Abstract—In spite of the recent advances in the experimental detection of x-ray spectra, theoretical or semi-empirical approaches for determining realistic x-ray spectra in the range of diagnostic energies are important tools for planning experiments, estimating radiation doses in patients, and formulating radiation shielding models. The TBC model is one of the most useful approaches since it allows for straightforward computer implementation, and it is able to accurately reproduce the spectra generated by tungsten target x-ray tubes. 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 the present work, the authors revisited the assumptions used in the original paper published by Tucker et al. (1991). They proposed a complementary formulation for taking into account the waveform and the representation of the calculated spectra in a dosimetric quantity. The performance of the proposed model was evaluated by comparing values of air kerma and first and second half value layers from calculated and measured spectra by using different voltages and filtrations. For the output, the difference between experimental and calculated data was better then 5.2%. First and second half value layers presented differences of 23.8% and 25.5% in the worst case. The performance of the model in accurately calculating these data was better for lower voltage values. Comparisons were also performed with spectral data measured using a CZT detector. Another test was performed by the evaluation of the model when considering a waveform distinct of a constant potential. In all cases the model results can be considered as a good representation of the measured data. The results from the modifications to the TBC model introduced in the present work reinforce the value of the TBC model for application of quantitative evaluations in radiation physics.

Key words: medical radiation; x rays; bremsstrahlung; spectroscopy, gamma radiation

INTRODUCTION

Computing diagnostic x-ray spectral distribution has been the subject of several scientific works in the last decades (Birch and Marshall 1979; Baird 1981; Archer and Wagner 1988; Tucker et al. 1991; Boone and Seibert 1997; Boone et al. 1997). The published papers demonstrating methods adopted by different authors and their respective results have shown many approaches with a common goal: the theoretical reproduction of the radiation spectra produced by x-ray tubes used in laboratory or clinical sites. However, each method presents its own limitations, such as the representation of the spectra in arbitrary units (Tucker et al. 1991), or the use of specific databases for determining fitting parameters (Boone and Seibert 1997). Some authors have been working on the performance evaluation of the available models, and the literature shows comparisons among the different approaches (Bissonnette and Schreiner 1992; Bhat et al. 1998; Meyer et al. 2004; Ay et al. 2005) and among calculated and experimental data (Blough et al. 1998; Bhat et al. 1999; Terini et al. 1999; Stumbo et al. 2004). On the other hand, some authors have been investigating practical applications of these models for the evaluation of calibration set-ups for non-invasive voltage devices (Silva et al. 2000; Terini et al. 2004; Kunzel et al. 2004), calculation of shielding design (Costa and Caldas 2002; Okunade 2004, 2005), evaluation of beam parameters (Kharati and Zarrad 2004), or the determination of dose behavior on computed tomography (Caon et al. 1998) or mammography (Kunzel et al. 2006) systems. Recently, Ay et al. (2005) presented a comparison of the behavior of different models when compared to experimental data and also their effects on the calculation of absorbed and effective doses.

In the past, several attempts have also been shown in the literature on developing practical and precise diagnostic spectral measurement methods (Fewell and Shuping 1978; Birch and Marshall 1979; Aoki and
Koyama 1989; Silva et al. 2000; Mercier et al. 2000; Miyajima 2003; Kunzel et al. 2004; Miyajima and Imagawa 2002; Pereira 2004). In the first of these approaches, the groups worked on measuring these spectra by using high-purity germanium (HPGe), Si(Li), or Ge(Li) detectors. These systems present high energy resolution spectra but have the disadvantage of high cost and low portability because of the required liquid nitrogen cryogenic dewars. Today, the use of HPGe detectors is primarily confined to calibration and research laboratories. However, there are some low cost semiconductor systems that offer the possibility of spectral detection by using Peltier cells to cool the sensitive sensors. These systems are based on materials such as Si or Cd$_{0.9}$Te$_{0.1}$Te (CZT) and produce spectra with energy resolution comparable to the ones produced by high performance detectors. Regardless of detection method, the row data provided by the detector must always be corrected for the inherent detector efficiency by using a stripping method.

Therefore, in spite of the recent advances in the experimental detection of x-ray spectra, theoretical or semi-empirical approaches for determining realistic x-ray spectra in the range of diagnostic energies are important tools for planning experiments, estimating radiation doses in patients, and formulating radiation shielding models. A review of the literature shows that the model proposed by Tucker et al. (1991), hereafter referred to as the TBC (Tucker-Barnes-Chakraborty) model, is one of the most useful approaches, since it allows for straightforward computer implementation, and it is able to accurately reproduce the spectra generated by tungsten target x-ray tubes. However, as originally presented, the TBC model fails in the following situations:

1. Determination of x-ray spectra produced by an arbitrary waveform; and
2. Representing realistic values of air kerma for a specific x-ray system.

In the present work, the authors revisited the assumptions used in the original paper published by Tucker et al. (1991). They proposed a complementary formulation for taking into account the waveform and the representation of the calculated spectra in a dosimetric quantity. The performance of the proposed model was evaluated by comparing values of air kerma and first and second half value layers (HVL) from calculated and measured spectra by using different voltages and filtrations. Comparisons were also performed with spectral data measured by using a CZT detector.

### MATERIALS AND METHODS

#### The original TBC model

The TBC model proposed the following equation in order to determine the bremsstrahlung spectra produced by a tungsten target x-ray tube:

\[
N^0(E, T_0) dE = \frac{\sigma_0 Z^2}{A} \int_{E}^{T_0} B(E, T) F(E, T) \left( \frac{1}{\rho} \frac{dT}{dx} \right)^{-1} dT, \tag{1}
\]

where \(T\) is the energy of the accelerated electrons incident on the tungsten target, \(T_0\) is the maximum energy of the electrons (numerically equal to the maximum voltage value), \(E\) is the energy of the photon produced, \(Z\) is the atomic number of the target, \(A\) is the atomic mass of the atoms of the target, and \(\sigma_0\) is the fine structure constant. \(B(E, T)\) is a slowly varying function of \(E\) and \(T\), which provides the intensity of photons with energy \(E\) produced by electrons with energy \(T\). It was modeled as a parametric function:

\[
b(E, T) = \begin{cases} [A_0 + A_1 T] \left[ 1 + B_1 \left( \frac{E}{T} \right) + B_2 \left( \frac{E}{T} \right)^2 + B_3 \left( \frac{E}{T} \right)^3 \right] & \text{for } E \geq T \\ 0 & \text{for } E < T \end{cases} \tag{2}
\]

The function \((1/\rho) dT/dx\) represents the mass stopping power for the material of the anode. It was also modeled as a parametric function:

\[
\frac{1}{\rho} \frac{dT}{dx} = A_m + B_m e^{-TC_m} \text{ (keV m}^2 \text{ kg}^{-1}). \tag{3}
\]

The attenuation of the photons produced by the target material and the tube filtration (inherent and additional) was computed by the equation:

\[
F(E, T) = e^{-[\mu_s(E) d_m + \mu_m(E) d_m]} \tag{4}
\]

In eqn (4), \(\mu_s(E)\) is the linear attenuation coefficient for the target material, \(\mu_m(E)\) is the linear attenuation coefficient for the reference material specified for the tube filtration (in general aluminum), \(d_m\) is the equivalent attenuation of the tube filtration, \(\theta\) is the anode angle, and \(C(T)\) is obtained from the Thomson-Widdington constant, which is empirically determined (Birch and Marshall 1979). All parameters of eqns (2), (3), and (4) were provided in the paper published by Tucker et al. (1991).
In addition, Tucker et al. (1991) proposed the following equation for modeling the characteristic contribution of the spectra:

\[ N^C(E_i, T_0) = A_k \left( \frac{T_0}{E_k} - 1 \right) n_k \int_0^{R_a} j(x/R_a) dx \times e^{-\mu_0(x/R_a) \sin \theta} \, dx. \]  

(5)

In this equation, \( f(E_i) \) is the fractional photon emission at the energy \( E_i \) for the target material, \( A_k \) and \( n_k \) are parameters of the model used for fitting experimental data, \( R_a \) is the distance at which the average kinetic energy of the electrons is equal to \( E_k \), and \( j(x/R_a) \) is calculated as:

\[ j(x/R) = \left\{ \begin{array}{ll} \left( \frac{3}{2} - \left( \frac{x}{R} \right)^2 \right) & \text{for } x \leq R \\ 0 & \text{for } x > R \end{array} \right. \]  

(6)

The model can be synthesized as the sum of the bremsstrahlung, eqn (1), and the characteristic, eqn (5), contributions for the spectrum:

\[ N(E, T_0) = N^B(E, T_0) + N^C(E, T_0). \]  

(7)

**Arbitrary waveform and additional filtration spectra generation**

The original TBC model was applied to spectra produced by an x-ray tube coupled to a constant potential generator. In order to produce a more general solution, that satisfies any kind of waveform generated by commercial x-ray equipment, the following expression can be introduced for representing the voltage applied to the x-ray tube (Costa and Caldas 2002):

\[ V_\phi(t) = \frac{1}{\phi} \sum_{j=1}^{\phi} V_{\text{max}} \sin \left[ \pi \left( 12 \times 10^{-3} t - j - \frac{1}{\phi} \right) \right]. \]

(8)

In this equation, \( t \) represents the time in milliseconds, \( V_{\text{max}} \) is the maximum voltage (peak), and \( \phi \) is a parameter relative of the frequency of the high-voltage generator. Similar approaches were also used by Matsumoto et al. (1991) and by Boone and Siebert (1997).

It is also useful to take into account the variations in the spectral shape resulting from the addition of different materials in the x-ray beam. These modifications can be readily incorporated by using Beer’s law. It is performed by multiplying the unattenuated spectra by a term \( \exp[-\mu(E) \times x] \), where \( -\mu(E) \) represents the linear attenuation coefficient of the added material and \( x \) its thickness. Therefore, considering a given ripple produced by the waveform \( V(t) \) during the exposure time \( t_{\text{exp}} \), and a total filtration \( f \) of a reference material \( m \) with linear attenuation coefficient \( \mu_m(E) \), the waveform generalized model can be written as

\[ N^\phi_i(E) = N_i^B(E) + N_i^C(E), \]  

(9)

where the bremsstrahlung component is defined as

\[ N_i^B(E) = \int_0^{t_{\text{exp}}} N_i^B[E, V_\phi(t)] \times e^{-\mu_0[E] dt}, \]  

(10)

and the characteristic component is defined as

\[ N_i^C(E) = \int_0^{t_{\text{exp}}} N_i^C[E, V_\phi(t)] \times e^{-\mu_0[E] dt}. \]  

(11)

In this general solution, the function \( V_\phi(t) \) is experimentally obtained using high voltage generators coupled to acquisition boards, which are able to sample the voltage applied to an x-ray tube.

**Calibration of the spectra**

For practical purposes, it is convenient that the results determined for the use of the TBC model become representative of typical radiation quantities. In order to calibrate eqn (9) to follow this concept, a two-step method was developed: (i) calibration of the bremsstrahlung component by using a polynomial fit, and (ii) calibration of the characteristic contribution considering the fraction of the characteristic radiation in comparison to the bremsstrahlung component.

The calibration function for the bremsstrahlung contribution was defined as

\[ C_i^B(V, f) = \frac{A_1 f + A_2 f V_t + A_3 f V_t^2}{\int_{0}^{E_{\text{max}}} N_i^B(E) \times E_t \times \left[ \frac{\mu(E)}{\rho(E)} \right]_{\text{air}} dE}. \]

(12)

In this equation, \( V \) is the voltage applied to the tube (in kV), \( f \) is the total filtration thickness of the exit window of the x-ray tube housing (in mm of aluminum or copper), \( E_{\text{max}} \) is the maximum energy of the spectra (numerically equal to the x-ray controller indicated voltage), \( [(\mu/\rho)(E)]_{\text{air}} \) is the mass attenuation coefficient for air, and \( E_t \) is the mean energy transferred to the electrons of the medium.

The fitting parameters \( A_1(f), A_2(f), \) and \( A_3(f) \) were modeled as Lorentzian functions:

\[ A_i(f) = v_i + \frac{2}{\pi} \frac{a_i}{(f-f_i)^2 + a_i^2}. \]

(13)
In these equations, the values of \( N_{i}^{b} \), \( a_{i}^{r} \), \( w_{i} \), and \( f_{i} \) with their corresponding indexes \( i = 1, 2, \) or \( 3 \), are parameters obtained from fitting procedures using experimental data of air-kerma (Gy) per current-time product (mAs) for different voltages and filters. Therefore, the bremsstrahlung component in units of air-kerma per mAs for a given potential \( V \) with reference ripple \( \phi \) and total filtration \( f \) can be defined as

\[
N_{C,\phi}^{b}(E) = C^{b}(V, f) N_{\phi}^{b}(E, f) E \left[ \frac{\mu}{\rho}(E) \right]_{\text{air}}.
\] (14)

For the calibration of the characteristic lines in air-kerma units, measured spectra acquired at 80, 90, 100, 120, and 150 kV were used (Pereira 2004). The gross data measured by using a XR-100T-CZT detector (Amptek Inc., Bedford, MA) were first corrected by a gross data measured by using an XR-100T-CZT detector. These corrected spectra were separated into the bremsstrahlung and characteristic peaks. Therefore, considering \( S_{C} \) as the area under the characteristic peaks, \( S_{R} \) as the area under the bremsstrahlung portion, and \( S_{T} \) as the area under the complete spectra, the characteristic x-ray ratio can be defined as

\[
R = \frac{S_{C}}{S_{T}} = \frac{S_{T} - S_{R}}{S_{T}} = 1 - \frac{S_{R}}{S_{T}}.
\] (15)

These ratios were evaluated for each measured spectrum available. The dependence of \( R \) in relation to the applied voltage was also modeled by using a Lorentzian function:

\[
R(V) = R_0 + \frac{2 \times A_R}{\pi} \times \frac{w_R}{4(V - V_c)^2 + w_R^2}.
\] (16)

In eqn (16) \( A_R \), \( R_0 \), \( w_R \), and \( V_c \) are fitting parameters. Therefore, considering \( E_k \) as each of the eight characteristic K-lines for a tungsten-rhenium alloy (Tucker et al. 1991), the calibration function for the characteristic component was defined as

\[
C_{C}(V, f) = R(V) \times \frac{\int_{E_{\text{min}}}^{E_{\text{max}}} N_{C,\phi}^{b}(E)dE}{\sum_{k} N_{\phi}(E_{k}) E_{k} \left[ \frac{\mu}{\rho}(E_{k}) \right]_{\text{air}}}.
\] (17)

Using eqn (17), the calibrated characteristic spectra can be written as

\[
N_{C,\phi}^{C,V}(E_{k}) = C^{C}(V, f) N_{\phi}^{C}(E_{k}, f) E_{k} \left[ \frac{\mu}{\rho}(E_{k}) \right]_{\text{air}}.
\] (18)

Finally, the total spectra generated by a tungsten-rhenium target x-ray tube powered by a high voltage with waveform ripple \( \phi \) and maximum applied potential \( V \), and filtered by a thickness \( f \) of a reference material can be expressed by

\[
N_{C,\phi}^{C,V}(E) = N_{C,\phi}^{b}(E) + N_{C,\phi}^{C,V}(E).
\] (19)

**Experimental measurements**

In order to evaluate the performance of calibration functions defined in eqns (12) and (17), a set of air-kerma measurements were performed using a constant potential Philips MGC 40 x-ray generator (Philips Medical Systems, 3000 Minuteman Road, Andover, MA 01810-1099) and a calibrated 10 × 5 – 6 (Radcal, Co., Monrovia, CA) ion chamber and a model 9015 (Radcal, Co.) radiation monitor. The calibration of the ion chamber and radiation monitor assembly is traceable to the national calibration network. The uncertainties of the measurements using this system were considered lower than 7% using a coverage factor \( k = 2 \) or a confidence level of 95% (Pereira 2004; ISO 1995). Additional filtration of aluminum and copper was added to the x-ray beam and the voltage varied from 40 to 150 kV in steps of 10 kV. The ion chamber was fixed at 1 m from the focal spot, and the ambient conditions (temperature, pressure and humidity) were monitored during the experiments.

These data were used on the fitting process of eqns (12) and (17). This fitting process used the Levenberg-Maquardt algorithm incorporated into the Origin 6.0 software (Microcal Software, Inc). The results of these parameters were incorporated into a Mathcad 2000 (Mathsoft, Inc.) worksheet specially designed to perform the calculation of the spectra according to the presented model.

**RESULTS**

The measurements of the air-kerma for each set-up of voltage, current-time product, and added filtration generated a group of equations with the functional form of the numerator of eqn (12), or \( A_{t}(f) + A_{c}(f)V + A_{k}(f)V^2 \). The range of filter thicknesses evaluated was 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mm for aluminum and 0.060, 0.140, 0.258, 0.390, and 0.482 for copper. Fig. 1 presents the plot of the experimental data for the output.
of the system in Gy A\(^{-1}\) s\(^{-1}\) with these different aluminum filtrations for the voltage range from 40 to 150 kV. A similar plot is presented in Fig. 2 for copper filtration. In both Figs. 1 and 2 the solid lines represent the fit of the equation \(A_1(f) + A_2(f)V + A_3(f)V^2\) to the experimental data. This fit was performed by using the polynomial fit algorithm incorporated into the Origin 6.0 software. The fitting parameters obtained for the aluminum and copper additional filtration are presented in Table 1. For each thickness of aluminum filtration, the coefficient of determination (Microcal Origin 1999), \(R^2\), was greater than 0.99959 and for the copper filters, each \(R^2\) was 0.99839 or greater.

The results for \(A_1(f), A_2(f),\) and \(A_3(f)\) for both sets of filters of aluminum and copper were fitted by using the Levenbeg-Maquardt method following the relationships defined by eqn (13). The fitting parameters obtained for each of these equations are presented in Table 2 for aluminum and copper filtration.

As previously presented, the calibration of the characteristic spectra takes into account the fractional contribution of the characteristic lines, \(R\), for the total spectra. Table 3 shows the values of \(R\) for each voltage evaluated from measured spectra (Pereira 2004). This table also compares these with the corresponding values from Tucker et al. (1991), \(R_{TBC}\). The largest discrepancy between these values is 18.2\% for 80 kV. These discrepancies can be attributed to the differences in the anode composition of the two x-ray generator tubes. Tucker et al. used a tungsten-rhenium alloy (90/10) and Pereira used a pure tungsten target. These \(R\) values were modeled by eqn (16). The data obtained by applying the Lorentzian fit procedure determined from the Origin software are presented in Table 4. Fig. 3 compares the calculated points obtained by applying the proposed methodology, the data points from Tucker et al. (1991), and the fitted curve.

The application of the methodology presented in this work was tested by comparing simulated results of the
Table 1. Results of the fitting parameters $A_1(f)$, $A_2(f)$, and $A_3(f)$ of eqn (12) obtained using additional filtration in aluminum and copper with thicknesses shown in the table. This fit was performed using the polynomial fit algorithm incorporated into the Origin 6.0 software.

<table>
<thead>
<tr>
<th>Additional filtration</th>
<th>Aluminum (mm)</th>
<th>Copper (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1(f)$</td>
<td>$-4.28 \times 10^{-2}$</td>
<td>$2.63 \times 10^{-3}$</td>
</tr>
<tr>
<td>$A_2(f)$</td>
<td>$-4.07 \times 10^{-2}$</td>
<td>$1.77 \times 10^{-3}$</td>
</tr>
<tr>
<td>$A_3(f)$</td>
<td>$-2.34 \times 10^{-2}$</td>
<td>$8.20 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$-1.65 \times 10^{-2}$</td>
<td>$4.43 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$-1.12 \times 10^{-2}$</td>
<td>$2.31 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$-7.75 \times 10^{-3}$</td>
<td>$8.87 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 2. Fitting parameters of the Lorentzian functions defined in eqn (13) corresponding to the parameters $A_1(f)$, $A_2(f)$, and $A_3(f)$ for set of aluminum and copper filters. The fitting process used the Levenberg-Maquardt method.

<table>
<thead>
<tr>
<th>Aluminum</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1(f)$</td>
<td>$-5.10 \pm 2.20 \times 10^{-3}$</td>
</tr>
<tr>
<td>$A_2(f)$</td>
<td>$-1.72 \pm 0.40 \times 10^{-1}$</td>
</tr>
<tr>
<td>$A_3(f)$</td>
<td>$2.88 \pm 0.53$</td>
</tr>
<tr>
<td></td>
<td>$5.9 \pm 1.6 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

Table 3. Values of $R$, the fractional contribution of the characteristic lines, for each voltage evaluated from measured spectra (Pereira 2004) and the corresponding values from Tucker et al. (1991), $R_{TBC}$-

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>$R$</th>
<th>$R_{TBC}$</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>0.011</td>
<td>0.009</td>
<td>18.2</td>
</tr>
<tr>
<td>90</td>
<td>0.029</td>
<td>0.024</td>
<td>17.2</td>
</tr>
<tr>
<td>100</td>
<td>0.046</td>
<td>0.042</td>
<td>8.7</td>
</tr>
<tr>
<td>110</td>
<td>-</td>
<td>0.054</td>
<td>-</td>
</tr>
<tr>
<td>120</td>
<td>0.075</td>
<td>0.071</td>
<td>5.3</td>
</tr>
<tr>
<td>130</td>
<td>-</td>
<td>0.083</td>
<td>-</td>
</tr>
<tr>
<td>140</td>
<td>-</td>
<td>0.088</td>
<td>-</td>
</tr>
<tr>
<td>150</td>
<td>0.096</td>
<td>0.096</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4. Results of the application of the Lorentzian fit procedure available in Origin software to the $R$ values modeled by eqn (16).

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>$R_0$</th>
<th>$V_c$</th>
<th>$w$</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>$-0.193 \pm 0.007$</td>
<td>150.15 $\pm 3.06$</td>
<td>218.54 $\pm 45.54$</td>
<td>99.26 $\pm 45.18$</td>
</tr>
</tbody>
</table>

generated spectra to similar data obtained experimentally. Figs. 4 to 6 show comparative results from calculated and measured (Pereira 2004) data for 80, 100, and 150 kV. Table 5 presents comparative results for the output, defined as the ratio of the air-kerrma per current-time product (mGy mA$^{-1}$ s$^{-1}$) and for the first and second HVL values calculated from these measured and calculated spectra. For the output, the difference between experimental and calculated data was better than 5.2%. First and second HVLs presented differences of 23.8% and 25.5% in the worst case. The performance of the model in accurately calculating these data was better for lower voltage values.

In order to evaluate the ability of our method to calculate the spectra from an actual waveform, one last test was done. For this purpose, two experimentally measured waveforms were used for representing the function $V_p(t)$ in eqns (10) and (11). These waveforms were obtained by sampling an input electrical signal applied to an x-ray tube by coupling a 12 bit acquisition board PCI-MIO-16E-4 (National Instruments, Austin, TX) to a high voltage divider (Dynalyzer III, Radcal Co.). The acquisition frequency was $200 \times 10^2$ samples per second. This voltage divider was coupled to a three-phase, six-pulse x-ray generator (Gigantus, Siemens Medical Systems, Munich, Germany).

The sensitivity of the model to differentiate spectra generated by different waveforms was evaluated by...
comparing spectra obtained from both 80 kV and 100 kV experimentally acquired waveforms and from similar theoretical waveforms calculated from eqn (8). Figs. 7 and 8 show the experimental and theoretical waveforms, and Fig. 9 shows the calculated spectra from each of the four waveforms.

CONCLUSION

The model presented in this paper introduces a group of equations that incorporate a number of fitting parameters. They assume that the experimental data exhibit Lorentzian behavior when their dependence on the additional filtration of the x-ray beam is considered. Several experimental measurements were used to determine the fitting parameters of these equations for different thicknesses of aluminum and copper filters and different voltages applied to the x-ray tube. The robustness of the model to simulate actual radiation spectra was tested by comparison of measured spectra output and first and second HVL measurements. Another test was performed to evaluate the model by considering a waveform distinct of a constant potential. In all cases, the model results can be considered as a faithful representation of the measured data.

This work presents a new methodology for obtaining x-ray spectra calculated by using the TBC model.
using dosimetric quantities (mGy keV$^{-1}$) and incorporating an arbitrary voltage waveform. Although the original model was introduced fourteen years ago, it remains robust in its physical concepts, and presents the advantage of being readily adaptable for computer implementation. The results introduced in the present work only reinforce its capability that it may be a useful model to be applied in quantitative evaluations of multiple applications in radiation physics.

Acknowledgments—The authors would like to thank Marco A. G. Pereira for providing spectral data for calibrating characteristic lines and for comparison of the calculated spectra, and João S. Pires for providing waveform data. This research was partially supported by the Brazilian Agency CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico).

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