SPECTRA AND DEPTH-DOSE DEPOSITION IN A PMMA BREAST PHANTOM OBTAINED BY EXPERIMENTAL AND MONTE CARLO METHODS

M.G. DAVID[a], E.J. PIRES[a], M.A. ALBUQUERQUE[b], M.A. BERNAL[c], L.A. MAGALHÃES[a], J.G. PEIXOTO[d], C.E. DE ALMEIDA[a], C.F.E. ALVES[a].

[a] Laboratório de Ciências Radiológicas/UERJ, Rio de Janeiro, Brazil.
[b] Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Eng. (COPPE), UFRJ, Rio de Janeiro, Brazil.
[c] Instituto de Física Gleb Wataghin, UNICAMP, Campinas, Brazil.
[d] Instituto de Radioproteção e Dosimetria/CNEN, Rio de Janeiro, Brazil.

E-mail address of main author: marianogd08@gmail.com

Abstract

This paper focuses on the determination of the photon spectra at various depths and depth-dose deposition curves for mammography-quality X rays beams on a PMMA breast phantom. Experimental and Monte Carlo-simulated (MC) methods were used. Spectra were obtained for 28 and 30 kV quality beams, from which the corresponding mean energy values (E_m) were calculated. A spectrometer Si-PIN photodiode was used for the experiments and the PENELOPE MC code, for simulations. The simulated and the experimental spectra show a very good agreement, which is corroborated by the low differences found between the E_m values. An increase in the E_m values and a strong attenuation of the beam through the depth of the PMMA phantom was also observed.

1. INTRODUCTION

On the one hand, mammography is the most effective method for breast cancer early diagnosis. On the other hand, it employs X ray beams of low energy whose potential for biological damage has been the subject of several studies [1, 2]. In this work, the energy spectra at various depths and the depth-dose deposition curves for X ray mammography beams impacting on a PMMA breast phantom were obtained. These spectra may be useful to study the impact of the radiation quality changes with depth on the radiation-induced biological effects. The knowledge of these spectra is also useful for investigations on the improvement of image quality in mammography [3].

Spectra were obtained experimentally by using a spectrometer. In addition, they have been determined by Monte Carlo simulations. The results obtained in this study were employed in a previous work in which the relative biological effectiveness (RBE) for mammography quality beams was determined [4]. The present study is the unfolding of a recently published work [5] focusing on the spectra of standard mammography beams used in metrology at the Radiological Sciences Laboratory (LCR) of the Rio de Janeiro State University (UERJ). All experiments were performed with the same experimental setup as that used for dosimeter calibration in an earlier study [6].

2. MATERIALS AND METHODS

2.1. Experimental spectra

The studied radiation beams were produced by a Philips X ray tube (PW 2185/00 model) with a Mo target and a Be window, powered by a high-voltage generator with a ripple factor lower than 1% [6]. Spectra have been measured using a Si-PIN photodiode detector (XR-100CR, with a sensitive volume of 6mm × 0.5mm^2) and a signal amplifier multichannel analyzer, both manufactured by Amptek (USA). A pinhole collimator of 1 mm diameter was placed at the entrance of the detector [5].

Beams were emitted at 28kV and at 30kV, and filtered through 0.03 mm of Mo in order to reproduce mammographic radiation qualities. The complete breast phantom is composed of nine polymethyl methacrylate (PMMA) plates with 150×70×5mm^3 size, totalizing a depth of 45 mm. The phantom was placed at 60 cm from the X ray focal point. Photon spectra were determined at four different depths in PMMA (5, 15, 30 and 45 mm) and without phantom. A circular radiation field with a 10cm diameter at the phantom surface was used for all determinations. For each spectrum, 10^6 photons were detected, keeping the dead time lower than 1%. Spectra were calibrated using the fluorescence lines of Mo and corrected by the efficiency of the detector for each energy range. In order to plot an experimental percentage depth-dose (PDD) curve, the air-kerma rate was measured with an ionization chamber (I.C.) (10X5-6M model, Radcal, USA) behind the PMMA phantom with every possible depth, from 5 to 45 mm. In all measurements, the detector and the I.C. were placed into a PMMA block to reproduce the back-scattering within the breast.

2.2. Spectra simulations

MC simulations were carried out with the PENELOPE code (2008 version). The experimental spectra acquired just after the X ray tube exit window (1.5cm from the focal point) in a previous work [5] have been used as the photon source during these simulations. These primary photons pass through a geometrical model that reproduces the experimental setup. Detectors with a 1.5cm radius and 0.1cm thickness were placed in the center of the primary beam at different depths of the PMMA phantom, to reproduce the same conditions used to obtain the experimental spectra.

For each different PMMA depths, 1.2×10^9 primary photons were simulated employing the following values for the PENELOPE code parameters: C_1=C_2=0.1 and W_{CC}=W_{CR}= 0.25keV. Simulations were performed on the LCR cluster (PCs with 12 cores processors each), using 10 machines parallelized by the *clonEasy* script [7] (totalizing 120 jobs) and consumed about 2 h for each spectrum. PDD curves were obtained in the PMMA phantom with 0.1cm depth bins. As in the experimental determinations, the PDD curves were normalized at 0.5cm depth.

2.3. Mean energy

It is possible to verify if the spectra obtained by the experimental and simulation methods are consistent by comparing the mean energy calculated from them. The mean energy for each energy spectrum was analytically calculated by the following equation:

$$E_m = \sum_{i=1}^{n} f_i \cdot E_i \qquad (1)$$

where:
f_i are the normalized photon frequencies, and
E_i are the energies at the center of the corresponding bin.

The expanded uncertainties presented in this work are for a coverage factor of k=2, based on a confidence level of approximately 95% [8], and their determination was detailed in a previous~~ly~~ work [5]. For the simulated spectra, uncertainties for the frequency determination were obtained from the normalized statistical uncertainty values (type A) provided by the PENELOPE code, combined with a 0.5% estimated uncertainty (k=2) for type B components [8].

3. RESULTS

The experimental 28kV spectra obtained at different depths are shown in Figure 1. The number of photons for each energy bin was normalized to the total number of photons of the respective spectrum. This way, the spectra exhibit a relative increment of the frequencies corresponding to high photon energies when the depth into the phantom increases. In other words, the spectrum hardens with depth. However, simulated spectra were obtained from a fixed number of primary photons (1.2×10^9). This way they can be presented not with the normalized frequencies but with the absolute number of photons that arrive at each depth. This presentation mode allows the visualization of the attenuation on the spectra caused by PMMA. Thus, the simulated 30kV spectra at all depths are shown in Figure 2. Not all the spectra determined in this work have been shown but all of them have a similar structure to those presented here.

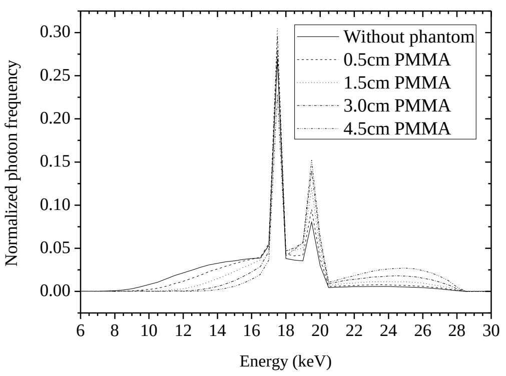

FIG. 1. Experimental 28kV spectra with the frequencies normalized to the total of photons, obtained at different PMMA depths.

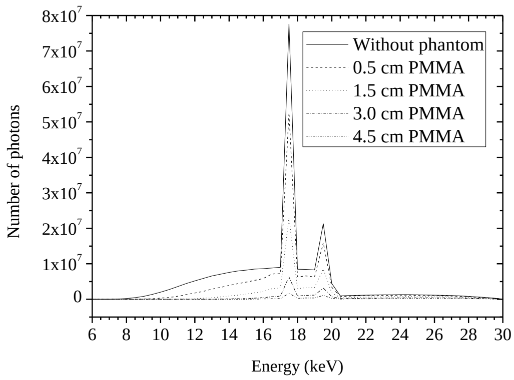

FIG. 2. Simulated 30kV spectra with the number of photons detected, obtained at different PMMA depths.

It is necessary to normalize all spectra for comparison purposes. This is what is shown in Figure 3, where the experimental and simulated 28kV spectra determined at 1.5cm depth in PMMA are depicted. A very good agreement between them is observed. Table 1 shows the E_m values obtained from equation (1) together with their estimated uncertainties. The relative difference of E_m values calculated from the corresponding experimental and simulated spectra are also shown. The beam hardening shown in this table may have some implications in the image quality degradation, especially for thick breasts.

TABLE I. E_m VALUES (keV) CALCULATED FROM THE 28 kV AND THE 30 kV SPECTRA, WITH THE RELATIVE DIFFERENCES (%) BETWEEN THE VALUES OBTAINED BY THE EXPERIMENTAL AND SIMULATION METHODS.

PMMA depth	28kV, Mo target, 0.03mm Mo			30kV, Mo target, 0.03mm Mo		
	Experimental	Simulated	Differ.	Experimental	Simulated	Differ.
Without phantom	16.89 ±0.15	16.63 ±0.13	1.5	17.28 ±0.15	17.01 ±0.10	1.6
0.5 cm	17.63 ±0.14	17.40 ±0.13	1.3	18.00 ±0.15	17.78 ±0.10	1.2
1.5 cm	18.46 ±0.14	18.28 ±0.13	1.0	18.94 ±0.15	18.72 ±0.11	1.2
3.0 cm	19.28 ±0.14	19.19 ±0.14	0.5	19.93 ±0.15	19.85 ±0.12	0.4
4.5cm	20.11 ±0.14	20.07 ±0.16	0.2	21.00 ±0.15	20.99 ±0.14	0.0

The PDD curves for 28 kV plotted from the values obtained by simulation and measuring the air-kerma rate with an ionization chamber (I.C.), both relative to the dose at 0.5cm depth in PMMA, are shown in Figure 4. The agreement between them is very good.

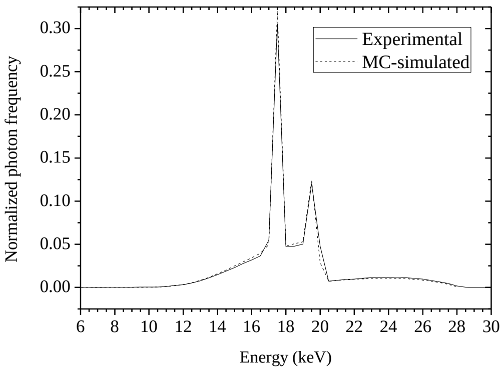

FIG. 3. *Comparison between experimental and simulated spectra for 28kV at 1.5cm PMMA depth (frequency normalized to the total no. of photons).*

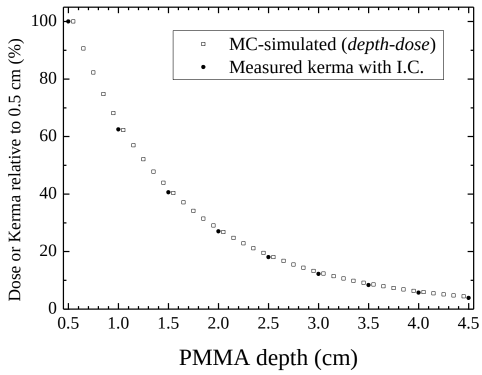

FIG. 4. *PDD curves for 28kV radiation quality relative to the dose at 0.5cm obtained by simulation and measurements with a I.C.*

5. DISCUSSION AND CONCLUSIONS

The small differences observed between the photon spectra obtained by both methods indicate that the instruments, the parameters, and methodologies employed are suitable. Likewise, the low differences in the E_m values obtained (maximum of 1.6%) confirm the similarity of the spectra and the results achieved previously [5], especially if we take into account the difficulties involved in acquiring experimental spectra and in simulations, as reported in several works [9, 10, 11]. The observed strong attenuation of the beam through the PMMA phantom depth suggests that the dose delivered by mammography is mostly deposited in layers near the breast surface. At 1.0cm depth, the dose falls down to about 60% of that absorbed at 0.5cm, while less than 5% is deposited at 4.5cm depth. The small increase of the mean energy of the beams in depth is compensated by the large decrease in the number of photons present.

The data obtained in this work can be used in studies on the mechanism of energy deposition by mammography radiation and on the damage induced by low energy photons in breast tissues [4]. The intense research in the field of micro and nanodosimetry being carried out worldwide [1, 2, 4] can contribute to the knowledge of the epidemiological impact of this important diagnostic tool.

REFERENCES

[1] FRANKENBERG, D., KELNHOFER, K., BÄR, K., FRANKENBERG-SCHWAGER, M., Enhanced neoplastic transformation by mammography x-rays relative to 200 kVp x-rays: indication for a strong dependence on photon energy of the RBEM for various end points, Radiat, Res, **157** (2002) 99-105.

[2] GÖGGELMANN, W., JACOBSEN, C., PANZER, W., et al., Re-evaluation 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, Radiat. Environ. Biophys. **42** (2003) 175-182.

[3] MEYER, P., BUFFARD, E., MERTZ, L., et al., Evaluation of the use of six diagnostic X-ray spectra computer codes, Br. J. Radiol. **77** (2004) 224-230.

[4] BERNAL, M.A., DE ALMEIDA, C.E,, DAVID, M.G., PIRES, E.J., Estimation of the RBE of mammography-quality beams using a combination of a Monte Carlo code with a B-DNA geometrical model, Phys. Med. Biol. **56** (2011) 7392-7403.

[5] DAVID, M.G., PIRES, E.J., BERNAL, M.A., et al., Experimental and Monte Carlo-simulated spectra of standard mammography-quality beams, Br. J. Radiol. **85** (2011) 629-635.

[6] PIRES, E.J., DAVID, M.G., PEIXOTO, J.G., DE ALMEIDA, C.E., Establishment of radiation qualities for mammography according to IEC 61267 and TRS 457, Radiat. Prot. Dosim. **145** (2011) 45-51.

[7] BADAL, A., SEMPAU, J., A package of Linux scrips for the parallelization of Monte Carlo simulations, Comput. Phys. Comm. **75** 6 (2006) 440-450.

[8] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Uncertainty measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), ISO/IEC Guide 98-3:2008, ISO, Geneva.

[9] KUNZEL, R., HERDADE, S.B., TERINI, R.A., COSTA, P.R., X-ray spectroscopy in mammography with a silicon pin photodiode with application to the measurement of tube voltage, Med. Phys. **31** 11 (2004) 2996-3003.

[10] AY, M.R., SHAHRIARI, M., SARKAR, S., et al., Monte Carlo simulation of X-ray spectra in diagnostic radiology and mammography using MCNP4C, Phys. Med. Biol. **49** (2004) 4897-4917.

[11] WILKINSON, A.L.E., JOHNSTON, P.N., HEGGIE, J.C.P., A comparison of mammography spectral measurements with spectra produced using several different mathematical models, Phys. Med. Biol. **46** (2001) 1575-1589.