radiography, mammography, fluoroscopy, computerized tomography etc.). Simultaneous measurements of multiple physical quantities such as air kerma, time and pseudo-quantities such as half-value layer (HVL) and total filtration (TF) (Krzanovic et al., 2021) can be performed. In general, they exhibit a pronounced energy response compared to reference class dosimeters (e.g. ionization chambers) (Witzani et al., 2004). Many commercial XMMs have a separate detector specified for mammography, because mammography procedures use photons with very low energies unlike other medical imaging modalities. To ensure that the X-ray multimeters provide reliable measurement data and are traceable to primary standards for measured quantities (air kerma rate and practical peak voltage) calibration against primary or secondary standard is necessary (Correa et al., 2012). In the case of pseudo-quantities such as half-value layer and total filtration calibration is not common (even though this data can be provided by manufacturers). Protocol for calibration of diagnostic dosimeters in reference radiation fields is given in the International Atomic Energy Agency (IAEA) document TRS 457 Code of Practice (IAEA, 2007). This protocol is established based on the radiation conditions described in the IEC 61267:2005 international standard (IEC, 2005). Calibration of such devices is performed in standard reference radiation fields of known properties, referred to as radiation qualities. It is common and recommended by the standards (IEC, 2005; IAEA, 2007) to use the HVL of the primary beam for characterization of the photon spectra radiation quality and to compare them between different laboratories. This is also the approach that is used in this research. However, other pseudo-quantities may be better suited for this purpose because different spectra can have the same HVL values. To describe the X-ray spectra, some authors use other quantities, such as effective energy or mean energy of the spectrum (Ketelhut et al., 2021; Hernandez-Guzman et al., 2022). In general radiography, standard radiation qualities from RQR series cover the most typical radiation fields used in clinical diagnostic procedures. The standard radiation quality series for mammography, labeled RQR-M (IEC, 2005) is defined for molybdenum X-ray tube anode and molybdenum filtration (Mo/Mo), although many novel combinations of anode/filter materials were recently introduced to the clinical practice (Brateman and Heintz, 2015; Salomon et al., 2020), due to developments in digital mammography. Conventional (screen-film) mammography units frequently utilize Mo/Mo, Rh/Rh and Mo/Rh anode/filter combinations, whereas in digital mammography tungsten (W) is the most commonly used anode material, with various filter materials (Ag, Rh) utilized. W/Al anode/filtration combination is not used for regular mammography screening but only for specific procedures such as tomosynthesis (Brateman and Heintz, 2015).

Recent research by Brateman and Heintz encompassed performance tests of several XMMs provided by different manufacturers (PTW, Radcal, Raysafe, and RTI) in terms of peak tube potential, HVL and air kerma. Calibration of the XMMs used in this research was provided by their respective manufacturers. Performance tests done on two mammography units with different anode/filter combinations showed that measurement results obtained with XMMs can significantly differ from the measurements obtained with reference class dosimeters, as well as that the measurements may not be within manufacturer-stated dosimeter specifications (Brateman and Heintz, 2015). In research by Salomon et al. (2020), several XMMs (manufactured by PTW, Radcal, Raysafe, and RTI) were examined in laboratory conditions for the measurement of X-ray tube potential, HVL and air kerma. Several anode/filtration setups in the 25 kV–35 kV voltage range were established. It was concluded that XMMs can be used in different radiation fields if specific calibration coefficients for each radiation field are known and applied. Otherwise, these settings can introduce additional measurement errors.

In the research presented in this paper, four different solid-state detectors used for QC measurements in mammography have been subjected to performance testing in terms of their response to different photon energy spectra in the range of X-ray tube voltage from 25 kV up to 35 kV. The detectors were tested both in laboratory conditions (W/Al) and in the radiation fields produced by clinical mammography units (Mo/Mo, Mo/Rh, W/Rh, W/Ag).

2. Materials and methods

2.1. X-ray multimeters

Four different commercial XMMs were investigated in this paper: MPD and R100B with associated Barracuda cabinet module (RTI Electronics, Sweden), Piranha stand-alone multimeter unit (RTI Electronics, Sweden) and RaySafe Xi base unit (Raysafe, Sweden) with R/F/MAM detector. Some tested XMMs were discontinued and are replaced by new models (such as Raysafe X2). R100B is a single-element detector intended for low or very low dose rate measurements. MPD and Piranha have multiple detector elements, some of which are used to compute the tube voltage, while others directly measure incident air kerma. Raysafe Xi has three detectors, two for radiography/fluoroscopy (R/F HIGH for high dose rate and R/F LOW for low dose rate) and one for mammography (MAM). Table 1 summarizes the properties of these detectors.

2.2. Traceability and reference chambers

Reference standard ionization chambers have good linearity and energy response in the diagnostic energy range (Hourdakis et al., 2010). The traceability of all measurements was established by using two reference chambers: Exradin Magna A600 and Exradin Magna A650 (Standard Imaging, USA). The chambers were used with UNIDOS Webline electrometer (PTW, Germany). These chambers are suitable for mammography as well as for general diagnostic radiology X-ray fields. Their detection volumes are 1.50 cm^3 and 3.46 cm^3 respectively.

The Exradin Magna A600 was calibrated in the IAEA Dosimetry Laboratory for W/Al based radiation qualities (25–35 kV) and it is the reference standard at the Secondary Standard Dosimetry Laboratory (SSDL). The Exradin Magna A650 is a working standard, and it was used for the clinical measurements. The working standard was calibrated against the reference at the SSDL with W/Al radiation qualities. To cover a larger HVL range of radiation qualities needed for clinical measurements, the Magna A650 was also calibrated for IEC 61267 (IEC, 2005) RQR 2 radiation quality against the secondary standard IC for general radiography (Exradin A3). RQR 2 is defined with 40 kV X-ray tube voltage and 1.40 mm Al first HVL. In the case of the radiation qualities that are validated according to procedures described in IAEA TRS 457 (IAEA, 2007) and that correspond to radiation qualities from calibration certificates, the calibration coefficient was used directly from the calibration certificate. Calibration coefficients for non-reference radiation qualities for clinical mammography units were interpolated by performing an exponential fit of the calibration coefficient as a function of the first HVL value of the primary beam (Fig. 1).

Table 1
Available software settings for anode/filter combination in XMMs.

XMM	X-ray tube voltage [kV]		Anode/filter combination available as per manufacturer software settings							
	min	max	Mo/Mo	Mo/Rh	Rh/Rh	W/Rh	W/Al	W/Ag	Mo/Al	Rh/Al
MPD, RTI Electronics	19	46	✓	✓	✓	✓	✓	✓	×	×
R100B, RTI Electronics	Not specified		✓	×	×	×	×	×	×	×
Black Piranha, RTI Electronics	18	49	✓	✓	✓	✓	✓	✓	✓	×
RaySafe Xi R/F/MAM, Unfors	20	49	✓	✓	✓	✓	×	×	✓	✓

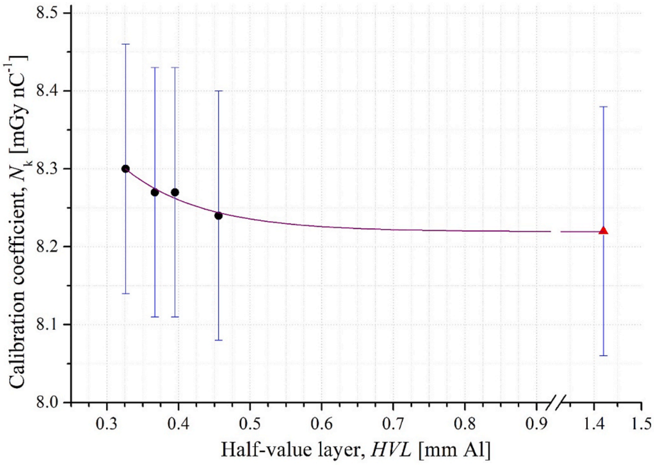

Fig. 1. Exponential fit of the working standard IC calibration coefficient as a function of the first half-value layer for W/Al and RQR2 radiation qualities.

2.3. Calibrations in laboratory settings

Secondary Standard Dosimetry Laboratories (SSDL) perform calibrations of dosimeters in X-ray fields that mostly utilize X-ray generators with tungsten anode (W) paired with aluminium (Al) and copper (Cu) filters (allowing for calibration of radiation protection level dosimeters and diagnostic radiology RQR and RQT series). Most calibration laboratories do not have X-ray generators with interchangeable X-ray tubes, or multiple X-ray irradiation units in the laboratories. Thus, in most cases, it is more convenient to establish non-standard radiation qualities such as the W/Al series.

The W/Al radiation quality series was established in the SSDL at Vinča Institute of Nuclear Sciences (VINS) by using the 0.5 mm Al additional filtration to the inherent filtration of the X-ray tube (following the IAEA Dosimetry Laboratory protocol) (IAEA, 2022). Radiation qualities were validated by performing HVL measurements for X-ray tube voltages of 25 kV, 28 kV, 30 kV and 35 kV, which are the same voltages as for the RQR-M series for Mo/Mo X-ray tubes (IEC, 2005). Hopewell Designs X80-225 kV-E X-ray generator with collimator diameter size of 3.2 cm and 0.4 mm Al inherent filtration was used.

2.4. Laboratory W/Al HVL measurements

HVL was measured following the standard procedure defined in the IAEA TRS 457 (IAEA, 2007) protocol, where the reference device was placed at a source-to-detector distance of 100 cm. Added filtration with a beam-size limiting lead aperture was positioned equidistantly (at 50 cm) from the radiation source and the detector, minimizing the scattered radiation contribution to the measured value. Added filtration thickness was successively increased to record the primary beam attenuation curve.

The HVL was determined by performing a linear regression of the obtained air kerma values for different Al filter thicknesses normalized to the air kerma value measured when no added filtration is present. Linear regression is used as an approximation due to beam hardening and scattered radiation, and it is only performed for data points close to the HVL value. W/Al radiation fields are not included in the IEC standard or the IAEA technical report (IEC, 2005; IAEA, 2007), so standard HVL values are not defined. In this research, the measured HVL values for W/Al radiation fields were compared to the HVL values reported by IAEA SSDL, to whom the VINS SSDL has established air kerma traceability for mammography radiation qualities. It is considered that the radiation quality is validated if the measured HVL differs from the IAEA HVL value less than 0.02 mm Al, which is the criterion defined in the IEC 61267 (IEC, 2005) for the RQR-M radiation qualities. Deviation of VINS HVL values for the established W/Al radiation fields is up to 0.02 mm Al from the IAEA SSDL values for all X-ray tube voltages (25 kV, 28 kV, 30 kV, 35 kV). Reported HVL values for the W/Al anode/filtration setup can significantly vary between different calibration laboratories. The discrepancy in HVL values may be caused by different inherent filtration of the X-ray tubes used in different laboratories, as well as the difference in added filtration thickness, since the manufacturer-stated uncertainty for the Al filter thickness can be significant. In Fig. 2 reported HVL values by four SSDLs (VINS, IAEA, STUK – Radiation and Nuclear Safety Authority, Säteilyturvakeskus, Finland, RBI - Ruđer Bošković Institute, Croatia) are presented. Even though the stated added filtration is 0.5 mm Al for all SSDLs, the differences in HVL can differ up to 0.04 mm Al (W/Al at 35 kV).

2.5. Laboratory W/Al XMM measurements

XMM performance was analysed by comparing the XMM measured values with the secondary standard conventional value. X-ray tube current was set to a constant value of 10 mA and the irradiation time was 10 s, which is equivalent to 100 mAs commonly used for QC in clinical conditions. Dosimeters were positioned at the reference source-to-detector distance of 100 cm following the standard calibration

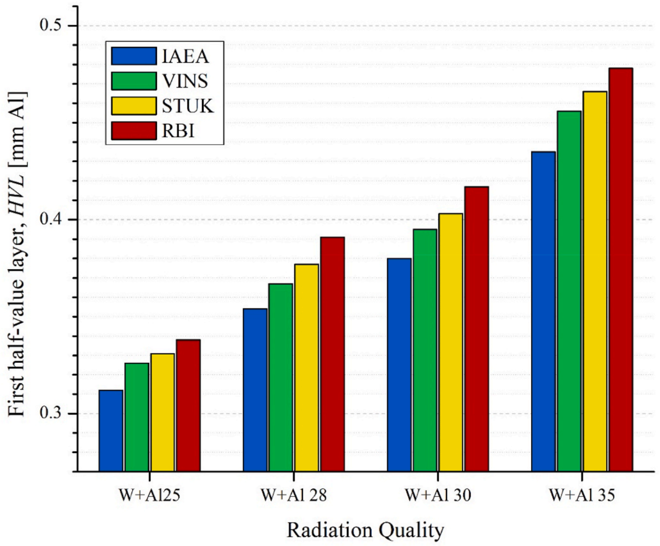

Fig. 2. W/Al radiation quality series HVL values stated by IAEA, VINS, STUK and RBI SSDLs.

procedure. The field diameter at the detector position was 13.4 cm, ensuring that the whole detector surface is irradiated while minimizing the scattered radiation influence, which could provide unreliable measurement data (it should be noted that only the primary radiation beam is of interest in diagnostic radiology calibrations).

XMM settings were adjusted to be in line with the actual radiation beam (W/Al) if possible. Due to detector software limitations for some of the devices, the default setting has been chosen instead (e.g., Mo/Mo for R100B and RaySafe Xi). The setting with no compression paddle (a polycarbonate) was selected for all XMMs since it was not present in the reference radiation beam under laboratory conditions.

Since XMMs usually have several settings for different anode/filter combinations (Table 1), the influence of a potentially incorrect setting of the detector in a radiation field was examined by altering the anode/filtration setting for each XMM while being irradiated in the W/Al fields.

2.6. Calibrations in clinical settings

In clinical conditions, the performance of XMMs was examined in three mammography units: Hologic Lorad M-IV (Mo/Mo, Mo/Rh), Fujifilm Amulet Innovality (W/Rh), Hologic Selenia Dimensions (W/Ag). Mo/Mo and Mo/Rh had the same geometry setup since the measurements were performed on the same mammography unit, Hologic Lorad M-IV (CR mammography), W/Rh measurements were recorded on FujiFilm Amulet Innovality (Digital mammography), and W/Ag on Hologic Selenia Dimensions (Digital mammography). All three mammography units had different focal spot – compression paddle default distance, but the distance remained the same for all measurements using the same mammography unit. In Table 2 the working standard calibration coefficient and determined HVL values are presented for these mammography units.

2.7. Clinical HVL measurements

HVL values were determined by positioning the Al filters of different thicknesses on the mammography unit compression paddle positioned between the X-ray source and the ionization chamber. The HVL measurement procedure was the same as in laboratory conditions, with one significant difference in geometry setup. Beam collimation and scattered radiation were not well controlled in clinical conditions, as opposed to laboratory conditions, where all requirements of IAEA TRS 457 (IAEA, 2007) were fulfilled. The compression paddle was in default position, not being equidistant from the unit's detector and focal spot.

2.8. Clinical XMM measurements

XMM performance evaluation in the hospitals was done for each mammography unit in Table 2. Air kerma reference value measured by the working standard was compared to the XMM measured value. The XMM detectors and the reference IC were positioned on the surface of the mammography unit detector, perpendicular to the cathode-anode axis of the X-ray tube to account for the anode heel effect. This effect is present in most modern diagnostic (and mammography) X-ray units and may cause wrong measurement data due to pronounced inhomogeneous radiation field. Measurement setup under clinical conditions included the compression paddle positioned between the mammography unit detector and the X-ray source. The distance of the compression paddle from the mammography unit detector was set to the default value and kept constant during all measurements. In this way, the effect of scattered radiation from the compression paddle (Brateman and Heintz, 2015; Toroi et al., 2013) is minimized. The default compression paddle position when no compression is applied is specific for each mammography unit, as presented in Table 2. Radiation fields used for irradiation of XMMs were generated using X-ray tube radiation output of 100 mAs and 25 kV, 28 kV, 30 kV, 35 kV for all mammography units and their anode/filtration setups, apart from 25 kV for Mo/Rh where this setting was unavailable. XMM software settings were chosen to correspond with the anode/filtration combination present at the clinical mammography unit if possible.

2.9. Dosimeter response and limits of variation

A way to assess dosimeter performance is to determine both absolute deviation from reference value and relative variation across different radiation qualities. One of the most important influence quantities is the energy dependence of the dosimeter response. As opposed to the broad photon energy range used in general radiography (25 keV up to 150 keV), photon energy range encountered in mammography applications is significantly narrower (15 keV – 35 keV). However, the shape of the spectra varies much more due to different anode/filtration setups.

Examples of the various mammography spectra encountered in this paper are presented in Figs. 3 and 4. The spectra were generated using the SpekPy toolkit (Poludniowski et al., 2021). Even though the energy range is quite narrow, due to different anode/filtration combinations, the spectra look quite distinct with different HVL values encountered.

2.10. XMM response

The response (R) of a dosimeter is defined as the ratio of the XMM

Table 2
Mammography unit properties.

Mammography unit	Unit type	Anode/filter combination	Default compression paddle – focal spot distance [cm]	X-ray tube voltage [kV]	Measured HVL [mm Al][a]	Calculated Nk [mGy/nC]
Fujifilm Amulet Innovality	Digital	W/50 μm Rh	13.9	25	0.527	8.232
				28	0.553	8.230
				30	0.564	8.229
				35	0.589	8.227
Hologic Selenia Dimensions	Digital	W/55 μm Ag	20.0	25	0.526	8.232
				28	0.560	8.229
				30	0.573	8.228
				35	0.596	8.226
Hologic Lorad M-IV	CR	Mo/30 μm Mo	25.7	25	0.332	8.295
				28	0.367	8.275
				30	0.385	8.266
				35	0.415	8.255
		Mo/25 μm Rh	25.7	28	0.470	8.241
				30	0.481	8.239
				35	0.500	8.236

[a] HVL was estimated by measuring the air kerma rate with working standard Exradin A650 ionization chamber by successively increasing added filtration, following the standard procedure (IAEA, 2007).

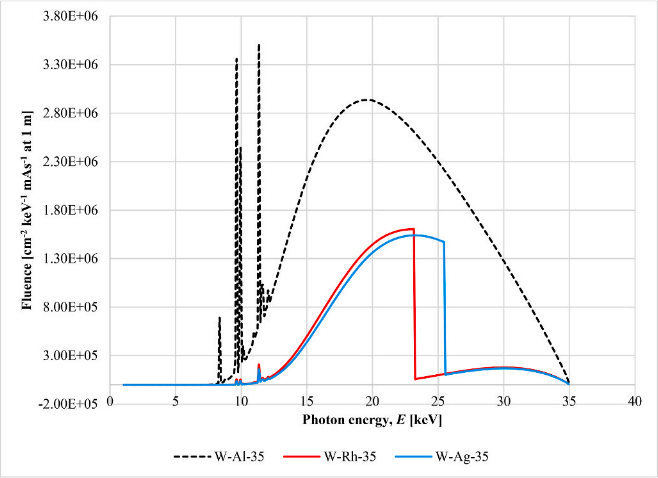

Fig. 3. Comparison of clinical tungsten (W) anode spectra with the W/Al radiation quality generated using the SpekPy toolkit (Poludniowski et al., 2021). All spectra are generated for X-ray tube voltage of 35 kV.

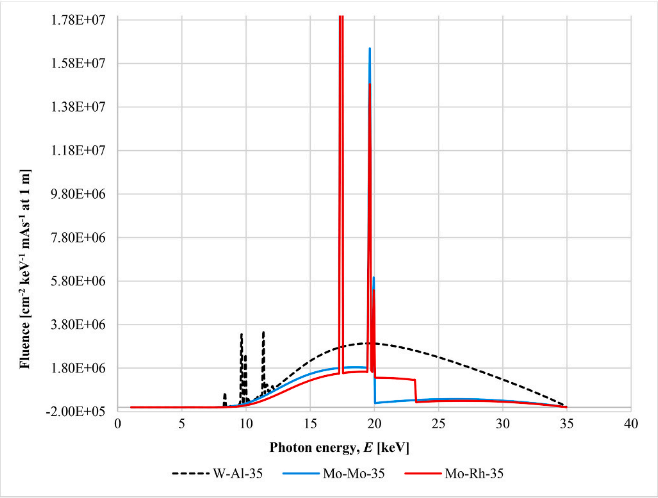

Fig. 4. Comparison of clinical spectra with molybdenum (Mo) target with the W/Al radiation quality generated using the SpekPy toolkit (Poludniowski et al., 2021). All spectra are generated for X-ray tube voltage of 35 kV.

measured value and the reference value obtained by a standard instrument under the same irradiation conditions. Response for specific X-ray radiation quality parameters (anode/filtration, A/F_i and X-ray tube voltage, U_j) can be expressed with the following equation:

$$R_{ij}\left(A/F_i;U_j\right)=\frac{M\left(A/F_i;U_j;XMM_{a/f}\right)}{q_{ij}*N_k\left(A/F_i;U_j\right)*k_D(t,p)} \tag{1}$$

where M represents the XMM measured value under these conditions with a $XMM_{a/f}$ software setting, while the denominator represents the reference value measured by the secondary standard, which is a product of collected charge (q_{ij}), IC calibration coefficient (N_k) and air density correction (k_d).

2.11. *XMM relative response*

Relative response (r) of a dosimeter is used for energy dependence evaluation. Compliance with the IEC 61674 (IEC, 2012) international standard is assessed by comparing the relative response values to the limits of variation (L). For mammography radiation qualities, these limits of variation are set to ±5 %, defined as the maximum deviation from the R value at 28 kV tube voltage, for each of the anode/filtration combinations separately. Relative response is represented by the following equation:

$$r_{ij}\left(A/F_i;U_j\right)=\frac{R_{ij}\left(A/F_i;U_j\right)}{R_{i0}\left(A/F_i;U_0\right)}=\frac{R_{ij}\left(A/F_i;U_j\right)}{R_{i0}\left(A/F_i;28\text{ kV}\right)} \tag{2}$$

where R_{i0} is the response value determined at the reference X-ray tube voltage (U_0).

2.12. *Measurement uncertainty evaluation*

Since XMM performance tests in the laboratory are performed in the established radiation fields and under controlled conditions, the main sources of measurement uncertainty are related to the secondary standard IC and the measurement procedure. Notable contributions to the reference air kerma measurement uncertainty budget in the W/Al radiation fields are related to the reference secondary standard IC and radiation field characteristics. Uncertainties regarding the reference IC A600 are the chamber calibration coefficient (0.8 %, $k = 1$) and long-term stability (0.5 %, $k = 1$). Radiation field-related contributions include field homogeneity (0.3 %, $k = 1$) and energy dependence of the IC due to changes in the radiation quality (0.3 %, $k = 1$). Considering other minor contributions to the measurement uncertainty budget such as the linearity of the reference system ionization chamber-electrometer, repeatability of the reference value measurement, ambient conditions (temperature and pressure) and detector distance from the X-ray source, the reference value combined expanded measurement uncertainty for laboratory conditions can be estimated as 2.1 % (for $k = 2$).

In the clinical conditions, the measurement uncertainty budget is expanded due to the calibration coefficient of the working standard IC A650 (1.0 %, $k = 1$). In addition, due to non-standard irradiation conditions, the energy dependence of the IC is considered. In the radiation fields with HVLs ranging from 0.33 (determined for Mo/Mo setup at 25 kV with compression paddle) to 0.59 (for W/Ag at 35 kV with compression paddle), the energy dependence of the working standard can be estimated as 0.7 % with $k = 1.73$.

3. Results and discussion

The results of XMM relative energy response in the W/Al radiation fields (normalized to W/Al 28) under laboratory conditions are presented in Fig. 5. The response of the detectors due to variation of detector mammography settings parameters in the W/Al SSDL radiation fields are presented in Fig. 6. The response of XMMs in radiation fields of different A/F combination under clinical conditions are presented in Fig. 7.

3.1. *XMM energy response in W/Al radiation fields*

For Piranha and MPD dosimeters, W/Al was chosen in the software settings to correspond to the radiation qualities used in laboratory, while Xi and R100B do not have W/Al as an option in settings and, therefore, Mo/Mo was chosen (Table 1). From the results in Fig. 5 it can be observed that the largest relative response deviation from W/Al 28 was 11.7 % at 35 kV for R100B which has only one anode/filter combination available in multimeter software settings. For Piranha, MPD and Xi, the relative responses were in the range from −1.6 % to +1.5 %. R100B shows the largest relative response range from −6.8 % to +11.7 %. These results imply that using non-adequate multimeter settings may produce unreliable measurement data, due to great discrepancies from the reference (conventional true) value. Even though Xi and R100B did not have the appropriate multimeter settings, Xi showed good results compared to the other multimeters with appropriate settings chosen, and especially to R100B. The cause of this difference could originate

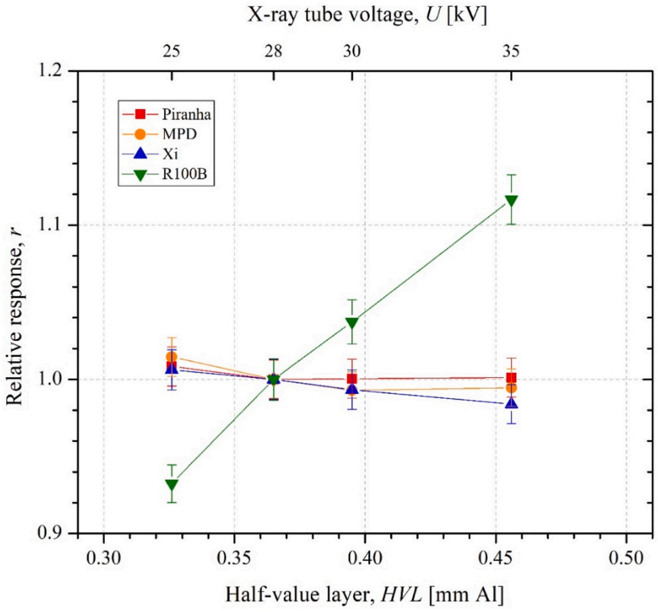

Fig. 5. Energy dependence of XMMs for W/Al radiation quality series in terms of relative response, normalized to the reference radiation quality at 28 kV.

from the structure of the dosimeters used, where Xi utilizes multiple detectors incorporated in the dosimeter while R100B is based on a single detector (Krzanovic et al., 2021).

The IEC 61674 standard (IEC, 2012) defines limits of variation in terms of deviation from reference conditions (at 28 kV) which should not exceed ±5 % indicating that three XMMs, Piranha, MPD and Xi comply with this criterion, whereas R100B shows significant change in detector response for all voltages.

In terms of energy response at the reference radiation quality (W/Al 28) the smallest deviation from unity was recorded for MPD with −0.6 %, followed by Piranha with +2.0 %, Xi with +5.1 % and R100B with +9.6 %. Xi and R100B display larger over-response values which may be caused by the use of Mo/Mo software setting.

3.2. Variation of XMM response due to different software settings

Having in mind that in some cases the XMMs do not have the software setting that matches the actual anode/filtration setup of the mammography unit, the influence of software setting on XMM response in the W/Al radiation fields was investigated. Fig. 6 shows the XMM response for different software settings in the W/Al radiation fields.

Fig. 6a and b shows the results for MPD and Piranha, respectively. Similar conclusions can be made for both XMMs. For W/0.5 mm Al (as the appropriate software setting), the deviation from unity is less than 2 % for MPD and less than 3 % for Piranha. Two settings for W/Al radiation field are available, the default setting (not considering the influence of the compression paddle) and the setting with the compression paddle that is used under clinical conditions (denoted as W/0.5 mm Al w.c.p.). Having in mind that no compression paddle was present in the laboratory radiation fields, a larger deviation from unity is observed for both XMMs for the software setting with the compression paddle. When improper software settings are selected, the response can differ up to 20 % for MPD and 15 % for Piranha. Response variations for the selected software setting were within 5 % for both XMMs, when W/Rh, W/Ag or Mo/Al were chosen, and were very pronounced when Mo/Mo, Mo/Rh or Rh/Rh were selected.

In Fig. 6c, results for Xi are presented, showing the over-response of less than 10 % for all software settings. For Mo/Mo settings (with and without the compression paddle considered) the dosimeter response decreases as the voltage increases, while for all other software settings the dosimeter response increases. The variations in response for the selected software setting were within 5 % for all settings. Even though Xi does not have the appropriate software setting (W/Al), the response of this XMM is least influenced by the software.

In the case of the R100B detector, only two options are available in the software, both of which are for the molybdenum anode and filter, one considering the compression paddle and one without it. No significant difference in the results is observed for these two settings. The response for both settings increases with the increase of tube voltage, up to 22 % for W/Al 35.

3.3. XMMs response under clinical conditions

In Fig. 7, the response of XMMs in clinical conditions is presented for four anode/filtration setups (Mo/Mo, Mo/Rh, W/Rh and W/Al) in the X-ray tube voltage range from 25 kV to 35 kV. The compression paddle was present in all radiation beams to reflect the standard mammography QC procedures.

In the Mo/Mo clinical radiation field (Fig. 7a), all XMMs had Mo/Mo with compression paddle setting available in the software, so the correct anode/filter setting was selected. The MPD displays a consistent under-response over the whole energy range, while the Piranha and the Xi display a variation in response with the increase of voltage within ±5 % from unity.

The Piranha, MPD and Xi have similar behaviour in Mo/Mo (Fig. 7a), Mo/Rh (Fig. 7b) and W/Rh (Fig. 7c) radiation fields, where these XMMs had matching software setting selected. Piranha exhibited an over-response and the largest response values amongst these XMMs, while MPD had the lowest response value and an under-response. Xi has displayed the least deviation from unity, within ±5 %. Overall, the response variation was relatively constant for the proper anode/filtration setting selected in the range from 25 kV to 35 kV.

In the case of W/Ag (Fig. 7d), the Piranha had an under-response and the lowest response values, while MPD displayed an over-response and

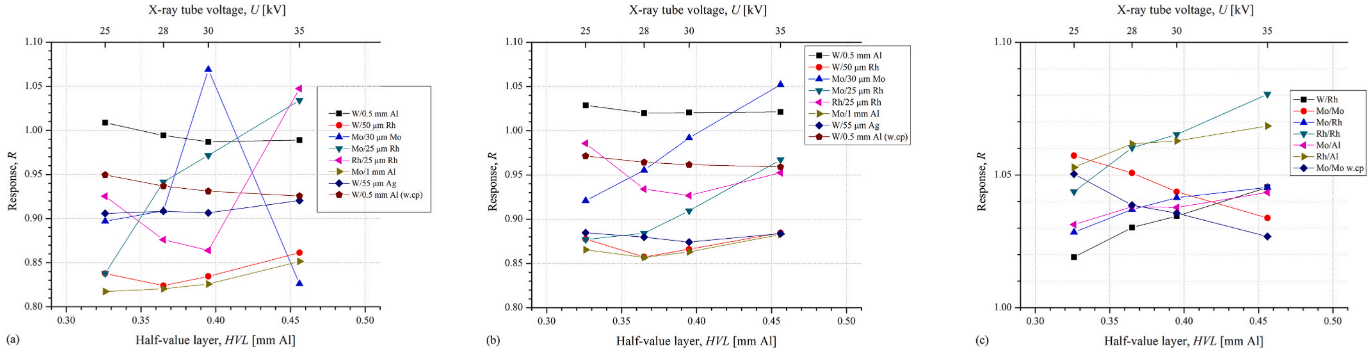

Fig. 6. Response of XMMs in the W/Al radiation quality series for different software settings: a) MPD; b) Piranha; c) Xi.

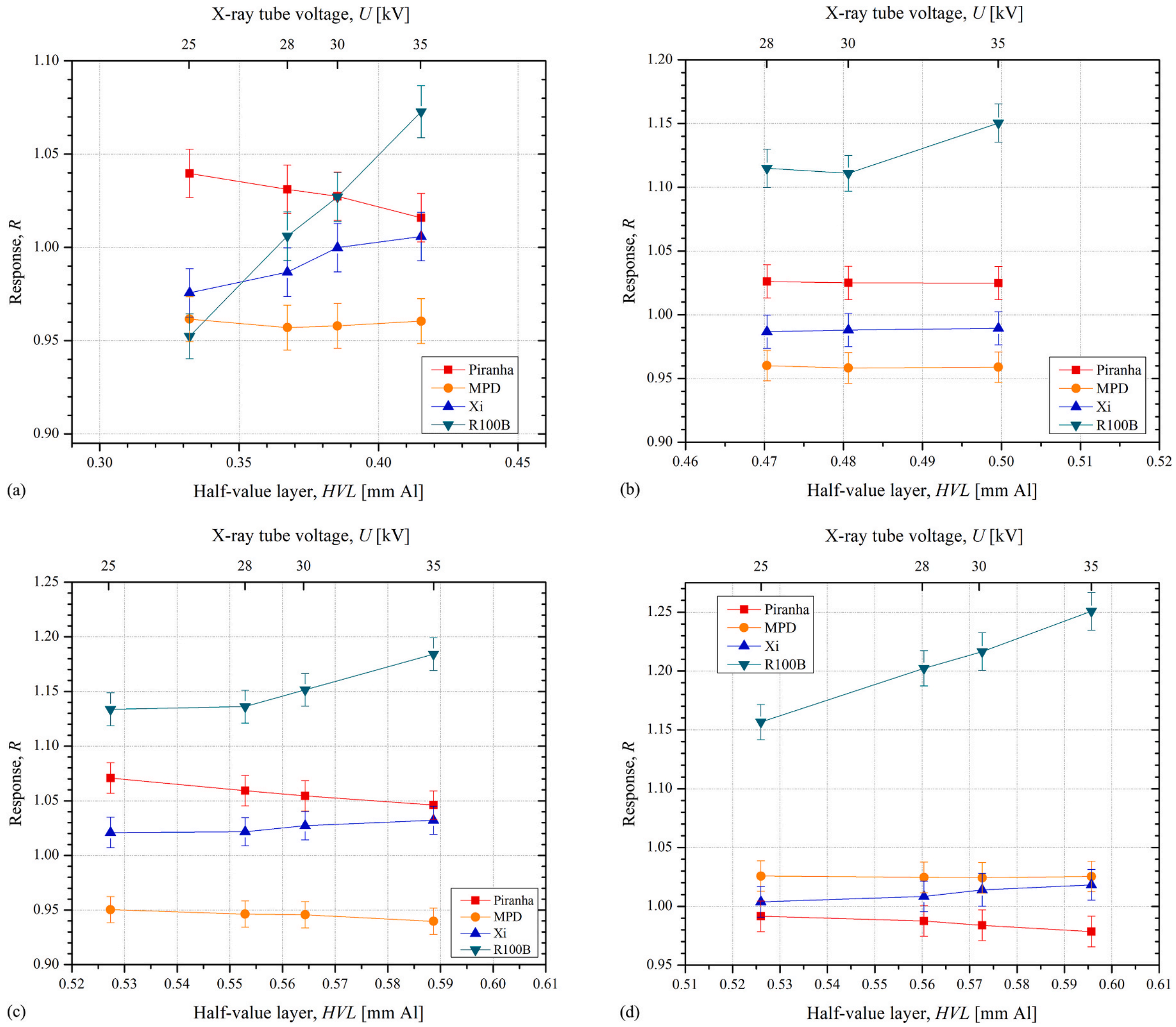

Fig. 7. Energy response of XMMs in clinical radiation fields: a) Mo/Mo; b) Mo/Rh; c) W/Rh; d) W/Ag.

the highest response values among these three XMMs. Since Xi does not have W/Ag in the software settings, W/Rh was selected. Even with the improper setting selected, Xi exhibited the smallest deviation from unity, while all three XMMs had deviation within ±5 %.

In the Mo/Mo radiation fields, the R100B displayed the steepest increase in response with the increase of tube voltage compared to other XMMs, which could be caused by insufficient energy compensation of this single-element detector. If the whole HVL range over all radiation fields is observed, R100B response deviation ranges from −5 % (for Mo/Mo 25, HVL = 0.332 mm Al) up to +25 % (for W/Ag 35, HVL = 0.596 mm Al). It is observed that R100B has a monotonously increasing trend in energy response with the increase of HVL. Since the software does not influence the dosimeter response, a calibration curve could be derived from this trend and appropriate corrections could be applied to the measured values.

4. Conclusion

The performance of solid-state detector-based XMMs has been examined for their use in mammography under laboratory conditions in the W/Al established radiation fields in SSDL in the 25–35 kV X-ray tube voltage range. In the laboratory conditions, the relative response of these dosimeters was tested against the criteria of the IEC 61674 standard (IEC, 2012). Three out of four XMMs (MPD, Piranha and Xi) have displayed congruent relative response for the W/Al radiation qualities. On the other hand, the responses for the Xi and the R100B, which do not have appropriate software settings for W/Al, have larger deviation compared to the MPD and the Piranha, which have appropriate settings. Based on this result, tests in the reference radiation fields with varying software settings of XMMs were done in the laboratory conditions. Improperly selected software settings of XMMs can produce an error in measured dose values up to 20 % compared to the reference value (obtained with a reference class dosimeter). XMM performance was evaluated in the clinical conditions in radiation fields at mammography units, which employ four different anode/filtration combinations (Mo/Mo, Mo/Rh, W/Rh and W/Ag). Suitable or available anode/filter combination in the software settings were selected. For most anode/filtration combinations (Mo/Mo, Mo/Rh, W/Ag) MPD, Piranha and Xi had response deviations within ±5 %, even though Xi had W/Rh setting chosen due to W/Ag setting missing in its software. In W/Rh radiation fields, all multi-detector XMMs except for Xi displayed deviations greater than ±5 %, compared to other anode/filtration setups. The single-element detector R100B had only one software setting available, Mo/Mo. It exhibited the widest range of dosimeter response over the whole HVL range (covering all the clinical radiation fields tested). This allows the calculation of the calibration curve and the application of an anode/filtration setup-dependent correction factor to the measured value. It is important to note that the XMMs used in this research are several years old and may have outdated software. The use of XMMs with up-to-date software and correct anode/filtration combination settings is recommended to ensure that the obtained data is reliable. Based on the results of this research, it is evident that, besides the XMM software setting, reference radiation fields used for dosimeter calibration have a great influence on the detector performance in clinical measurements. It is important to note that even though the IEC 61267 (IEC, 2005) standard defines reference radiation qualities in mammography only for Mo/Mo anode/filtration setup, the IEC 61674 (IEC, 2012) standard defines limits of variation for dosimeter response for any anode/filtration setup (Eq. (2)). Therefore, there is a clear need for an update of mammography reference radiation fields in the standards. The solid-state detector response is greatly influenced by the anode/filtration setup, which is why improper settings in the software can cause errors in the measured value. XMMs can be used for dose measurements in various anode/filtration setups with appropriate corrections applied keeping in mind the differences in HVL of the primary radiation beams between the laboratory and clinical conditions. These differences include the influence of polycarbonate compression paddle and associated scattered radiation in clinical conditions which are omitted under laboratory conditions by using proper lead collimators. Limitations of this study include the use of the latest software for the examined XMMs as well as other XMM models.

CRediT authorship contribution statement

Andrea Kojić: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nikola Kržanović:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miloš Živanović:** Writing – review & editing, Validation, Supervision, Methodology. **Paula Toroi:** Writing – review & editing, Supervision. **Luka Bakrač:** Writing – review & editing, Visualization, Investigation. **Predrag Božović:** Writing – review & editing, Resources, Conceptualization. **Jelena Stanković Petrović:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The research data is uploaded in Zenodo repository.

Laboratory and Clinical Measurements - Influence of anode/filtration setup on X-ray multimeter energy response in mammography applications (Original data) (Zenodo)

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