MEASUREMENT OF CHARACTERISTIC TO TOTAL SPECTRUM RATIO OF TUNGSTEN X-RAY SPECTRA FOR THE VALIDATION OF THE MODIFIED TBC MODEL

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Abstract

Primary X-ray spectra were measured in the range of 80 to 150 kV in order to validate a computer program based on a semiempirical model for X-ray spectra evaluation (tbc&mod). The ratio between the characteristic lines and total spectrum was considered for comparing the simulated results and experimental data. The raw spectra measured by the CdTe detector were corrected by the detector efficiency, Compton effects and characteristic Cd and Te X-rays escape peaks, using a software specifically developed. The software Origin 8.5.1 was used to calculate the spectra and characteristic peaks areas. The obtained result shows that the experimental spectra have higher effective energy than the simulated spectra computed with tbc&mod software. The behavior of the ratio between the characteristic lines and total spectrum for simulated data presents discrepancy with the experimental result. Computed results are in good agreement with theoretical data publicated by Green, for spectra obtained with 3.04 mm of additional aluminum filtration. The difference of characteristic to total spectrum ratio between experimental and simulated data increases with the tube voltage.

Keywords: Characteristic to total spectrum ratio, X-ray spectrum, CdTe detector.

1.- INTRODUCTION

Since the discovery of the X-ray radiation by Wilhelm Roentgen in 1985, many applications for X-ray beams has been developed, considering a special focus in medical applications. Various issues are important for this kind application, such as, estimating radiation doses in patients, diagnostic and therapy procedures, and formulating radiation shielding models. Therefore, it is important the assessment of the energy distribution of the X-ray beam. On the other hand, routine measurement of X-ray spectra in diagnostic radiology is uncommon due to the complexity of the measurement procedures (Bhat et al., 1998). However, theoretical and semiempirical models have been developed in order to calculate spectrum emitted by specific X-ray tube for diagnostic energies (Birch and Marshall, 1979, Baird, 1981, Archer and Wagner, 1988, Tucker et al., 1991, Boone et al., 1997, Boone and Seibert, 1997).

A very used semiempirical model for generating tungsten target X-ray spectra was proposed by Tucker, Barnes and Chakraborty (Tucker et al., 1991) (TBC model). However, as originally presented, the TBC model fails in situations where the determination of X-ray spectra produced by an arbitrary waveform or the calculation of realistic values of air Kerma for a specific X-ray system is desired. In this sense, for the present work, the modified TBC model, hereafter called tbc&mod (Costa et al., 2007) was used. This model takes into account the waveform and a representation of the calculated spectra using a dosimetric quantity (Costa et al., 2007). The performance of the proposed model was evaluated by comparing values of effective energy and first half value layer from calculate and measured spectra for different voltages and filtrations. For evaluate the contribution of the characteristic photons to total spectrum, the ratio between characteristic to total spectrum was calculated. In addition, results obtained with the tbc&mod code were compared with the measured spectra.

2.- MATERIALS AND METHODS

2.1.- Equipment

The spectroscopy system employed in this study features a Cadmium Telluride diode detector (CdTe), Amptek Inc. Model: XR-100T-CdTe that is a high performance X-ray and Gamma ray detector mounted on a two-stage thermoelectric cooler. The CdTe detector has a nominal area of 9 mm^2 and a thickness of 1 mm with a Schottky diode structure and Peltier cooling. The detector has a Be window with 100 μm of thickness. Due to its portability and high stopping power, CdTe is considered a good choice for energies above 30 keV (Redus et al., 2009). One tungsten collimator of 2000 μm of diameter, 2 mm of thickness and a brass spacer were used so that photon penetration through the collimator wall was negligible for tube potential up to 150 kV. The other element of the spectroscopy system was an Amptek PX4 processor that includes digital pulse shaping amplifier, integrated multichannel analyzer and power supplies. The nominal bias voltage was 400 V. More than 5,000 counts were taken for each measurement to provide good statistics. The dead time of the spectroscopy system was less than 12% for all the measurements.

The X-ray unit used was a Philips MG 450 X-ray system. It consists of an unit control MGC 30 and a MCN 421 industrial X-ray tube with stationary Tungsten target. The X-ray tube was powered by a constant-potential generator, operating at tube voltage between 40 and 150 kV. The measurements were made with additional filters of Al with 3.04, 4.71 and 5.98 mm of thickness. Table 1 indicates the X-ray tube specifications used in this work. The X-ray tube was used with a collimator that produced one elliptic field of 6.91 cm x 5.76 cm diameters at 1 m of the focal spot. Figure 1 shows the experimental arrangement used.

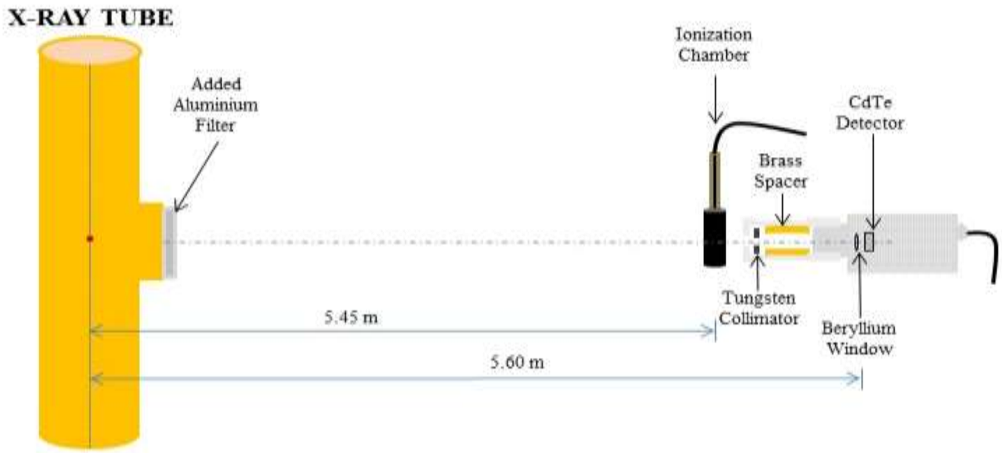

Figure 1 – Experimental setup for spectral measurements.

Table 1.- X-ray tube specifications.

Tube	Philips MCN 421
Type N°	9421 172 57032
Target	Tungsten
Target angle	22°
Emergent beam angle	30°
Inherent filtration value	2,2 mm Beryllium
Ripple	2,5kV max.

Measures of the Air Kerma were made using a PTW Unidos E electrometer coupled to a 30 cm^3 PTW ionization chamber, model TW 23361. The ionization chamber and CdTe detector were located at 5.45 m and 5.60 m of the X-ray tube focal spot, respectively.

The calibration of the energy scale, linearity checks and resolution of the CdTe detector were performed using ^{241}Am and ^{152}Eu calibration sources. In CdTe, the centroid of the photopeak is shifted by the asymmetry due to hole tailing effect. This centroid shift increases with energy (Redus et al., 2009). To correct this, were used the peak channel rather than the centroid for high photon energies in ^{241}Am and ^{152}Eu, 59.4 keV and 121.7 keV, respectively. Origin 8.5.1 (OriginLab, Co.) software was used to fit the energy distribution for each calibration source, using the Gaussian distribution option of the fitting program. The energy conversion per channel observed was 0.1702 keV.

2.2.- Software correction

The measured spectra were corrected by the detector energy response using the stripping procedure. The detector's response was corrected by the detector efficiency, escape peaks of Cd and Te K X-rays and escape of Compton photons. The response function was calculated through Monte Carlo simulation using PENELOPE code version 2003 (Salvat et al., 2003). The simulation of the detector response was based in a previous work (Tomal et al., 2012) for mammographic energy range from 5 to 40 keV, and extended for diagnostic range, 5 to 160 keV (Tomal et al., 2014).

2.3.- Software to generate X-ray spectra

The tbc&mod code used to generate diagnostic X-ray spectra is based on the semiempirical TBC model (Tucker et al., 1991). The TBC model rectifies an error in the relativistic correction factor used in the derivation of the Birch and Marshall model (Bissonnette and Schreiner, 1992, Birch and Marshall, 1979) and both bremsstrahlung and characteristic X-ray production are assumed to occur at varying depths within the target. (Tucker et al., 1991). In order to takes into account the waveform and a representation of the calculated spectra using a dosimetric quantity, TBC model was modified to produce the tbc&mod code. In addition, the tbc&mod code is able to produce X-ray spectra for different target angles and a wide range of X-ray tube potentials. The tbc&mod code was developed in the Laboratory of Radiation Dosimetry and Medical Physics, Physics Institute of São Paulo University.

2.4.- Characteristic to total spectrum ratio

One issue for evaluated the fractional contribution of the characteristic photons in the total spectrum is the characteristic to total spectrum ratio, R, defined as the ratio of the areas under each characteristic and total spectrum. Therefore, considering S_C as the area under the characteristic peaks and S_T as the area under the complete spectrum, the characteristic to total spectrum ratio can be defined as the Equation 1:

$$R = \frac{S_C}{S_T} \tag{1}$$

All areas were calculated using the Origin 8.5.1 (OriginLab, Co.) software. S_T and S_C were determined using the tools Integration and Polygon Area, respectively.

On the other hand, the spectra data in air Kerma units were used to calculate the HVLs and effective energies, both for data measured and computed.

3.- RESULTS

3.1.- Measured X-ray spectra

To obtain the characteristic to total spectrum ratio, three groups of X-ray spectra in the range of 80 to 150 kV were measured for 3.04, 4.71 and 5.98 mm of additional Aluminum filtration. All spectra were measured using the preset-time option of the ADMCA 2.0 acquisition software. The acquisition for all spectra was made at 0.2 mA and 2 min. With the same technique, three groups of X-ray spectra were computed with the tbc&mod code. The Figure 2 shows the comparison between measured and computed spectra at 80 keV for 3.04 mm additional Aluminum filtration. Figure 3 present the comparison at 100kV. Each spectrum is normalized to unit area. The X-ray spectra show the Tungsten K X-rays at 57.9, 59.3, 67.2 and 69.1 keV.

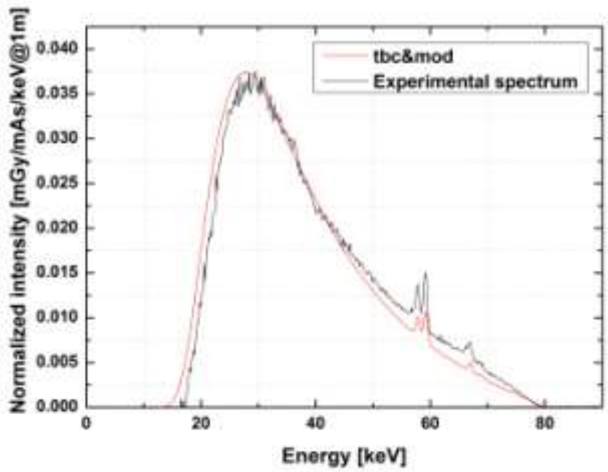

Figure 2 – Comparison between experimental (rough line) and simulated (smooth line) data for 80 kV tube potential and 3.04 mm additional Aluminum filtration

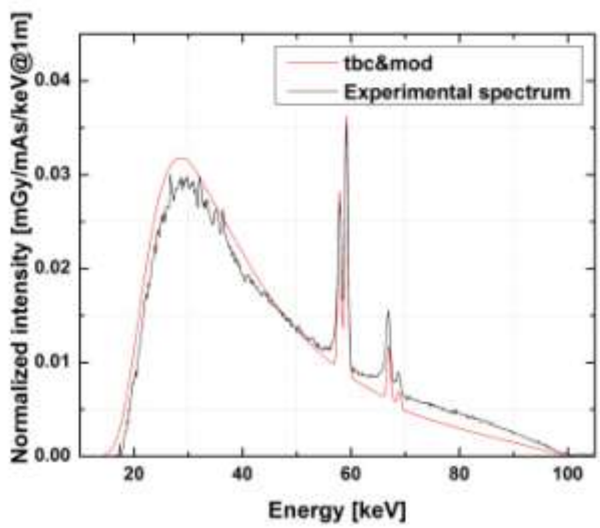

Figure 3 – Comparison between experimental (rough line) and simulated (smooth line) data for 100 kV tube potential and 3.04 mm additional Aluminum filtration

Table 2 and Table 3 list the HVLs and effective energies values for each thickness of additional aluminum filtration and for all voltage evaluated.

Table 2.- First Half Value Layer for 3.04, 4.71 and 5.98 mm of additional Aluminum filtration

Voltage (kV)	Experimental (mmAl)			tbc&mod (mmAl)		
	3.04 mmAl	4.71 mmAl	5.98 mmAl	3.04 mmAl	4.71 mmAl	5.98 mmAl
80	3.23	4.04	4.51	2.85	3.66	4.16
90	3.68	4.59	5.12	3.10	4.00	4.55
100	4.14	5.12	5.69	3.34	4.30	4.89
110	4.59	5.63	6.22	3.56	4.56	5.18
120	5.06	6.11	6.72	3.77	4.81	5.45
130	5.49	6.57	7.20	3.97	5.04	5.69
140	5.95	7.02	7.65	4.18	5.26	5.92
150	6.41	7.48	8.09	4.38	5.47	6.14

Table 3.- Effective energy for 3.04, 4.71 and 5.98 mm of additional Aluminum filtration

Voltage (kV)	Experimental (keV)			tbc&mod (keV)		
	3.04 mmAl	4.71 mmAl	5.98 mmAl	3.04 mmAl	4.71 mmAl	5.98 mmAl
80	38.9	42.3	44.1	36.9	40.5	42.5
90	42.2	45.9	47.9	39.0	42.8	45.1
100	45.5	49.3	51.5	40.9	45.0	47.4
110	48.7	52.7	54.9	42.7	47.0	49.5
120	52.0	56.0	58.3	44.4	48.9	51.5
130	55.1	59.1	61.5	46.1	50.7	53.4
140	58.3	62.4	64.7	47.8	52.5	55.4
150	61.6	65.7	68.0	49.5	54.4	57.3

Table 4 presents R for each thickness of additional aluminum filtration and for all voltage evaluated.

Table 4.- The values are the ratio of tungsten characteristic X-ray to total X-ray spectrum, R.

Voltage (kV)	Experimental			tbc&mod		
	3.04 mmAl	4.71 mmAl	5.98 mmAl	3.04 mmAl	4.71 mmAl	5.98 mmAl
80	0.010	0.017	0.017	0.006	0.008	0.009
90	0.030	0.039	0.047	0.015	0.020	0.023
100	0.049	0.058	0.068	0.023	0.030	0.035
110	0.062	0.074	0.084	0.031	0.039	0.045
120	0.073	0.087	0.093	0.037	0.047	0.053
130	0.083	0.094	0.103	0.042	0.052	0.059
140	0.090	0.101	0.109	0.047	0.057	0.063
150	0.095	0.105	0.112	0.051	0.061	0.067

Figure 4 shows the ratio of characteristic to total spectrum for measured and simulated X-ray spectra.

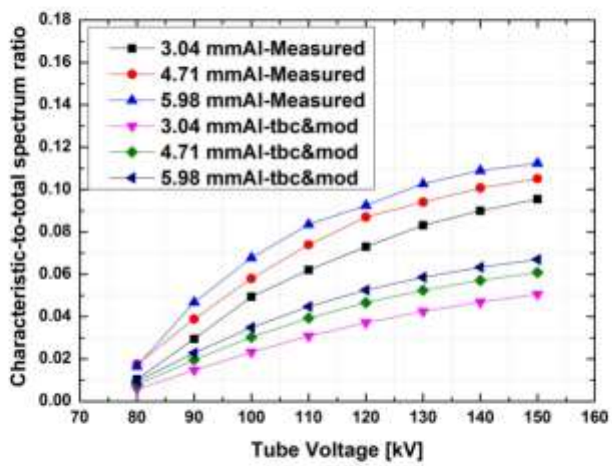

Figure 4.- Ratio of characteristic to total spectrum for experimental and simulated spectra at 3.04, 4.71 and 5.98 mm of additional aluminum filtration

Comparison between measured, computed and data obteined of the literature are presented in the Figure 5. Fewell's data, was obtained of the work publicated by Tucker (Tucker et al., 1991).

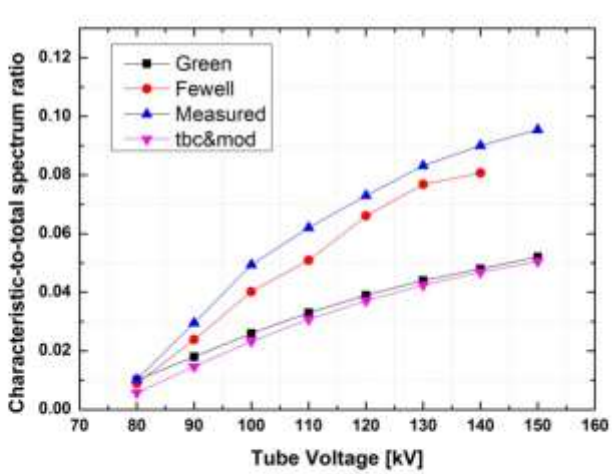

Figure 5 – Comparison between the experimental result and simulation data for 3.04 mm additional aluminum filtration and literature data, (Fewell et al., 1981, Green and Cosslett, 1968, Green and Cosslett, 1961).

4.- DISCUSSION AND CONCLUSIONS

Figure 2 and Figure 3 show that the computed spectra at 80 and 100 kV are in good agreement with the measured spectrum for energies below of 55 keV. For energies above of 55 keV, measured spectra are slightly higher than the computed spectra. In both cases, the measured spectra are “harder” than the computed spectra. This is reflected in the Table 2 and Table 4, the difference of HVLs and effective energies values between measured and simulated data, increases at high tube potentials.

As previously presented, the calibration of the characteristic spectrum takes into account the fractional contribution of the characteristic photons, R, to the total spectrum. The contribution of the characteristic photons to the total spectrum is greater for high tube potential. In the Figure 4, R increases with the applied voltage. For spectra measured at 5.98 mm and 3.04 mm of additional aluminum filtration, the contribution of the characteristic photons to total spectrum is larger in the first case at the same tube potential. The reason is due to the added filtration removes more low energy photons for 5.98 mm than for 3.04 mm of additional Aluminum filtration.

The largest discrepance, R, between experimental results and experimental data of Fewell (Fewell et al., 1981) is 22% for 110 kV. This discrepancy between these values is attributed to the differences in the anode composition of the two X-ray generator tubes. Fewell had obtained their data from a Computed Tomography X-ray tube with a Tungsten-Rhenium (90/10) alloy target, and our data was obtained using a pure Tungsten target. Computed results are in good agreement with theoretical result of Green (Green and Cosslett, 1968, Green and Cosslett, 1961).

Finally, our results showed that tbc&mod produced X-ray spectra that are in good agreement with experimental results at tube potentials below of 110 kV. For high tube potentials the differences increase, especially for high energy photons.

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