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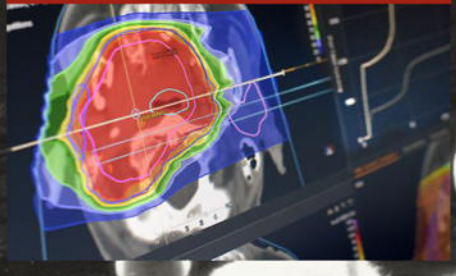

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Direct measurement of clinical mammographic x-ray spectra using a CdTe spectrometer

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Purpose: To introduce and evaluate a method developed for the direct measurement of mammographic x-ray spectra using a CdTe spectrometer. The assembly of a positioning system and the design of a simple and customized alignment device for this application is described.
Methods: A positioning system was developed to easily and accurately locate the CdTe detector in the x-ray beam. Additionally, an alignment device to line up the detector with the central axis of the radiation beam was designed. Direct x-ray spectra measurements were performed in two different clinical mammography units and the measured x-ray spectra were compared with computer-generated spectra. In addition, the spectrometer misalignment effect was evaluated by comparing the measured spectra when this device is aligned relatively to when it is misaligned.
Results: The positioning and alignment of the spectrometer have allowed the measurements of direct mammographic x-ray spectra in agreement with computer-generated spectra. The most accurate x-ray spectral shape, related with the minimal HVL value, and high photon fluence for measured spectra was found with the spectrometer aligned according to the proposed method. The HVL values derived from both simulated and measured x-ray spectra differ at most 1.3 and 4.5% for two mammography devices evaluated in this study.
Conclusion: The experimental method developed in this work allows simple positioning and alignment of a spectrometer for x-ray spectra measurements given the geometrical constraints and maintenance of the original configurations of mammography machines. © *2017 American Association of Physicists in Medicine* [https://doi.org/10.1002/mp.12287]

Key words: CdTe detector, detector alignment, mammography, spectrometry

1. INTRODUCTION

Mammography x-ray spectra measurement is a complex task due to the high photon fluence rates produced by clinical systems.[1–4] The design of the equipment constitutes a constraint owing to the short distance between the focal spot and breast support. Additionally, an important factor to consider in x-ray spectra measurements is the alignment between the radiation source and the detector.[5,6] The high photon fluence rates associated with the short distance between the x-ray tube and a detector positioned over the breast support require the use of pinhole collimators to limit the exposed detector area. However, it makes the alignment a delicate and laborious process.

Due to the aforementioned limitations, the most common method for obtaining mammography x-ray spectra is by means of mathematical models.[7–11] However, in some cases, not all parameters that characterize the x-ray spectra are available in these models.[4] Indirect methods to obtain a representation of x-ray spectra can also be found in the literature, for example, the reconstruction of measured scattered x-ray spectra[12,13] and nonclinical spectra.[14] However, the measurement of x-ray spectra can provide an accurate representation of a mammography radiation beam, and it is the best procedure to improve image quality and dose optimization in mammography.[15]

Portable and room temperature detectors are the most suitable devices for mammographic x-ray spectroscopy

measurements using clinical machines. Previous measurements using portable detectors such as CdZnTe[2,3,16] and CdTe[15,17] have been reported in the literature. Matsumoto and col.[2] employed a CdZnTe (CZT) detector coupled to a 35 μm diameter collimator to measure mammographic x-ray spectra using 25–32 kV and Mo/Mo and Mo/Rh anode/filter combinations in a clinical equipment. They concluded that this detector is adequate for quality control and quality assurance of a mammographic x-ray unit. Miyajima and col.[3] also used a CZT detector to measure x-ray spectra for both mammographic and diagnostic units. However, they focused the work on the alignment method and few spectra were presented in their paper. Abbene and col.[15] used a CdTe detector and a 100 μm collimator diameter to measure direct clinical Mo x-ray spectra focused on the characterization of detection system for low and high photon counting rates. They found a good agreement between their data in comparison with transmission curves and HVLs obtained from the measured and simulated spectra. Zhang and col.[17] also used a CdTe detector for x-ray spectra measurements in mammography, but they modified the original configuration of the x-ray system and reduced the tube-current. This adaptation is adequate for spectra measurement, but it is not practical since it is difficult to reproduce it in a clinical environment. Therefore, the literature do not present practical methods for x-ray spectra measurement keeping the original configurations of the x-ray machines used for clinical purposes, neither consistent methods to allow the detector alignment with the beam axis for different positions on the breast support.

The present work proposes a method to measure x-ray spectra produced by mammographic equipment in clinical settings using a CdTe detector. The paper also describes the design of a positioning system and a customized alignment device. Measured x-ray spectra produced by Mo and W targets using two different clinical machines were compared with spectra computed from mathematical models.[7,10] The effect of the spectrometer misalignment was also evaluated by comparing the spectra measured when the developed device is aligned relatively to when the setting is deliberately unaligned.

2. MATERIALS AND METHODS

2.A. Positioning system and alignment device

A positioning arrangement was designed and constructed by adapting three mechanical positioners (Optron Ltda., Campinas, Brazil): one mini-goniometer and two horizontal translators (Fig. 1). The system was assembled on a base that leaves space for the spectrometer cable plugs. The two horizontal translators were installed perpendicular to each other on the base. This set-up enables movement on the *xy* plane in steps of 1 mm. In addition, the mini-goniometer was installed on the horizontal translators. This arrangement allows for angle variation relative to the vertical axis within 0.1° steps. Finally, the spectrometer was fixed on the mini-goniometer base.

FIG. 1. Positioning system manufactured from the mechanical adaptation of commercial positioners (Optron Ltda, Campinas, Brazil). [Color figure can be viewed at wileyonlinelibrary.com]

Figure 2(a) shows the alignment device designed to operate with the described positioning system. This device, manufactured in PMMA has the same external dimensions as the spectrometer assembly. This design was intended to allow for the perfect replacement of the device by the spectrometer after conclusion of the alignment procedure [Fig. 2(b) and 2(c)].

The alignment device has two 1 mm diameter tungsten spheres adapted in its extremities, and these spheres are mechanically positioned on the line that crosses the center of the detector, see Fig. 3.

2.B. Alignment method

Initially, the alignment device is positioned over the breast support, and a preliminary visual alignment is performed. Next, a radiographic image is acquired to verify the relative position of the spheres [Fig. 4(a)]. By observing the spheres separately [Fig. 4 (b)], adjustments in the position should be made using the mechanical controls to produce overlapping spheres as shown in Fig. 4(c). Radiographic images should be taken as many times as necessary to obtain overlapping spheres in the image. When the spheres appear superimposed on the image, it can be concluded that the device is aligned adequately with the central axis of the radiation beam. Then, the alignment system is carefully replaced with the spectrometer without changing its position over the breast support, and the spectrometric measurements can be initiated.

2.C. Experimental *vs* computer-generated x-ray spectra comparisons

Radiation beams were generated using two clinical mammography systems: a Selenia DR System (Hologic Inc., Marlborough, MA, USA) and a Mammomat 3000 Nova (Siemens

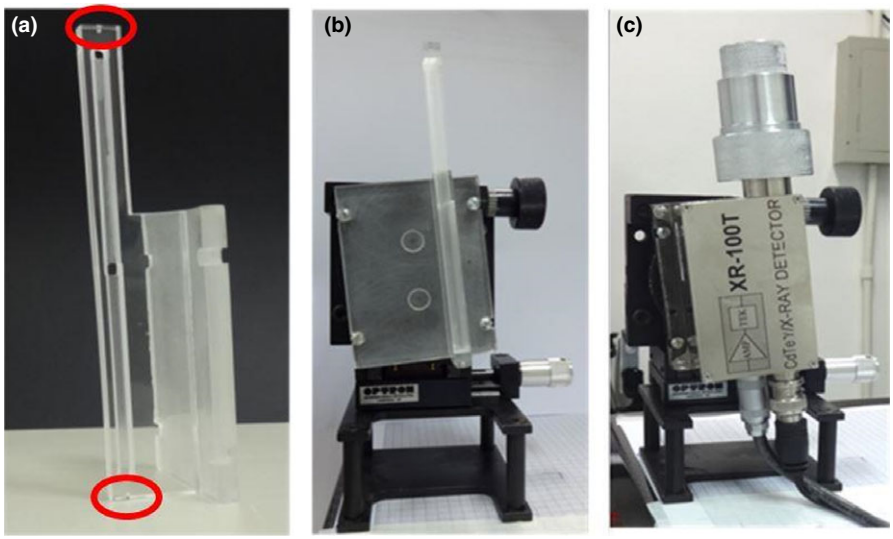

FIG. 2. (a) PMMA alignment device with circles representing the position of the tungsten spheres; (b) the alignment device positioned on the positioning system and (c) the portable CdTe spectrometry system positioned on the positioning system. [Color figure can be viewed at wileyonlinelibrary.com]

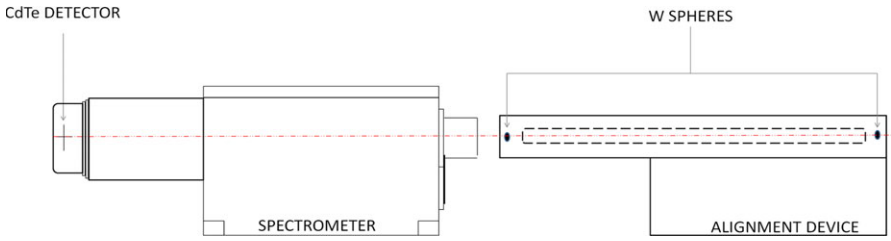

FIG. 3. Cross section of the basic mechanical structure of the spectrometer (based on Amptek Inc.) and alignment device. [Color figure can be viewed at wileyonlinelibrary.com]

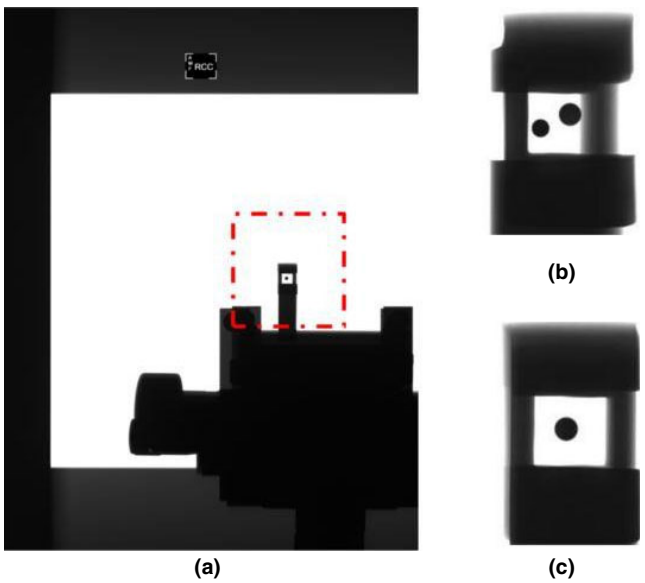

FIG. 4. (a) Radiographic image of the alignment system on the breast support obtained using a 15 cm × 15 cm mammographic radiation field. The dashed box highlights the location of tungsten spheres; Details of the image emphasizing the region of the tungsten spheres when (b) the device is not aligned and (c) the device is aligned. [Color figure can be viewed at wileyonlinelibrary.com]

AG., Munich, DEU). Selenia DR equipment has available Mo/Mo and Mo/Rh target/filter combinations. The tube window is composed of 0.8 mm of Be. The small focal spot size was selected using the magnification table and it allows the use of low tube-current (approximately 30 mA). The Mammomat 3000 Nova system has Mo/Mo, Mo/Rh, and W/Rh target/filter combinations. The tube window is composed of 1 mm of Be. X-ray spectra were measured in this equipment using the large focal spot. For both mammography devices, direct x-ray spectra were measured for tube voltages from 25 to 28 kV and all available target/filter combinations.

Primary x-ray spectra were measured using a 9 mm^2 CdTe spectrometer model XR-100T (Amptek, Inc., Bedford, MA, USA). The collimators used in this work are made of a tungsten alloy (EXVC collimator kit, Amptek, Inc.). For x-ray measurements in the Selenia system, a 50 μm aperture collimator was coupled to the detector to reduce the photon fluence and to avoid pulse pile-up. The measurements in the Mammomat 3000 Nova device were done using a 25 μm aperture collimator. Sequential irradiations of the spectrometer detector were required to obtain between 2 to 7 × 10^4 counts of total detected events, with a sensitive region of the detector positioned at 20.5 cm from the breast support. Each individual irradiation was performed using a charge of

100 mAs. Air kerma measurements were performed using a dedicated mammography ionization chamber model 10 × 5–6 M (Radcal Corp., Monrovia, CA, USA), calibrated according to RQR-M beam qualities in a SSDL[18] (Laboratory of Calibration of Instruments of the Institute of Energy and Nuclear Research - IPEN, São Paulo, Brazil) that is traceable to the *Physikalisch-Technische Bundesanstalt* (PTB, Germany).

Figure 5 presents the positioning of the spectrometry system in both clinical mammography devices: Selenia (left) and Mammomat 3000 Nova (right). For x-ray spectra measured with the Selenia equipment, the maximum dead time found was 8.4%. For the measurements with the Mammomat 3000 Nova, neither the compression paddle nor the magnification table was used. The maximum dead time for measurements using this equipment was 9.3%.

The measured Mo and W x-ray spectra were compared with those predicted by the MASMIP[7] and TASMICS[10] models, respectively. The MASMIP and TASMICS models produce spectra minimally filtered by 0.5 mm Be and 0.8 mm Be, respectively, and allow the inclusion of several additional types of material attenuators to compute the corresponding filtered x-ray spectra.

The computer-generated x-ray spectra equivalent to those produced by the Selenia equipment were obtained considering 27.5 μm Mo and 25 μm Rh filters, used in Mo/Mo and Mo/Rh combinations. Additional filtration of 0.3 mm Be, due to the Be window, and 2.35 mm PMMA (magnification table in the Selenia system) was also considered.

The computer-generated x-ray spectra equivalent to those spectra measured using the Mammomat 3000 Nova equipment, were generated by using a 30 μm Mo filter for the Mo/Mo combination, 25 μm Rh for Mo/Rh and 50 μm Rh for W/Rh. An additional filtration of 0.5 mm Be was considered for Mo spectra (MASMIP model), and 0.3 mm Be was considered for W spectra (TASMICS model). The HVL values computed from both experimental and computer-generated spectra were also compared. The methodology for the derivation of HVL from x-ray spectra was described in previous studies.[19,20]

2.D. Inadequate alignment effects on spectra measurements

A test was performed to demonstrate the influence of variations in the spectrometer position on the resulting measured x-ray spectra. The quantitative evaluation was done in terms of the total photon fluence and HVL. The spectrometric system and methodology presented in the previous sections were used to measure x-ray spectra from a clinical mammography equipment (Selenia Dimensions, Hologic). The diagram in Fig. 6 presents the spectrometer after alignment in the radiation beam. The system was considered aligned when the inclination of the spectrometer relative to the line perpendicular to the cathode-anode axis (z-axis) was 4.3°.

A set of eight x-ray spectra was measured from the alignment position to the z-axis for variation in inclination of the spectrometer choosing steps of 0.3° and 0.5° (2.9°, 3.4°, 3.7°, 4.0°, 4.3°, 4.6°, 4.9°, and 5.4°). All spectra were measured using the same exposure technique (acquired after three irradiations) using W/Rh, 28 kV, and 120 mAs. A small focal spot (0.1 mm), a field size of 7 × 8.5 cm^2 and a compression paddle coupled to mammography equipment were used. The spectrometer collimation was 50 μm (aperture) by 1 mm (thickness).

2.E. Spectra corrections

The measured spectra were corrected for the detector efficiency, Compton distortion and fluorescent escape fraction

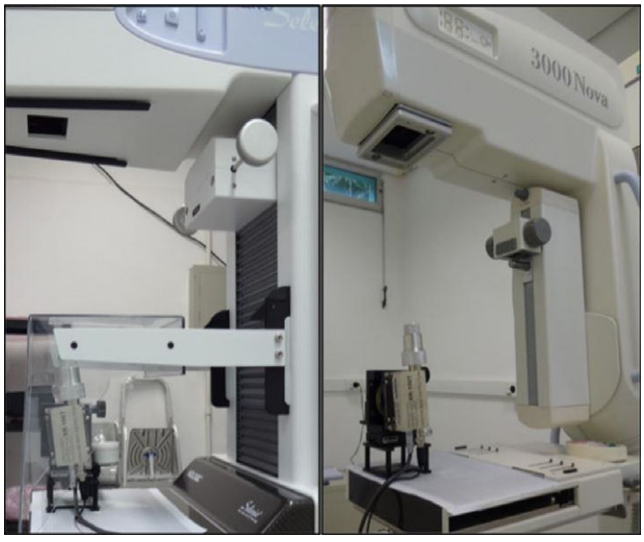

FIG. 5. Positioning of a spectrometer in the two mammography systems used in this study: Selenia (left) and Mammomat 3000 Nova (right). [Color figure can be viewed at wileyonlinelibrary.com]

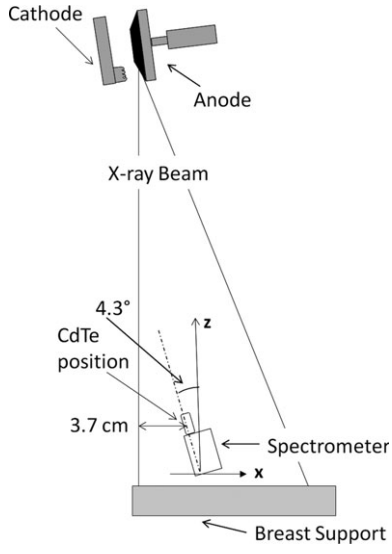

FIG. 6. Position of the aligned spectrometer according to an adopted reference system.

using a stripping procedure.[21] The determination of the Compton efficiency was described by Terini et al.[22] The detector efficiency and fluorescent escape fraction were obtained by Monte Carlo simulations.[23–25] Additionally, an area correction factor was applied to the set of spectra that were compared with the ones predicted by MASMIP[7] and TASMICS[10] models. This correction turns the spectra area numerically equal to the air kerma produced by the respective photon fluence spectra. Using this method, when the air kerma is derived from the corrected fluence spectra [photons/(mm^2·mAs·keV) at 1 m], the same measured air kerma value is obtained. This area correction factor was not applied to the set of spectra used to evaluate the misalignment effect. These spectra were measured using the same exposure technique, and their intensity would be approximately the same if this area correction was applied. Consequently, the effect of the misalignment in the spectra intensity would not be visible.

3. RESULTS

3.A. Spectra comparisons

Figures 7–9 compares x-ray spectra measured in mammography equipment (solid lines) and those computed by the MASMIP and TASMICS models[7,10] (dashed lines). Figure 7 presents the spectrum generated in the Selenia equipment using Mo/Mo and 25 kV and the corresponding MASMIP spectra. Figure 8 shows similar comparative results for the same clinical equipment considering a Mo/Rh combination and tube voltage of 26 kV. Figure 9 presents the spectrum generated in the Selenia Dimensions equipment using W/Rh and 27 kV and the corresponding TASMICS spectrum. The spectra are normalized in fluence units (Photons/mm^2·mAs·keV) at 1 m.

Table I presents the calculated HVL from experimental and computer-generated x-ray spectra considering the exposure characteristics of the Mammomat 3000 Nova and Selenia equipment. For these values, the considered uncertainties were due to the statistics of the counts of each spectrum. The maximum uncertainty for the HVL values obtained from the Mammomat 3000 Nova experimental spectra was 1% and that for the Selenia was 0.3%. The maximum differences observed between HVL values obtained from experimental and computed spectra was 4.5% for the Mammomat 3000 Nova beams and 1.3% for the Selenia equipment.

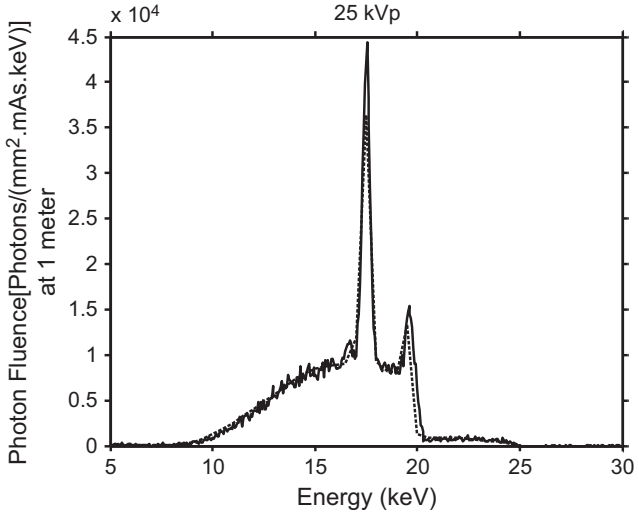

FIG. 7. Experimental (solid line) and computer-generated x-ray spectrum (dashed line) using the MASMIP model: 25 kV (Mo/Mo) spectrum generated by the Selenia equipment.

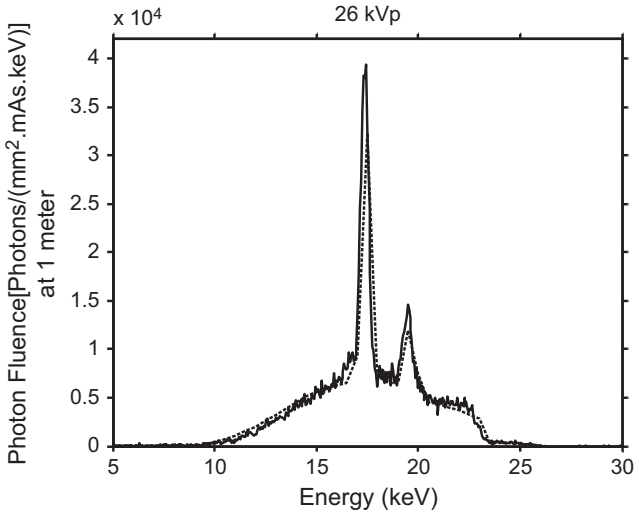

FIG. 8. Experimental (solid line) and computer-generated x-ray spectrum (dashed line) using the MASMIP model: 26 kV (Mo/Rh) spectrum generated by the Selenia equipment.

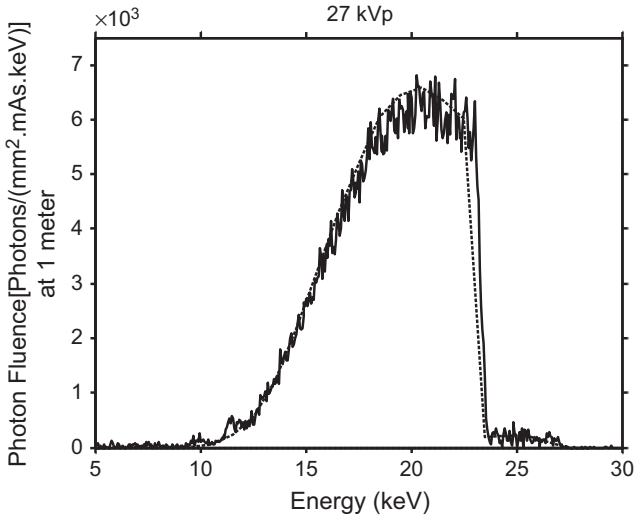

FIG. 9. Experimental (solid line) and computer-generated x-ray spectrum (dashed line) using the TASMICS model: 27 kV (W/Rh) spectrum generated by the Selenia Dimensions equipment.

3.B. Misalignment effects

The spectrometer misalignment can affect the measured spectra in two important aspects: quantity (intensity) and

TABLE I. Calculated HVL from experimental (Exp.) **X**-ray spectra generated by the Mammomat 3000 Nova and Selenia equipment and for computed (Comp.) **X**-ray generated considering the exposure characteristics of the equipment.

		Calculated HVL (mmAl)			
		MAMOMAT 3000 Nova		SELENIA	
Anode/filter	Tube voltage (kV)	Exp. x-ray spectra	Comp. x-ray spectra	Exp. x-ray spectra	Comp. x-ray spectra
Mo/Mo	25	0.296	0.295	0.313	0.314
	26	0.311	0.310	0.327	0.326
	27	0.323	0.321	0.335	0.337
	28	0.333	0.330	0.346	0.348
Mo/Rh	25	0.346	0.335	0.381	0.376
	26	0.360	0.350	0.395	0.391
	27	0.370	0.363	0.404	0.404
	28	0.378	0.374	0.415	0.415
W/Rh	25	0.473	0.452	–	–
	26	0.487	0.465	–	–
	27	0.493	0.476	–	–
	28	0.503	0.486	–	–

quality (shape). When the spectrometer is misaligned, the small collimator aperture leads to an unwanted filtration of low-energy photons. Therefore, the number of counted photons is decreased and the spectral shape is changed. It results in a "hard" measured beam and in the increase of the estimated HVL.

The spectral intensity is a practical parameter to assess the quality of the alignment. The difference between the amount of photons measured with the spectrometer when it is correctly aligned and when it is misaligned is an indicator for choosing the adequate positioning. This effect is displayed in Fig. 10 that presents photon fluence spectra measured for W/Rh target/filter combination at 28 kV as a function of energy. This figure displays the spectra measured when the spectrometer angle is larger [Fig. 10(a)] and smaller [Fig. 10(b)] than the angle of alignment (4.3°).

The total photon fluence corresponds to the integral of the photon fluence across all energy bins. When deviating the spectrometer from the alignment angle, its maximal variation was of 44%, and occurred for the spectrum measured at 5.4°. The minimal variation was of 3% for the spectra measured at 4.0°. The uncertainty of the total photon fluence was propagated from the Poisson's distribution of each spectrum's channel. The average relative uncertainty was 0.5%.

The change of the spectral shape, and consequently in the HVL, due to the spectrometer misalignment is an important issue to consider in spectra measurements. The effect of the spectrometer misalignment in the estimated HVL is presented in Fig. 11. HVL values derived from the x-ray spectra measured in different positioning angles are presented.

The lowest HVL value is related to the best alignment, since the spectral distortions due to low-energy photons filtration caused by misalignment are minimal. Figure 11 shows that the minimal HVL refers to the spectrum measured with the spectrometer aligned at 4.3°, which also presents high photon fluence. The maximum HVL variation was 5%. These results suggest that the beam characterization from the x-ray spectra can only be accurately done if the spectrometer is correctly aligned.

4. DISCUSSION

The method described in this paper is appropriate for measurements of x-ray spectra in clinical mammography systems. However, it has limited use in mammographic beams generated with tube voltages higher than 28 kV due to the high fluence rate and dead time. This limitation can be improved using collimators with smaller apertures than the ones used

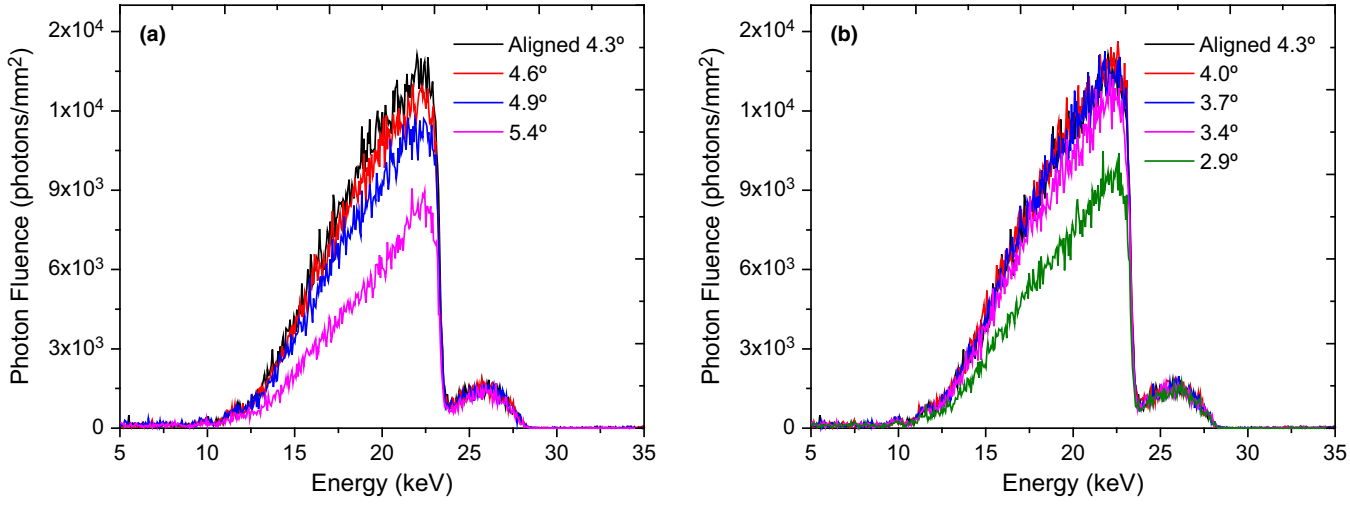

FIG. 10. A comparison of the 28 kV photon fluence spectra measured using W/Rh combination with the spectrometer at different inclinations for angles larger [Fig. 10(a)] and angles smaller [Fig. 10(b)] than the spectrometer angle in the position of alignment (4.3°). [Color figure can be viewed at wileyonlinelibrary.com]

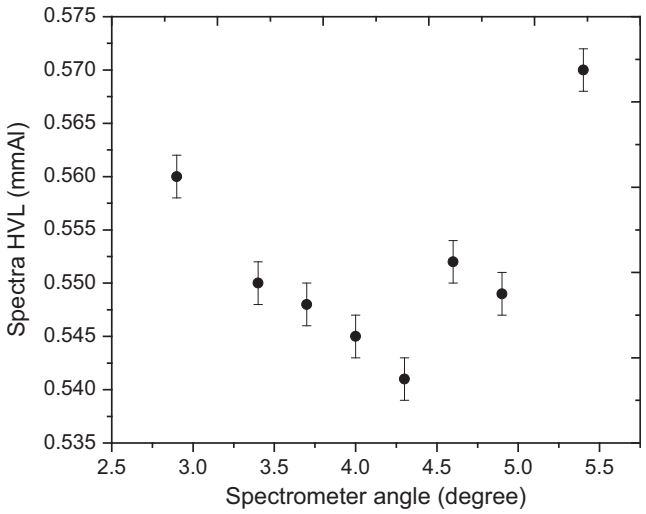

FIG. 11. HVL values derived from the x-ray spectra measured with the spectrometer positioned at different angles.

in this study. Considering that the high photon fluence is the main problem in this type of measurement, the method presented in this work is suitable for measurements in clinical devices, with tube voltages from 20 to 28 kV.

The results of the misalignment test showed that the spectrometer positioned at 4.0° in the Selenia Dimensions equipment provided a spectra measurement with the total count slightly larger than the spectrometer positioned at 4.3°, the position considered the alignment position. This difference is possibly due to the movement of the experimental arrangement when the alignment device is replaced with the spectrometer. Thus, we recommend that after the alignment be performed using the methodology proposed in this work, the user should verify the count rates for the spectrometer in positions adjacent to the alignment position in search of the highest count rate. This procedure should make the alignment more accurate.

The HVL values obtained for measured spectra with the spectrometer at different positions presented a maximum variation of 5%. The minimal HVL value was found for the measured spectra when the spectrometer is aligned. Since the minimal HVL is related with minimal spectral distortions due to the misalignment filtration, the alignment method presented in this work provided the most accurate x-ray spectral shape.

The results are consistent between the experimental and computer-generated Mo/Mo and Mo/Rh x-ray spectra for the Selenia device (Figs. 7 and 8), related to the high performance of the alignment device developed in this work. This conformity is also noted for the HVL values deduced from these x-ray spectra.

The HVL values obtained for computer-generated and measured spectra show maximum differences of 1.3% and 4.5% for the x-ray spectra measured from Hologic and Siemens mammography devices, respectively. The best agreement between HVL values extracted from the measured and calculated x-ray spectra is for the Selenia equipment. This agreement occurs because the tube current used in this equipment in the magnification mode (approximately 30 mA) is lower than that used in the Mammomat 3000 Nova equipment device in the large focal spot mode (approximately 150 mA). The use of low tube currents to generate radiation beams in a mammographic tube results in x-ray spectra measurements with smaller count rates, which reduce the spectral distortions and dead time losses.

The HVL values obtained from the measured x-ray spectra are systematically higher than the ones ensuing from the calculated spectra, mainly for W/Rh spectra. The reason may be the slightly larger number of high-energy photons found in measured spectra. This excess of high-energy photons is caused by the radiation scattered by the spectrometer housing and it should be considered when dosimetric quantities are derived from these spectra.

5. CONCLUSIONS

An experimental methodology was developed to measure x-ray spectra from clinical mammography devices. This methodology allowed robust positioning and alignment of the spectrometer, so that mammographic x-ray spectra could be measured directly. The results demonstrate that a misalignment of a few degrees can result in a quantitatively high inaccuracy of the measured spectra. Consequently, the alignment procedure presented in this study is useful to ensure that the spectrometer is positioned at the optimal location that yields approximately the maximum count rates. This positioning is possible with the proposed alignment device and cannot be set-up quickly and precisely using an "eye-balled" method. This is an important issue when these measurements must be performed in clinical equipment.

The x-ray spectra measured from two clinical devices were compared with x-ray spectra produced by the computer models MASMIP (Mo anode)[7] and TASMICS (W anode).[10] The measured x-ray spectra agreed well with those generated by the MASMIP and TASMICS models. The presented method for the spectrometer alignment in mammography radiation field provided x-ray spectra measurements with minimal shape distortion and high total photon fluence in comparison with spectra measured with a misaligned spectrometer. The accuracy of the measured spectra proved to be highly sensitive to the correct alignment of the spectrometer.

Finally, we conclude that the experimental method developed in this work allows simple and easy positioning and alignment of spectrometers for x-ray spectra measurements in clinical settings. The system is compact, can be reproduced at low cost and can be used in other clinical machines to facilitate these measurements. Better results could be achieved with the use of collimators with an aperture less than 25 μm and by reducing the tube current. We believe the method outlined in this work is promising for the complete characterization of mammographic x-ray beams that can be adopted in advanced optimization of mammography systems.

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CONFLICTS OF INTEREST

The authors have no relevant conflict of interest to disclose.

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