Evaluation of a tissue equivalent ionization chamber in X-ray beams

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Resumo: Materiais equivalentes ao tecido têm uma grande variedade de usos, incluindo programas de controle de qualidade e segurança em diagnóstico e em terapia. Estes materiais são frequentemente utilizados em pesquisas para medir as doses nos pacientes submetidos a vários procedimentos clínicos. Este trabalho apresenta o desenvolvimento e a avaliação de uma câmara de ionização feita de material equivalente ao tecido, com um volume sensível de 2,3 cm^3, para dosimetria de feixes de raios-X. Esta câmara de ionização foi desenvolvida no Laboratório de Calibração de Instrumentos/IPEN. O material equivalente ao tecido foi desenvolvido no Instituto de Física da Universidade de São Paulo. Para avaliar o desempenho dosimétrico da nova câmara de ionização, vários testes descritos em normas internacionais foram realizados, e os resultados obtidos estão dentro dos limites recomendados.

Palavras-chave: Câmara de ionização, material equivalente ao tecido, feixes padrões de raios-X.

Abstract: Tissue equivalent materials present a variety of uses, including routine quality assurance and quality control programs in both diagnostic and therapeutic physics. They are frequently used in research facilities to measure doses delivered to patients undergoing various clinical procedures. This work presents the development and evaluation of a tissue equivalent ionization chamber, with a sensitive volume of 2.3 cm^3, for routine use in X-rays beams. This ionization chamber was developed at the Calibration Laboratory/IPEN. The new tissue equivalent material was developed at the Physics Institute of the University of São Paulo. In order to evaluate the dosimetric performance of the new ionization chamber, several tests described by international standards were undertaken, and all results were within the recommended limits.

Keywords: ionization chamber, tissue equivalent material, standard X-ray beams.

1. INTRODUCTION

Several medical exams employ the use of X-ray devices, such as general radiography, computed tomography, fluoroscopy, mammography and interventional radiological procedures. In these examinations X-ray beams with tube voltages ranging from about 20 kV to 150 kV are utilized. The number of these procedures lead to the greatest source of exposure for the population.

According to the UNSCEAR (2008) there are approximately 3.6 billion diagnostic radiological examinations undertaken every year worldwide. Consequently, the implementation of quality control programs is necessary in order to verify periodically the image quality and the doses delivered to patients submitted to diagnostic radiology procedures.

The doses and image related information associated to diagnostic radiological procedures need to be accurately determined in order to guarantee a good balance between image quality and patient exposure. In this scenario, suitable dosimetric methods have to be applied to ensure appropriate levels of accuracy and long-term stability (IAEA (2007)).

There are several types of radiation detectors employed in diagnostic X-ray dosimetry: ionization chambers, scintillation detectors, semiconductor devices, luminescent dosimeters and solid-state detectors (De Werd and Wagner (1999)). Among these dosimeters, the ionization chamber is the most commonly used. This may be justified in part by its robustness, high precision, easy handling and stable response within a wide range of energies.

Ionization chambers are normally constructed using materials that present properties similar to air or water, in relation to the interaction of the radiation with matter. Graphite is usually employed to represent air and PMMA water; although some ionization chambers make use of some sort of tissue equivalent material. In this case, the interaction of the radiation with matter is similar to human tissue.

Ionization chambers were assembled and characterized at the Instituto de Pesquisas Energéticas e Nucleares (IPEN/CNEN-SP) to be utilized in diagnostic radiology and radiotherapy dosimetry (Maia and Caldas (2005); Perini *et al* (2013); Neves *et al* (2013)). These ionization chambers are robust, present low manufacture cost, and their performance comply to the international recommendations.

The objective of this work was to develop and use a novel tissue equivalent material to design a new ionization chamber, for the dosimetry of diagnostic X-ray qualities.

2. MATERIALS AND METHODS

The new tissue equivalent material was developed at the Physics Institute of the University of São Paulo. The method adopted for the determination of the tissue equivalent chemical composition used the procedure originally developed by Hermann et al. (Hermann *et al* (1985); Hermann *et al* (1986)). This method provides the proportions which must be combined using a base material and two addictive in order to produce a material with the mass attenuation coefficient equal to the tissue being simulated in two specific energies.

Therefore, if $\mu_1(E)$ is the linear attenuation coefficient of the base material at energy E, $\mu_2(E)$ and $\mu_3(E)$ are the linear attenuation coefficient of the addictive compounds 1 and 2, respectively, at the same energy, and $\mu_T(E)$ is the linear attenuation coefficient of the tissue to be simulated, the following linear system of equations can be defined:

$$\begin{cases} q_1\mu_1(E_1) + q_2\mu_2(E_1) + q_3\mu_3(E_1) = \mu_T(E_1) \\ q_1\mu_1(E_2) + q_2\mu_2(E_2) + q_3\mu_3(E_2) = \mu_T(E_2) \\ q_1 + q_2 + q_3 = 1 \end{cases} \quad (1)$$

In these equations, the energies E_1 and E_2 are arbitrarily chosen in the range of interest and the values of q_i represent the volume fractions of each component of the material. Therefore, the mass fractions needed to be combined in the mixture can be obtained by using the individual densities of their components, ρ_i, using the equation:

$$p_i = \frac{\rho_i q_i}{\sum_i \rho_i q_i} \quad (2)$$

The linear attenuation coefficient of the tissue equivalent material can be estimated by using the results of the implementation of the linear system of Equation (1):

$$\mu(E) = q_1\,\mu_1(E) + \; q_2\,\mu_2(E) + \; q_3\,\mu_3(E) \quad (3)$$

A group of polymeric materials and addictives were studied and tested by Kimura *et al* (2011) at the Physics Institute of the University of São Paulo. The mass attenuation coefficient of each material was obtained by using the software XCOM (NIST (2010)). The possible combinations of the materials were evaluated taking into account their chemical properties. The mass attenuation coefficient of the ICRU soft tissue was also obtained by the same method.

A computer routine was developed in order to run the linear equation systems of each chemical combination, considering the energy range of 5–150 keV. These calculations generated values of mass and volume fractions of each component of these materials. The material used for manufacturing the ionization chamber studied in the present work is a combination of polyethylene (C_2H_4), calcium carbonate ($CaCO_3$), and Tyrin (C_2H_3Cl), with mass densities of 0.93 g.cm^{-3}, 2.83 g.cm^{-3} and 0.46 g.cm^{-3}, respectively. The appropriated combination of these materials resulted in a tissue equivalent material with adequate response to the absorption of radiation in the range of 5–150 keV.

The mass fractions of each material were weighted in a calibrated scale (Marte model AY220), and the materials were carefully selected and mixed. The polymerization process was done in an extrusor machine with internal temperatures in the range of 120–130°C. The samples were produced in discs of 130 mm in diameter and 10 mm in thickness, approximately.

As a control test of the sample, it was submitted to an X-ray fluorescence analysis. This test was performed at the Center of Chemistry and Environment at the IPEN/CNEN-SP, and it provided the fractional composition per atomic number of the material. These data were again introduced at the XCOM software, and the final mass attenuation coefficients were generated as a function of energy. These coefficients were compared to those initially expected. Differences between these data have been originated by impurities of the used materials or by the imprecision on the manufacture process. All obtained materials presented less than 5% of differences on the mass attenuation coefficients from those theoretically calculated in the energy range of interest at the present work.

The tissue-equivalent material was used for assembling the wall and the collecting electrode of the ionization chamber described as follows. The tissue equivalent walled ionization chamber, assembled at the IPEN is shown in figure 1 and the scheme, in figure 2. The ionization chamber has a sensitive volume of 2.3 cm^3. The stem is made of Teflon, which is also used as insulator between the collecting electrode and the guard ring. The entrance window has 0.5 mm thickness and a thin layer of graphite, in order to generate the necessary electric field to collect the electric charges in the sensitive volume. The dimensions of this dosimeter are described in table 1.

Figure 1: New ionization chamber developed at IPEN.

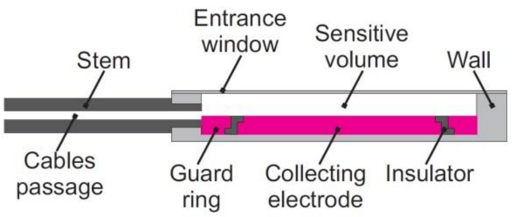

Figure 2: Scheme of the plane-parallel ionization chamber developed at IPEN and characterized in this work.

In order to perform the measurements, the dosimeter was connected to an electrometer model UNIDOS E, Physikalisch-Technische Werkstätten (PTW), Germany, that allows the polarization voltage to vary from -400 V to +400 V in 50 V steps. The measurements were undertaken at an X-ray industrial system (ISOVOLT 160HS/Pantak-Seifert) with already established direct (RQR) and attenuated (RQA) standard radiation qualities. The radiation qualities, recommended by the IEC 61267 standard (IEC (2005)), utilized in this work are listed in table 2.

The reference system, used to calibrate the dosimeters, was a secondary standard ionization chamber, RADCAL RC6, calibrated at the German primary standard laboratory Physikalisch-Technische Bundesanstalt (PTB).

Table 1. Ionization chamber technical specifications.

Characteristics	Dimensions (mm)
External height	8.5
External diameter	56.0
Internal height	3.0
Internal diameter	46.0
Entrance window thickness	0.5
Bottom wall thickness	4.0
Side wall thickness	5.0
Electrode diameter	32.0
Electrode thickness	1.0

The short- and medium-term stability tests were carried out using a $^{90}Sr+^{90}Y$ radioactive check source, PTW, model 8921, with nominal activity of 33 MBq (1994), positioned in a special PMMA support, which allows the reproducibility of the measurements (figure 3).

The uncertainties associated to all results in this work are expanded uncertainties, obtained by the combination in quadrature of type A and B uncertainties, using a coverage factor of 2.

Figure 3: Special PMMA support and radioactive check source positioned on the ionization chamber during its stability tests.

Table 2. Characteristics of the direct (RQR) and attenuated (RQA) standard radiation qualities (IEC (2005)) established at the IPEN.

Radiation Quality	Voltage (kV)	Half-value Layer (mmAl)	Air kerma Rate (mGy/min)
Direct beams			
RQR3	50	1.78	21.99±0.22
RQR5	70	2.58	38.70±0.39
RQR8	100	3.97	69.42±0.69
RQR10	150	6.57	117.43±1.17
Attenuated beams			
RQA3	50	3.8	3.83±0.04
RQA5	70	6.8	3.60±0.04
RQA8	100	10.1	5.67±0.06
RQA10	150	13.3	13.3±0.12

3. RESULTS AND DISCUSSION

The dosimeter, in this work, was characterized according to the IEC standard (IEC (1997)) tests: saturation curve, ion collection efficiency, polarity effect, stability, leakage current, energy dependence and linearity of response.

3.1. Short- and medium-term stability

The short-term stability test was performed by taking measurements with the ionization chamber exposed to the check source under reproducible conditions. According to international recommendations (IEC (1997)), the maximum acceptable variation is 1%. The highest variation obtained was 0.5%, and therefore within the recommended limit.

In the medium-term stability test, the variation of the chamber response was normalized by its medium values. This test comprehended a time period of 4 months (figure 4). All values in figure 4 were lower than the recommended limit of 2% provided by the IEC 61674 standard (IEC (1997)).

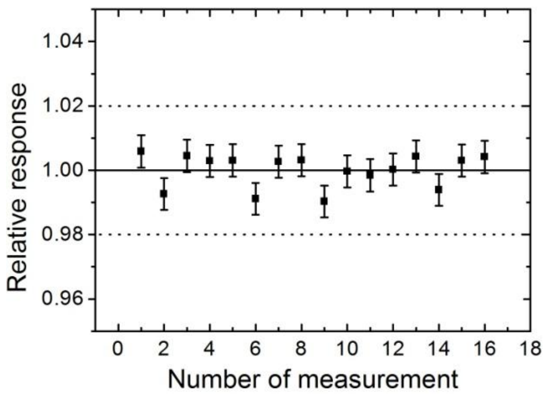

Figure 4: Medium-term stability of the new ionization chamber. The dashed lines represent the recommended limits of 2% (IEC (1997)).

3.2. Saturation curve, ion collection efficiency and polarity effect

The saturation curve of the ionization chamber was obtained for the RQR 5 radiation quality (table 2), which is the standard quality at the IPEN for diagnostic radiology. This test was made varying the voltage applied to the ionization chamber from -400 to +400 V (50 V steps), and an ionization current associated to each voltage was obtained. The results are shown in figure 5.

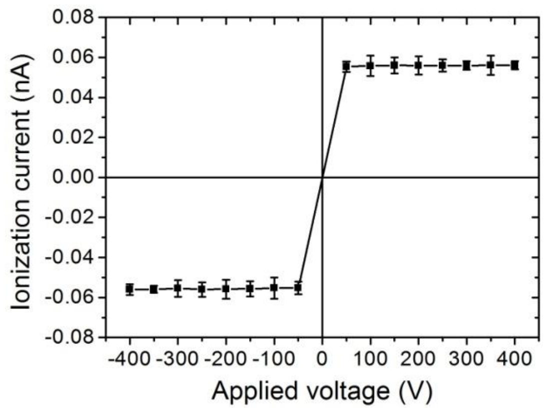

Figure 5: Saturation curve obtained with the RQR 5 radiation quality for the ionization chamber.

From this test it is possible to observe that the ionization chamber achieved saturation over the entire tested interval. The value of -300 V was chosen as the applied voltage for all further tests with the dosimeter developed in the present work.

The ion collection efficiency was obtained taking into consideration the collected charges and the two polarity voltage method, given by the following equation (IAEA (2001)):

$$K_S = \frac{(V_1/V_2)^2 - 1}{(V_1/V_2)^2 - M_1/M_2} \quad (4)$$

where M_x is the collected charge at a V_x voltage, and $V_1/V_2 = 2$. For V_1= 300 V (or -300 V) and V_2 = 150 V (or -150 V), the ion collection efficiency was better than 99.9% for both polarities. This result presents agreement with the value of 5% of ionic recombination losses, recommended by IEC 61674 (IEC (1997)).

For the determination of the polarity effect, the bias voltages of ±300 V were used. The polarity effect was obtained following the recommendations of the IAEA TRS 398 protocol (IAEA (2001)).

$$K_{pol} = \frac{M_{+300} + |M_{-300}|}{2M_{+300}} \quad (5)$$

where $M_{\pm300}$ is the electric charge collected by the ionization chamber using the applied voltages of ±300 V.

The value of K_{pol} was 0.4%; therefore, the K_{pol} value is within the recommended limit of 1% (IEC (2011)).

3.3. Leakage Current

Following the IEC recommendations (IEC (1997)), the leakage current was measured in time intervals of 20 min, before and after all measurements undertaken in this work. The highest value obtained was 0.6% of the ionization current produced at the used minimum air kerma rate. Therefore, it is in accordance to the recommended limit of 5% (IEC (1997)).

3.4. Linearity of response

This test was carried out varying the tube current from 2 mA to 25 mA with the RQR 5 standard radiation quality. The irradiation time of the ionization chamber was 15 s. The responses (ionization currents) were normalized for the response at a tube current of 2 mA. A linear fit was obtained with correlation coefficient R^2 of 0.9999. Thus, the ionization chamber presented a linear behavior, which is adequate for its use in X-ray dosimetry.

3.5. Energy dependence

The energy dependence test was conducted for all radiation qualities presented in table 2. In this case, the ionization chamber was calibrated against the RADCAL RC6 reference dosimeter. The correction factors were obtained dividing the calibration coefficients of each radiation quality to the reference radiation qualities for RQR 5 and RQA 5 beams. The results obtained are presented in table 3.

Table 3. Calibration coefficients and correction factors for the new ionization chamber developed at the IPEN.

Radiation qualities	Calibration coefficient (10^6Gy/C)	Correction factor
Direct beams		
RQR3	9.978±0.060	1.020±0.010
RQR5	9.785±0.078	1.000±0.011
RQR8	9.734±0.071	0.995±0.011
RQR10	9.733±0.074	0.995±0.011
Attenuated beams		
RQA3	9.325±0.051	1.043±0.009
RQA5	8.942±0.060	1.000±0.009
RQA8	8.880±0.050	0.993±0.009
RQA10	8.924±0.064	0.998±0.010

According to these results, the energy dependence for ionization chamber was 2.5% for RQR beams and 4.8% for RQA beams. These values are within the recommended limit of 5.0% (IEC (1997)).

4. CONCLUSION

The aim of the present work was to develop a tissue equivalent ionization chamber to be utilized for X-ray beam dosimetry. This dosimeter presents the advantage of simulating the interaction of radiation with matter similar to human tissue. For this purpose a new tissue equivalent material was developed and characterized, showing an appropriate response to the absorption of radiation in the energy range of 5–150 keV.

The mass attenuation coefficients were determined utilizing the XCOM software, and they were calculated theoretically and after the X-ray fluorescence analyses of the samples. The maximum difference among these results was lower than 5% in the range of energies of interest to the present work. As the tissue equivalent material presented good indication to be utilized in the X-ray energy range, the ionization chamber was assembled.

In the characterization tests, this ionization chamber presented results within the international recommendations. Therefore, this dosimeter presented satisfactory results to be applied to X-ray dosimetry at calibration laboratories and clinics.

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