Experimental and Monte Carlo-simulated spectra of standard mammography-quality beams

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ABSTRACT. A spectrometric study of standard mammography-quality beams by using experimental and Monte Carlo simulation methods was carried out in this work. The qualities of these beams are described according to the International Electrotechnical Commission 61267 standard and the Technical Report Series 457 International Atomic Energy Agency report. Specifically, the non-attenuated RQR-M beam series was studied.

Methods: A Si-PIN diode-based spectrometer and the PENELOPE Monte Carlo code (v. 2008F1) were used for experiments and simulations, respectively. In addition, an ionization chamber was used to determine the half-value layers (HVLs) of each beam quality. The measurements were done in the mammography dosimeter calibration setup of our laboratory, and the Monte Carlo simulations reproduced such conditions.

Results: The relative differences between the HVLs calculated from experimental and simulated spectra were lower than 2.4% for all the beam qualities studied. These differences are 1.2% and 3.1% when comparing the HVLs calculated from the experimental and simulated spectra to those determined by using the ionization chamber, respectively. A semi-empirical relation was found to obtain the nominal tube potential from the effective tube potential.

Conclusion: According to our results, the mammography beams used in this work have energy spectra similar to clinical beams.

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A complete characterisation of an X-ray beam is achieved by the determination of its photon fluence spectrum [1]. Such information is necessary to set up a calibration system in a dosimetry laboratory. The first and second half-value layers serve as a quality index of the X-ray beams. However, the X-ray spectrum provides more detailed information about the X-ray beam [2] and allows the user to improve the dosimetry equipment calibration [3]. In addition, knowledge of these spectra can help to improve the design of X-ray detectors and the diagnostic imaging techniques [4]. Furthermore, such spectra have been recently used in studies where the relative biological effectiveness (RBE) of mammography beams has been determined by Monte Carlo simulations. The latter is related to the very controversial issue of the possible enhancement of the collective risk due to mammography screening programmes [5, 6]. Another reason to obtain these spectra is that the real tube voltage can be accurately determined and compared to that provided by the high voltage generator. The International Atomic Energy Agency (IAEA) Technical Report Series (TRS) 457 [1] recommends carrying out an invasive measurement of the supplied potential.

The determination of mammography-beam energy spectra implies some difficulties that have been

addressed in previous studies [7–10]. For example, the air kerma rate should be reduced to values that make negligible the signal pile-up effect in the detection system. It is necessary to carry out the energy calibration of the detector and to correct the spectrum according to the efficiency of each energy bin [11]. During Monte Carlo calculations, it is necessary to optimise the simulation parameters to overcome the low photon production rate, due to the impact of electrons on the target mainly at low energies.

The scope of this work was to carry out a spectrometry study of standard mammography-quality beams by using experimental and Monte Carlo simulation methods. The beams as described in the International Electrotechnical Commission (IEC) 61267 standard [12] were established in our laboratory considering also the recommendations of the IAEA TRS 457 report [1]. The details of the experimental setup have been described previously [13]. These mammography beams are used as the references for calibration of instruments used in clinical environments, once they are similar to the ones used in the clinics. In this case, the non-attenuated beams identified as RQR-M series [1, 12] were the ones selected for this study.

Si-PIN diode-based spectrometer and the PENELOPE Monte Carlo code (v. 2008) were used for experiments and simulations, respectively. The experimental and simulated energy spectra were compared, and the effective tube voltages were extracted from these spectra.

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Methods and materials

Experimental spectrometry

The beams used in this work were produced by a Philips (Eindhoven, Netherlands) PW 2185/00 X-ray tube with a molybdenum (Mo) target and a beryllium (Be) exit window (0.1–1.0 mm). This tube is water cooled which allows long exposure times. This is beneficial for calibration procedures and for the spectra measurements. The X-ray tube is powered by a Seifert (Ahrensburg, Germany) ID 3003 high-voltage generator that provides constant potential (ripple <1%). The minimum value allowed for the tube current is 2 mA, which was the value used during the spectra measurements.

Spectra were measured with an Amptek (Bedford, MA) Si-PIN photo-diode (XR-100CR) spectrometer with a 1 mm Be window. The sensitive volume of this detector is 6 mm² × 0.5 mm, which presents a high energy resolution for low-energy radiographs (145–165 eV for 5.9 keV) and low detection efficiency. The selection of this type of detector to study mammography beams is supported by several previous works [2, 8, 14]. The detector was coupled to a PX2CR signal amplifier and to a Pocket MCA 8000 A multi-channel analyser, both manufactured by Amptek. The whole system was connected to a PC, and Amptek-ADMCA software was used for the data acquisition and processing. A pinhole-type collimator was placed close to the detector.

The beam series studied, the RQR-M, uses an additional filtration of 0.03-mm Mo and the measurements were conducted at a source-to-detector distance of 100 cm using a total of 10⁶ counts.

The energy calibration of the system was carried out using the K α and K β peaks of the Mo discrete emission spectrum which correspond to 17.44 keV and 19.60 keV, respectively. Such a calibration was based on the linear response function of the detector. The original 16384 channels were grouped in such a way as to obtain bin widths of 0.5 keV.

Spectra correction

Detection data must be corrected for photo-electron escape. The method proposed by Aoki and Koyama [14] was followed to estimate the fraction of electrons escaping from the detector (f_e) as:

$$f_e = [1 - \exp(-0.277r_e^{2.67})]^{0.7} \quad (1)$$

where $r_e = E/E_0$ is the ratio between the incident photon energy (E) and the energy of electrons with range equal to the width of the depletion layer (E_0). In our case (500 μ m layer), $E_0 = 300$ keV and the maximum value of E was about 35 keV, so only 0.8% of photo-electrons escaped from the detector. Thus, this effect was regarded as negligible.

Any correction for the fluorescent emission from the silicon K-shell was also neglected due to the corresponding low energy (1.84 keV) and yield (5%) [14]. In addition, no correction was made for Compton scattering because for the maximum energy in our spectra (35 keV) the Compton

energy threshold [7, 8, 15] was about 4.2 keV, which is an energy for which the spectral intensity is negligible.

Spectra were corrected for the detector efficiency as a function of the photon energy, as previously reported [2, 8]. The response curve of the Si-PIN photo-diode was provided by the manufacturer and was used to correct the intensity of each energy bin by carrying out a polynomial fit. After this correction, the spectra were normalised by dividing each bin yield by the total number of counts.

Monte Carlo simulations

Monte Carlo simulations were done to verify the consistency of our experimental results. The PENELOPE code (v. 2008) [16] was used in conjunction with a detailed geometrical model of the X-ray tube. The exit window was modelled as a 0.5 mm Be foil, and the target was a Mo slab placed at 26° with an area of 1.6 × 0.9 cm². Simulations were divided into two stages. First, the spectrum coming out from the tube exit window was obtained. Later, such a spectrum would be used as the source for the simulations of photon passage through the experimental setup. The detector was placed 1 m from the tube exit window, and photons arriving at the detector within a circumference of 1.5-cm diameter ($\sim 10^6$) were post-processed to construct the energy spectra. Bin widths of 0.5 keV were used. The use of the forced-interaction variance reduction technique was mandatory during the first stage of simulations (within the tube). This allowed an increment of the photon production yield due to the impact of electrons on the target, both by the bremsstrahlung process (continuous spectrum) and inner shell ionization (fluorescent emission). The PENELOPE simulation control parameters were taken as IFORCED=10³ (interaction forcing parameter) and C₁=C₂=0.1 (elastic-scattering parameters) during all the simulations. However, the threshold energy parameters Wcc and Wcr were set equal to 0.1 keV for the first simulation stage and 0.25 keV (half of the energy bin width) for the second one. The number of histories simulated were about 10⁹ electrons and 10⁷ photons in the first and second stages, respectively. Using a PC with Intel Core 2 Quad Q6600 processor (2.40 GHz, 2 GB of RAM memory), the simulation time for the first and second stages were about 6.10⁵ s and 4.10³ s, respectively.

Mean energy, half-value layer and uncertainty determinations

The air kerma produced by a photon spectrum can be determined to a good approximation by:

$$K^{\text{air}} = \sum_{i=1}^n \Phi_i E_i \left(\frac{\mu_{\text{ir}}}{\rho} \right)_i^{\text{air}} \quad (2)$$

where E_i , Φ_i and $(\mu_{\text{ir}}/\rho)_i^{\text{air}}$ are the photon energy, fluence and mass-energy-transfer coefficient of air corresponding to the i_{th} bin of the spectrum. The first half-value layer (HVL) was then obtained by solving the equation:

Figure 1. Comparison between the experimental and simulated spectra obtained in this work for the (a) 25 kV, (b) 28 kV, (c) 30 kV and (d) 35 kV beams.

$$\frac{1}{2} \sum_{i=1}^{N_{\text{bin}}} K_i^{\text{air}} = \sum_{i=1}^{N_{\text{bin}}} K_i^{\text{air}} \exp[-\mu_i \text{HVL}] \quad (3)$$

where μ_i and K_i^{air} are the linear attenuation coefficients of the reference material (aluminium in our case) and the air kerma corresponding to the i th energy bin, respectively [2, 17]. The attenuation coefficients of air and aluminium were extracted from the National Institute of Standards and Technology (NIST) website [18]. Five points were plotted in a graph logging the transmitted air kerma vs the attenuation layer width. The width value (first HVL, Equation 3) was found from the best linear fitting curve for these five points.

The first HVLs were experimentally measured using a Radcal (Monrovia, CA) ionization chamber, model 10X5-6M (parallel plate with an active volume of 6 cm³), coupled to a Keithley (Cleveland, OH) electrometer,

model 6517A, as recommended by the IAEA TRS 457 report [1]. The source-chamber distance was 100 cm.

The frequency-mean energy of each spectrum was calculated as:

$$\bar{E} = \sum_{i=1}^{N_{\text{bin}}} f_i E_i \quad (4)$$

Table 1. Average energies (keV) of experimental and simulated spectra, and the relative differences (%) between them

Quality	kV	Experimental (keV)	Simulated (keV)	Difference (%)
RQR-M1	25	16.30 ± 0.14	16.16 ± 0.20	0.9
RQR-M2	28	16.92 ± 0.15	16.77 ± 0.20	0.9
RQR-M3	30	17.31 ± 0.15	17.15 ± 0.18	0.9
RQR-M4	35	18.30 ± 0.17	18.05 ± 0.22	1.4

Table 2. Half-value layers (mm Al) of the mammography-quality beams studied in this work. Values were determined by using an ionization chamber (IC) and from the experimental and simulated spectra. Reference values were extracted from the IEC 61267 standard [12]

Quality	kV	IEC (mm Al)	IC (mm Al)	Experimental (mm Al)	Simulated (mm Al)
RQR-M1	25	0.28 ± 0.02	0.294 ± 0.003	0.291 ± 0.007	0.285 ± 0.011
RQR-M2	28	0.31 ± 0.02	0.326 ± 0.003	0.322 ± 0.007	0.317 ± 0.010
RQR-M3	30	0.33 ± 0.02	0.341 ± 0.003	0.340 ± 0.007	0.336 ± 0.008
RQR-M4	35	0.36 ± 0.02	0.378 ± 0.003	0.380 ± 0.006	0.371 ± 0.007

IEC, International Electrotechnical Commission.

where f_i is the normalised frequency corresponding to the bin with energy E_i . Uncertainty determinations were based on ISO Guide 98 [19]. The uncertainties associated with the mean energies in the experimental and simulated spectra were obtained as:

$$u_E = \sum_{i=1}^{N_{\text{bin}}} E_i u_{f_i} \quad (5)$$

where u_{f_i} is the uncertainty of the spectral frequency corresponding to the i_{th} bin. The uncertainties of the experimental frequencies were calculated as $N_i^{1/2}/N$, where N_i and N are the counts in the i_{th} bin and the total counts, respectively. The uncertainties of the simulated spectral frequencies were reported by the PENELOPE PENMAIN user code. Finally, the relation

$$u_{\text{HVL}} = \frac{d\text{HVL}}{dE} u_E \quad (6)$$

was used to assess the uncertainties (u_{HVL}) involved in the first HVLs calculated from the measured and simulated spectra.

For the estimation of the overall uncertainties associated with the HVL measurements determined by using the ionization chamber, the standard deviation of the

measurement series was taken as uncertainty type A and the electrometer resolution, the linear fitting process, and the thickness of Al filters as type B.

The overall uncertainties stated in this work are reported for a confidence level of 95% with a coverage factor of $k=2$ [19].

Determination of peak tube voltage

The experimental spectra obtained in this work were used to determine the effective peak kilovoltage used to generate the beams under investigation. About 10 points representing the high-energy extreme of the spectrum were used to find, by a fitting process, the intercept of the spectrum with the energy axis, according to the method proposed by Silva *et al* [20]. The bin width used in these determinations was 0.1 keV to improve the precision of such calculations. The uncertainties corresponding to the kVps are mainly influenced by the counting statistics, detector calibration and energy bin width. A linear relationship was found between the effective kVp and that set in the control panel of the X-ray equipment.

Results

The experimental and simulated spectra for each radiation quality are shown in Figure 1. The agreement observed requires a quantitative comparison based on some quantities associated with the spectra. For example, the HVL and frequency-weighted mean energy of the spectra allow us to make a more sensitive comparison [9]. Table 1 shows such mean energies calculated from the experimental and simulated spectra. The corresponding uncertainties were determined by using Equation 5 and are also shown. They are about 0.9% and 1.2% for the experimental and simulated spectra, respectively. The relative differences between experimental and simulated $\bar{E}$ are consistently below 1.4% which confirms the accord observed in Figure 1.

Table 3. Relative differences (%) between the HVLs obtained in this work. Comparing values measured and calculated from the experimental spectra (IC-Exp), calculated from experimental and simulated spectra (Exp-Sim), measured and calculated from simulated spectra (IC-Sim)

Quality	kV	IC-Exp(%)	Exp-Sim(%)	IC-Sim(%)
RQR-M1	25	1.0	2.1	3.1
RQR-M2	28	1.2	1.6	2.8
RQR-M3	30	0.3	1.2	1.5
RQR-M4	35	-0.5	2.4	1.9

Figure 2. Half-value layers (HVLs) obtained in this work from ionisation chamber measurements (IC meas.), experimental spectra (exp. spect.) and simulated spectra (sim. spect.). The corresponding values and tolerances reported in the IEC standard (IEC std) are also shown. IEC, International Electrotechnical Commission.

Figure 3. Comparison between (a) experimental spectra determined in our work and that reported in [21] (IPEM97) and (b) simulated spectra obtained using the PENELOPE (this work) and MCNP MC [23] codes. IPEM, Institute of Physics and Engineering in Medicine.

First HVLs are more sensitive to the differences between energy spectra. The results of the HVLs calculated from the measured and simulated spectra (by solving Equation 3) and those determined by ionization chamber measurements are shown in Table 2 and Figure 2. The corresponding values recommended by the IEC 61267 standard are also shown. The uncertainties in the HVLs calculated from spectra and those determined with the ionization chamber are about 2.4% and 0.9%, respectively. Table 3 shows that the relative differences between the HVLs calculated from the experimental spectra and those measured with the ionization chamber range from 0.3 (30 kV) to 1.2% (28 kV). These results were achieved because the high workload tube characteristics allow long exposure times using low air kerma rates, in conjunction with the high energy-resolution and the low detection efficiency of the Si-PIN photodiode. The data used to plot the experimental spectra are available on the website of our laboratory (www.lcr.uerj.br/lm/spectra.pdf).

Regarding the HVLs calculated from the experimental and simulated spectra, the differences remained between 1.2 (30 kV) and 2.4% (35 kV). The values obtained from experimental spectra are systematically higher than those obtained from simulated spectra, in the same way that was reported previously [17]. It should be noted that even for the 35-kV beam, the HVLs calculated from the experimental and simulated spectra coincide within the corresponding uncertainties. Comparing the HVLs calculated from the simulated spectra and those measured with an ionization chamber, the differences remained between 1.5 and 3.1% for the 30 kV and 25 kV beams, respectively. These relative differences are presented in Table 3.

Figure 3a shows the 30-kV beam experimental spectrum determined in this work and that calculated by following the recommendations of the Report 78 of the Institute of Physics and Engineering in Medicine (IPEM) [21]. Despite small differences in the frequencies near the characteristics emission lines of Mo, these spectra show an agreement. The HVL calculated for the IPEM spectrum

Table 4. Previously published first half-value layers (mm Al) direct measured and calculated from spectra. For each work, the filtrations, the anode angle, and the distance from focal point reported are shown

Works	Nominal kV			
	25	28	30	35
IPEM (1997) [21]	0.276	0.305	0.321	–
calc. from modelled spectra				
0.5 mmBe; 0.03 mmMo; anode 23°; 100 cm				
Kunzel (2006) [23]	0.315 ± 0.025	–	0.374 ± 0.014	0.405 ± 0.035
measured in Mammomat 3000 Nova (Siemens)				
1 mmBe; 0.03 mmMo; anode 20°; 60 cm				
Wilkinson (2001) [9]	0.300 ± 0.010	0.341 ± 0.005	0.350 ± 0.004	–
measured in Diagnost U-M (Philips)				
2 mmBe; 0.03 mmMo; anode 20°; 60 cm				
Ay (2004) [24]	–	–	0.35	–
calc. from simul. spectra (MCNP)				
0.5 mmBe; 0.035 mmMo; anode 12°; 50 cm

Figure 4. Transmission curves in aluminium determined from the experimental and simulated spectra.

(attenuations of 0.03 mm Mo, 0.5 mm Be and 985 mm of air and an anode angle of 23°) is 0.321 mm of Al, which is 5.6% lower than that calculated from the spectrum measured in this work. In fact, as shown in Table 4, the $\bar{E}$ and HVLs obtained according to the IPEM Report are systematically lower than the experimental values, in the same way that was reported by others research groups [9, 22]. On the other hand, the $\bar{E}$ and HVL values published by Künzel [23] and the HVL measured by Wilkinson *et al* [9] are systematically higher than our results. Table 4 shows that, in general, the first HVLs measured or calculated from measured spectra in mammography shows large variations. Based on the IPEM modelling program, a decrease of 7° in the anode angle leads to an increment of the HVLs in 1.4 and 1.9% for 25 and 30 kV, respectively. The differences in equipment and methods may affect the comparisons even for similar clinical beams. Considering that the HVLs measured and calculated from the experimental spectra obtained in our laboratory remain within the limits established by IEC 61267, the X-ray beams under investigation are similar to those used for clinical purposes.

In Figure 3b, the simulated 30 kV spectra obtained by using the MCNP4C [24] and PENELOPE (this work) codes are displayed. Despite the slight differences between the models involved the coincidence of the normalised frequencies is good. Quantitatively, the HVL reported for the MCNPC spectrum is 0.35 mm of Al, which is 4.0% higher than the value found in our simulations. In this case, it should be mentioned that the simulated beam was released by Mo anodes with different angles and passed through different filters (Ay *et al* used 12° anode angle, and filters of 1 mm Be and 0.035 mm Mo) [24].

It was shown by Wilkinson *et al* [9] that mammography spectral distributions predicted by different mathematical models need to be corrected by beam hardening using additional filtration in order to allow a better matching with the measured values. Regarding the Monte Carlo simulations, the use of the MCNP4C code to generate mammography spectra requires an adjustment of the parameter XNUM that controls characteristic X-ray

Table 5. kVps values obtained from experimental spectra

Quality	kV	kVp
RQR-M1	25	25.3 ± 0.1
RQR-M2	28	28.3 ± 0.1
RQR-M3	30	30.5 ± 0.1
RQR-M4	35	35.5 ± 0.1

emissions [24]. In the present work, the low-energy model used by the PENELOPE code made it possible to obtain results similar to those obtained from the measured spectra without any additional correction.

It is also possible to evaluate the results obtained for the experimental and simulated spectra based on the corresponding transmission curves. Figure 4 shows the air kerma-transmission curves as a function of the Al attenuation thickness for all the experimental and simulated spectra. Agreement was observed between the experimental and simulated transmission values down to less than 10% transmission. The maximum differences observed between the transmission curves for each beam quality shown in Figure 4 are 4.4, 5.3, 4.9, and 5.9% for 25, 28, 30, and 35 kV, respectively.

The kVp values obtained for each beam quality from the experimental spectra are shown in Table 5. These data allow us to establish the following relation:

$$kVp_n = (kVp_e + 0.19841)/1.0211 \quad (7)$$

where kVp_n is the nominal tube voltage to be selected in the equipment control panel and kVp_e is the effective voltage applied to the X-ray tube. In the calibrations made with our setup, nominal kVp_n values calculated through Equation 7 are used to obtain beams with kVp_e values close to the reference values published in the IEC 61267 standard [12] and the TRS-457 report [1].

Conclusions

The maximum difference observed between the HVLs calculated from the experimental spectra and those measured with the ionisation chamber was less than 1.2%, indicating that the methods and parameters used for acquisition and correction of the spectra were suitable. The use of a constant potential and cooled X-ray tube and the high resolution Si-PIN photodiode detector were also helpful to obtain these results. The agreement between the $\bar{E}$ and HVLs calculated from the experimental and simulated spectra shows that the parameters adopted in our simulations were adequate to provide the modelling of the X-ray tube and experimental conditions. An overall consistency can be observed when comparing all the HVLs obtained in this work, a quantity that is very sensitive to changes in energy spectra. Furthermore, our experimental and simulated HVLs are equivalent, within the corresponding tolerances, to those reported in the international standards. In addition, it was shown that the mammography beams used in this work have energy spectra similar to those used in clinical environments. This statement is based on the results obtained from the comparison of the HVLs determined in this work and those reported by the IEC and others publications [9, 12, 21, 23, 24].

The PENELOPE code provided spectra results similar to those obtained experimentally. Thus, it was not necessary to adjust the simulated spectra to make them comparable to those determined experimentally. Simulations using the PENELOPE code in the mammography energy range can be done to enhance the metrological knowledge of the dosimeter–calibration systems and to improve diagnostic imaging systems.

The experimental spectrometry method was very helpful to determine the kVps of beams used in our metrological laboratory. Based on the results of this work, the spectrometry study will be extended to mammography-standard attenuated beams and to investigate the spectral changes as a function of depth in a breast phantom.

It is encouraging to know that the use of this type of X-ray equipment to calibrate measurement instruments used in clinical environments does not compromise the image quality needed for clinical diagnosis or the safety of the staff.

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References

1. International Atomic Energy Agency (IAEA). Dosimetry in diagnostic radiology: An international code of practice. Technical Report Series 457. Vienna: IAEA; 2007.
2. Kunzel R, Herdade SB, Terini RA, Costa PR. X-ray spectroscopy in mammography with a silicon pin photodiode with application to the measurement of tube voltage. *Med Phys* 2004;31:2996–3003.
3. DeWerd LA, Micka JA, Laird RW, Pearson DW, O'Brien M, Lamperti P. The effect of spectra on calibration and measurement with mammographic ionization chambers. *Med Phys* 2002;29:2649–54.
4. Meyer P, Buffard E, Mertz L, Kennel C, Constantinesco A, Siffert P. Evaluation of the use of six diagnostic X-ray spectra computer codes. *Br J Rad* 2004;77:224–30.
5. Göggelmann W, Jacobsen C, Panzer W, Walsh L, Roos H, Schmid E. Reevaluation of the RBE of 29 kV x-rays (mammography x-rays) relative to 220 kV x-rays using neoplastic transformation of human cgl1-hybrid cells. *Rad Env Biophys* 2003;42:175–82.
6. Hemminki K, Rawal R, Bermejo JL. Mammographic screening is dramatically changing age-incidence data for breast cancer. *Jour Clin Oncol* 2004;22:4652–3.
7. Aoki K, Koyama M. Measurement of diagnostic X-ray spectra using a silicon photodiode. *Med Phys* 1989;16:529–36.
8. Pani R, Laitano RF, Pellegrini R. Diagnostic X-ray spectra measurements using a silicon surface barrier detector. *Phys Med Biol* 1987;32:1135–49.
9. Wilkinson ALE, Johnston PN, Heggie JCP. A comparison of mammography spectral measurements with spectra produced using several different mathematical models. *Phys Med Biol* 2001;46:1575–89.
10. Llovet X, Sorbier L, Campos CS, Acosta E, Salvat F. Monte Carlo simulation of X-ray spectra generated by kilo-electron-volt electrons. *J Appl Phys* 2003;93:3844–51.
11. Knoll G. Radiation detection and measurement. New York: John Wiley and Sons; 2003.
12. International Electrotechnical Commission (IEC). Medical diagnostic x-ray equipment – radiation conditions for use in determination of characteristics. Report IEC-61267; 2005.
13. Pires EJ, David MG, Peixoto JG, deAlmeida CE. Establishment of radiation qualities for mammography according to IEC 61267 and TRS 457. *Radiat Prot Dosim* 2012;145:45–51.
14. Aoki K, Koyama M. Photoelectron escape from a silicon X-ray detector: Monte Carlo study. *Phys Med Biol* 1990; 35:1051–63.
15. Seelentag WW, Panzer W. Stripping of X-ray bremsstrahlung spectra up to 300 kVp on a desk type computer. *Phys Med Biol* 1979;24:767–80.
16. Salvat F, Fernandez-Varea JM, Sempau J. A code system for Monte Carlo simulation of electron and photon transport. Issy-les-Moulineaux, France: OECD-NEA; 2008.
17. Mainegra-Hing E, Kawrakow I. Efficient X-ray tube simulations. *Med Phys* 2006;33:2683–90.
18. Hubbell J, Seltzer S. Table of X-ray mass attenuation coefficients and energy absorption coefficients. National Institute of Standards and Technology (NIST) webpages (cited August 2010). Available from: <http://www.nist.gov/physlab/data/xraycoef/index.cfm>.
19. ISO, IEC. Guide to the expression of uncertainty in measurement (GUM). Guide 98. ISO, IEC, 1995.
20. Silva MC, Herdade SB, Lammoglia P, Costa PR, Terini RA. Determination of the voltage applied to X-ray tubes from the bremsstrahlung spectrum obtained with a silicon PIN photodiode. *Med Phys* 2000;27:2617–23.
21. Cranley K, Gilmore B, Fogarty G, Desponds L. Catalogue of diagnostic X-ray data and other data. Tech. Rep. 78. Institute of Physics and Engineering in Medicine (IPeM); 1997.
22. Ay MR, Sarkar S, Shahriari M, Sardari D, Zaidi H. Comparative assessment of different computational models for generation of X-ray spectra in diagnostic radiology and mammography. *Nuc Sci Symp Conf Rec, IEEE* 2004; 7:4190–4.
23. Künzel R. X-ray spectroscopy in mammography applied to radiological protection. Ph.D. thesis. São Paulo, Brazil: Universidade de São Paulo (USP), 2006. In Portuguese. Available from: <http://www.teses.usp.br/teses/disponiveis/43/43134/tde-11042007-120136/pt-br.php>.
24. Ay MR, Shahriari M, Sarkar S, Adib M, Zaidi H. Monte Carlo simulation of X-ray spectra in diagnostic radiology and mammography using MCNP4C. *Phys Med Biol* 2004; 49:4897–917.