Radiation Physics and Chemistry 160 (2019) 89–95

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

X-ray spectrometry applied for determination of linear attenuation coefficient of tissue-equivalent materials

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ARTICLE INFO

Keywords:
Phantoms
Tissue-equivalent
Attenuation coefficient

ABSTRACT

Resin-based materials equivalent to water were developed and four different samples were obtained. The linear attenuation coefficients of all samples was evaluated using X-ray spectrometry with primary and transmitted beams using voltages at the ranging from 60 to 120 kV. The experimental measured values were compared with theoretical reference values to water and with that obtained using the Least Square Method algorithm methodology (method applied to diagnostic radiology and radiotherapy). Our results show that differences between the measured values and the target μ(E) was lower than 7% ± 0.3 in the energy range from 20 to 80 keV. These results enable to consider that the material developed and produced is a good option to be used as a water-equivalent material and the experimental method adequate to its quantitative evaluation.

1. Introduction

X-ray imaging is a powerful tool in modern Medicine and this modality of image production allows the detection and investigation of several disease and other health problems. These modalities include general x-ray images, dental x-rays, mammography, fluoroscopy, interventionist radiology and computed tomography. However, the production of adequately qualified images, which allows high probability of correct interpretation of a the disease under investigation by a trained radiologist, is a complex task involving technical and human limitations that must be correctly balanced in order to get the best output of the applied modality. In this sense, it must be emphasized that the use of ionizing radiation for this purpose must be correctly justified and optimized, since there is always an associated risk in its use (World Health Organization and IAEA, 2013). The correlation between image quality and the potentially harmful biological effects of radiation can be studied from the relationship between physical parameters of the image, such as contrast, noise, spatial resolution, and absorbed dose (Navarro et al., 2007). This correlation has been investigated and registered in diagnostic radiology by the application of group or procedures known as Quality Control (QC), which is part of the Quality Assurance (QA) programs (Barrett et al., 2015; Pianykh, 2014; IEC, 2006).

QC procedures are essential in modern diagnostic imaging to provide reproducible information on image quality and dose (Azevedo et al., 2005) and they are required by law in several countries (Agency, 2011). In practice, the part of the procedures are empirical implementation of experimental measurements which are dependent on special instrumentation and metrological definitions (IAEA, 2007). An important group of this instrumentation has been historically called “phantoms”. These objects mimics tissues, parts of the human body and simulate specific characteristics of the interaction of the ionizing radiation with the matter which are of interest for the QC measurements (Dewerd and Lawless, 2014). Thus, production of these phantoms depends on the manufacture of special tissue-equivalent materials for simulating specific human tissues properties or materials of dosimetric interest.

Different materials have been applied to simulate specific physical properties of human tissues (Amini et al., 2018). These materials were developed to represent similar absorption and/or scattering properties of the real human tissue in order to allow the investigation of doses received by patients exposed to ionizing radiation. These tissue-equivalent materials can also be used to produce special devices for exploring specific quality or dosimetric information from equipment used in the main radiological modalities, such as general radiography (Ng and Yeong, 2014), dental radiography, mammography (Tomal, 2014), interventional radiology (Tomal and Costa, 2017) and computed tomography (Costa, 2014).

Material can be considered tissue-equivalent if its transmission and

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https://doi.org/10.1016/j.radphyschem.2019.03.021
Received 14 December 2018; Received in revised form 15 March 2019; Accepted 18 March 2019
Available online 18 March 2019
0969-806X/

Fig. 1. Tissue equivalent samples produced A, B C and D resin-based materials.

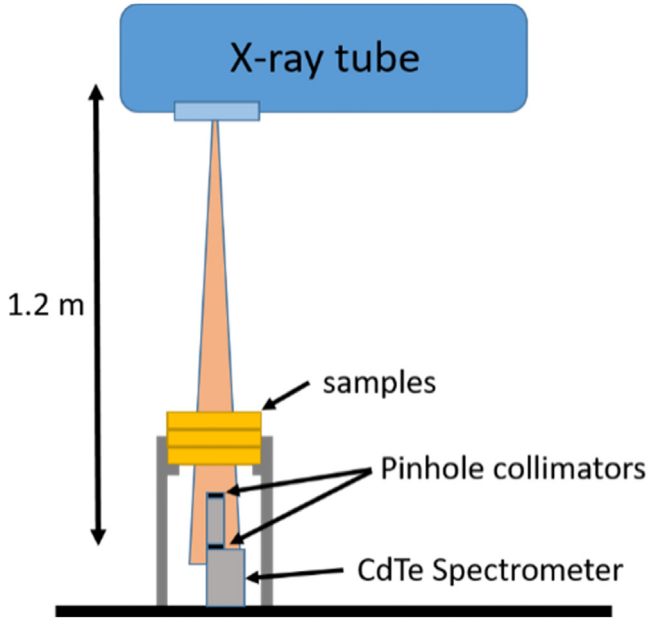

Fig. 2. Experimental Set-up for spectra transmitted and attenuation coefficient measurements using ionization chamber or spectrometer.

scattering properties are equivalents to the target-tissue into a given acceptance level. Therefore, depending on the goal to simulating soft tissues, bones, breast or any other human tissue, the design and production of the tissue-equivalent material must consider what is the combination of physical and chemical properties which allows an adequate representation of the real material as accurately as possible. For this purpose, the attenuation properties of the developed material as a function of the energy of the photons to be used in the practical purposes of the phantom are the gold standard for quantify how accurately the material will represent the target tissue.

Considering applications of these tissue-equivalent materials in diagnostic radiology, the total mass attenuation coefficient (μ/ρ) and mass energy-absorption coefficient (μ_{en}/ρ) as a function of photons in the energy range from 10 to 150 keV are usually considered. These quantities can be calculated using the photon energy, taking into account the mixture rule and for the relevant composition of interest to the production of an adequate tissue-equivalent material (Jones et al., 2003; Hubbell, 2006). The effective atomic number and its mass and electronic densities are also important properties to be considered (Prasad et al., 1997; Manohara et al., 2008; Taylor et al., 2012; Saito and Sagara, 2017; Dewerd and Kissick, 2014; Shrimpton, 1981).

According to Report 44 of the International Commission on Radiation Units and Measurements (ICRU, 1989), in some of the periodic QC tests required on x-ray imaging equipment it is necessary to use phantoms. The adequacy and qualification of these phantoms are done by the determination of the maximum difference between the linear attenuation coefficient of the tissue-equivalent materials and the target material. According to ICRU, this difference should be no more than 5%. A useful criteria to be adopted for a given material to be considered as a human tissue-equivalent is that it must exhibit a radiation transmission behavior as a function of its thickness, similar to that of the reference material (Nascimento et al., 2018). Quantitatively, the maximum difference between the linear attenuation coefficient of tissue-equivalent materials and the target tissue shall not exceed 5% in the range of energy of interest.

Based on the fact that about 75% of human body is considered water, this material was defined as a typical reference standard to develop sample tissue-equivalent materials. Liquid water is still used in radiotherapy applications for calibration purposes (Meigooni, 1994), but it has been replaced by more practical solid materials with water absorption equivalence (Meigooni, 1994; Tello et al., 1995; Hill et al., 2005, 2008). In the diagnostic range of energies, however, polymethylmethacrylate (PMMA) has been widely adopted as a water equivalent, instead it, is only roughly a water equivalent material in this range of energy. Other materials have been investigated by other authors in order to be characterized as tissue-equivalent materials in the diagnostic range of energy (Hill et al., 2010; Gorjiara et al., 2011; Jones et al., 2003; Argo et al., 2004).

One of the fundamental properties that tissue-equivalent materials must present to be considered potentially useful in diagnostic radiology range of energies is it´s radiation transmission properties, Hill et al. studied the linear attenuation coefficients for water equivalence of four solid phantoms (solid water RMI457, plastic water, RW3 solid water and Perspex) (Hill et al., 2008). Ferreira et al. determined experimentally the linear attenuation coefficient of several tissue-equivalent materials (wax, nylon, paraffin and PMMA) used in CT, including water, in a small and specific range of energy (12–54 keV) (Ferreira et al., 2010). Geraldelli et al. (2013) characterized seven tissue-equivalent materials, including water, through their attenuation and scattering properties.

Thirty years ago, D. R White published studies about tissue substitute materials (White, 1977, 1978b, 1978a; White et al., 1980). Ten years later, Hermann and colleagues (Hermann et al., 1985) described a methodology to obtaining materials which can be potentially adopted as tissue-equivalent materials using water as reference. The

Table 1
Tissue equivalent samples A, B, C and D, Chemical elements composition, density (Nascimento et al., 2018) and thickness.

Samples	Thickness (mm)	Density (g/cm^3)	Chemical elements composition
A	12.0 ± 0.65	1.1519 ± 0.001	C(0.3263); H(0.49); O(0.1726); Mg(0.01)
B	10.8 ± 0.66	1.1437 ± 0.001	C(0.3296); H(0.495); O(0.1709); Ti(0.0033)
C	10.0 ± 0.68	1.1407 ± 0.001	C(0.3321); H(0.495); O(0.1693); Ca(0.0025)
D	10.1 ± 0.63	1.1444 ± 0.001	C(0.3296); H(0.495); O(0.1643); Ca(0.0033); F(0.0066)

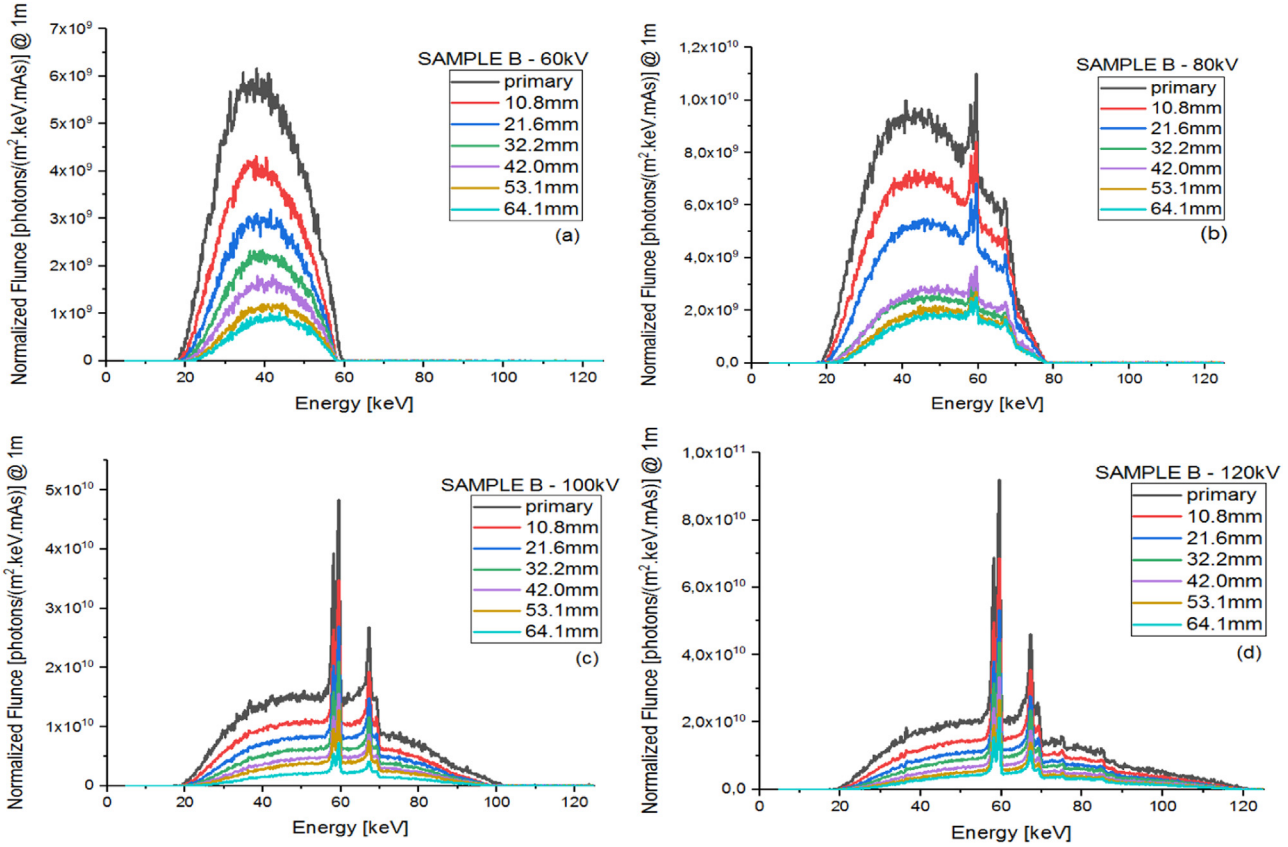

Fig. 3. Show primary x-ray spectrum and spectra transmitted by different thicknesses of sample B measured using 60 kV (a), 80 kV (b), 100 kV (c) and 120 kV (d).

methodologies developed by Hermann and White were used as theoretical bases to the development of a recent study that improved the accuracy of the determination of compositions of tissue-equivalent materials (Mariano, 2017). This approach was developed to design new formulations combining alternative materials and additives in specific proportions for simulating the attenuation properties of a given target-tissue. It consists of fitting the linear attenuation coefficient of the given proposed mixture of materials with the linear attenuation coefficient of the reference material (Mariano and Costa, 2017). The quality of the fitting adopts the Least Squares Method in a range of energy that depends on the purpose of the phantom. The developed methodology was used to obtain water equivalent materials in the range of energy used in general diagnostic radiology (10–150 keV) (Mariano, 2017). The same algorithm allows the development of others potentially useful tissue-equivalent mixtures employing a larger numbers of chemical compounds.

In the present work, four different formulations of resin-based water equivalent materials were developed using the algorithm described before (Mariano, 2017; Mariano and Costa, 2017). An experimental methodology was also developed in order to estimate the linear attenuation coefficient of each developed materials. This empirical approach use the transmitted x-ray spectra measured after transmission through different thicknesses of the developed samples in order to do these estimations. The linear attenuation coefficients obtained for each developed sample were compared with the linear attenuation coefficient of water, adopted as reference, and with the calculated coefficients. The comparative results allow the evaluation of the sample which better represents the reference material.

2. Materials and methods

2.1. Design and production of the water equivalent materials

The adequate selection of the chemical compounds to be part of a mixture which intend to be a tissue equivalent material is essential to allow the production of qualified final materials. Additionally, these compounds require compliance with the main characteristic in terms of expected effective atomic number and mass and electron density in order to mimic the target tissue efficiently. Other issues that can be concerned are related to the non-toxicity, non-volatility and if are they are potentially recyclable or not.

For the purpose of the present work, four different materials formulations were proposed as water substitute. All the formulations had the same base (resin) with different additives. These four samples were prepared in the laboratory, using a precision scale (model AY220, Marte). The mixtures were constantly mixed for a good homogenization in order to avoid air bubble formation. The chemical compounds used to produce the samples of the formulas developed were calcium carbonate ($CaCO_3$, Purity: 98%) and titanium dioxide (TiO_2, Purity: 99%) obtained from Basile Química Ltda (São Paulo, Brazil), calcium difluorite (CaF_2, Purity: 99%) from ABC-Lab Produtos e Equipamentos para Laboratórios (São Paulo, Brazil), and magnesium oxide (MgO, Purity: > 99%) from Labsynth (São Paulo, Brazil). These compounds were mixed and homogenized using with glycidyl (C_2H_3O, Purity:99%) from Química Ltda (São Paulo, Brazil). The trace amounts of impurities in the chemical compounds above are neglected in the formulations.

After preparing each different formula, the mixture was immediately transferred to an aluminium container measuring 350 mm x 235 mm x 20 mm to obtain solid sheets of each formulation. The moulds were allowed to stand for 24 h at a temperature of about 25 °C. Samples were named and identified as A, B C and D showed in the Fig. 1. Subsequently, each sheet was cut into six pieces measuring

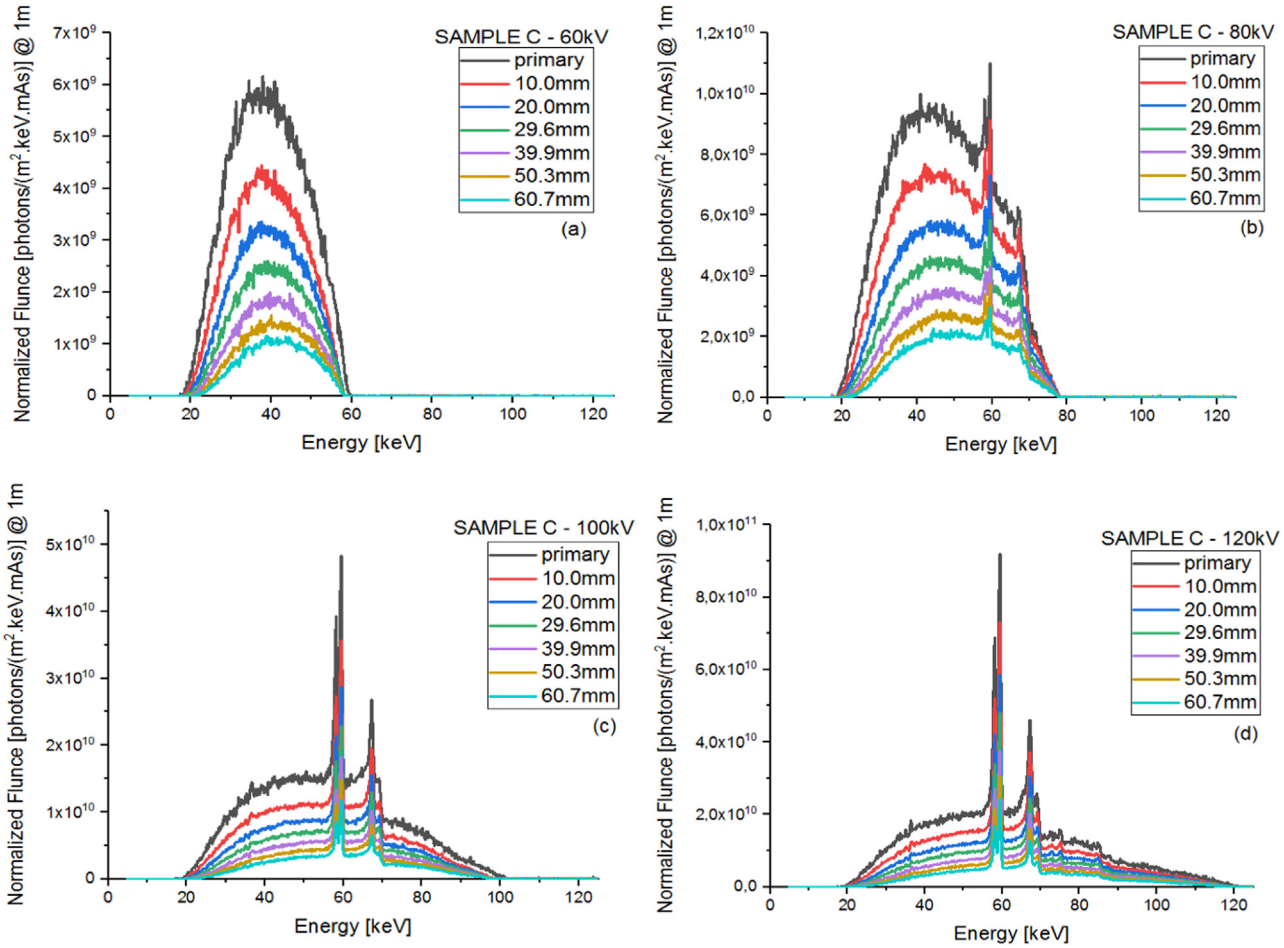

Fig. 4. Show primary x-ray spectrum and spectra transmitted by different thicknesses of sample B measured using 60 kV (a), 80 kV (b), 100 kV (c) and 120 kV (d).

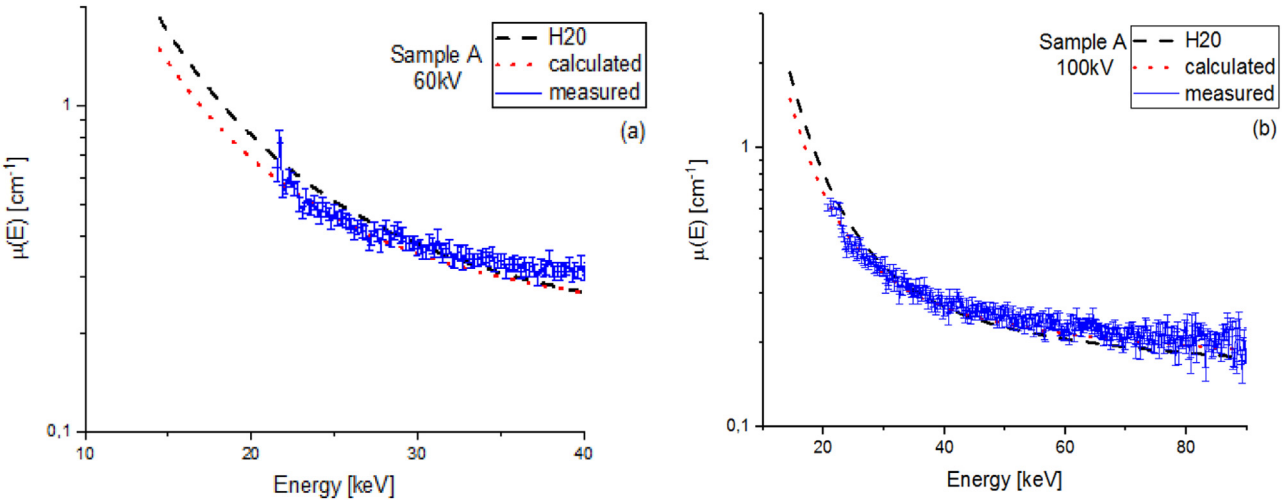

Fig. 5. Presents the result of the application of Eq. (1) to this set of spectra, to sample A measured using 60 kV (a) and 100 kV (b) with thickness ranging from 12 to 74.6 mm. The figure also plots the linear attenuation coefficient of the water and the calculated using the mathematical model (Mariano, 2017).

approximately 100 mm × 100 mm each with known thickness to be used for x-ray attenuation measurements. Table 1 shows the elemental materials composition, thickness and physical density of the samples. The thickness of each sample produced was measured at least three times using a precision calliper (model 150 mm/6" 0.05 mm/1/128" 530-104BR,Mitutoyo) in three positions on the sample centre.

2.2. Mean linear attenuation coefficient ($\bar{\mu}$) calculation

In order to evaluate the quality of the produced material in terms of its similarity to the water, the linear attenuation coefficients μ(E) of the samples were estimated according to the Lambert-Beer´s law. The transmission of polyenergetic x-rays through samples was measured, for each set of sample-thickness-voltage, using an approximate narrow

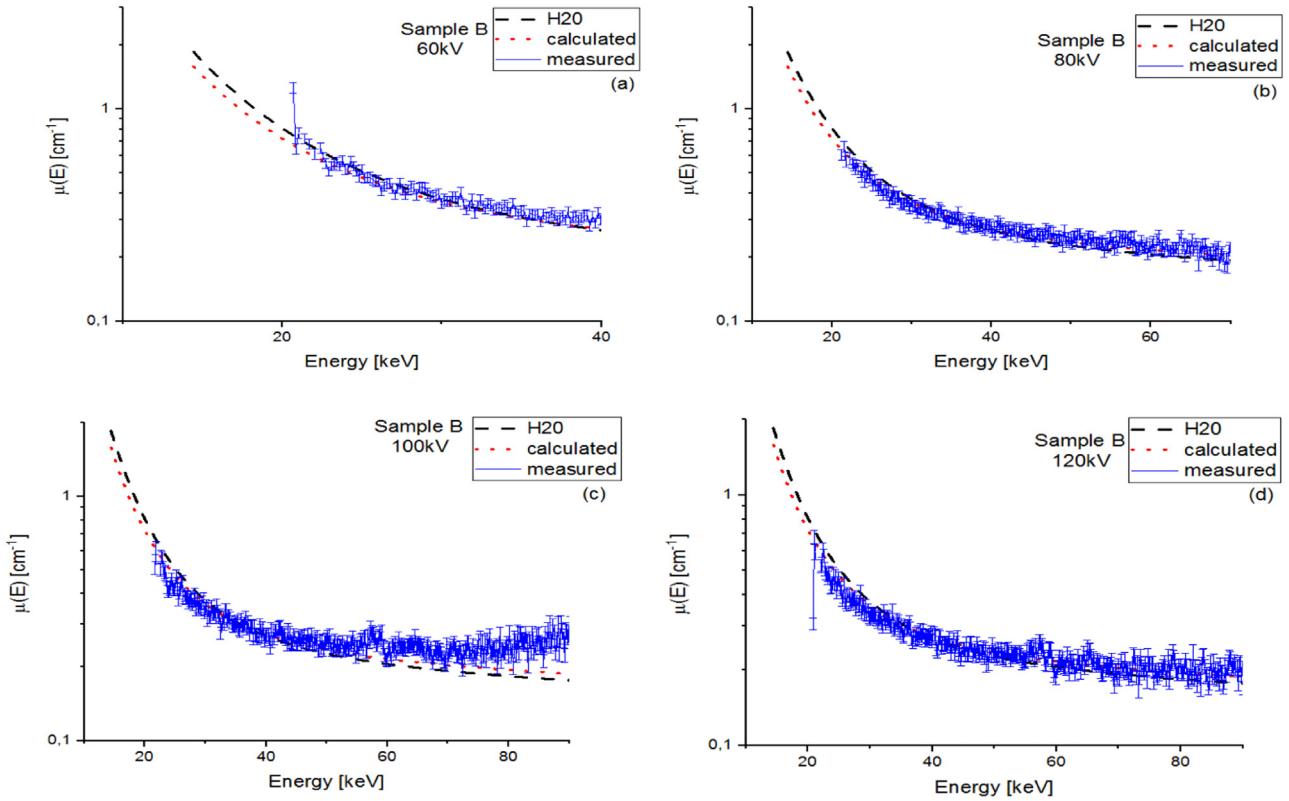

Fig. 6. Presents the result of the application of Eq. (1) to this set of spectra, to sample B measured using 60 kV (a) 80 kV (b), 100 kV (c) and 120 kV (d) with thickness ranging from 10.8 to 64.1 mm. The figure also plots the linear attenuation coefficient of the water and the calculated using the mathematical model (Mariano, 2017).

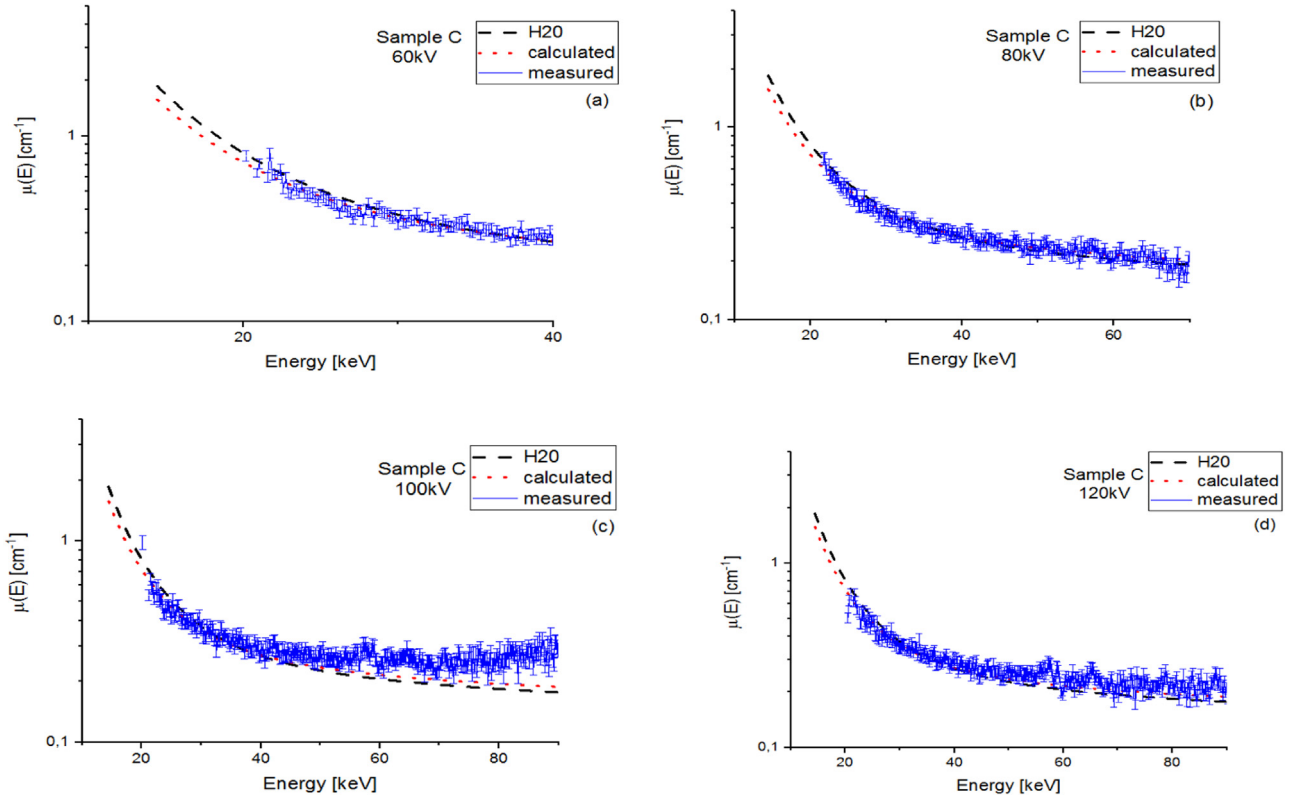

Fig. 7. Presents the result of the application of Eq. (1) to this set of spectra, to sample C measured using 60 kV (a) 80 kV (b), 100 kV (c) and 120 kV (d) with thickness ranging from 10 to 60.7 mm. The figure also plots the linear attenuation coefficient of the water and the calculated using the mathematical model (Mariano, 2017).

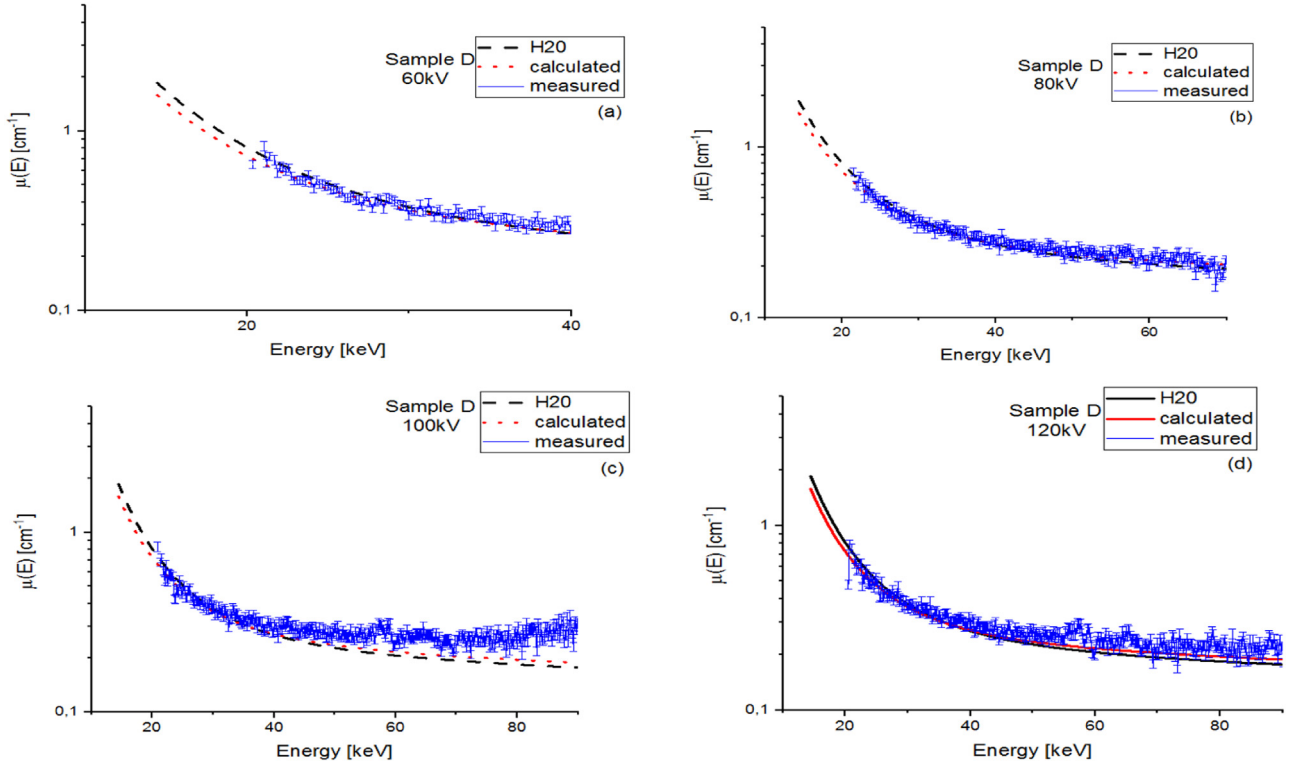

Fig. 8. Presents the result of the application of Eq.(1) to this set of spectra, to sample D measured using 60 kV (a) 80 kV (b), 100 kV (c) and 120 kV (d) with thickness ranging from 10.1 to 62.1 mm. The figure also plots the linear attenuation coefficient of the water and the calculated using the mathematical model (Mariano, 2017).

beam geometry as described at Section 2.3. The mean linear attenuation coefficient, $\bar{\mu}(E)$, was calculated using the Eq. (1) following the work of Tomal et al. (2010):

$$\bar{\mu}(E) = -\frac{1}{M}\sum_{i=1}^{M}\frac{1}{x_i} ln\left[\frac{N(E, x_i)}{N(E,0)}\right] \quad (1)$$

where $N(E, 0)$ is the primary x-ray spectra, $N(E,x_i)$ is the x-ray spectra transmitted by a thickness x_i of a given sample, and M is the number of thicknesses studied.

2.3. Experimental set-up

X-ray spectroscopy was used to estimate the input functions of Eq. (1). Measured values of $N(E, 0)$ and $N(E,x_i)$ were used to determine mean values of linear x-ray attenuation coefficients (μ) as a function of energy for each designed composition. These primary and transmitted spectra were determined in approximate narrow beam geometry. The transmission measurements were done through samples of known thickness at energies between 10 and 150 keV, experimental set-up illustrated in the Fig. 2.

In the measurement process a Cadmium Telluride (CdTe) spectrometer (model XR-100T, Amptek, Inc, EUA) was used. The detection system was collimated by a set of tungsten allot pinholes with diameters of 1 mm (distal collimator) and 0.02 mm (proximal collimator) in order to reduce the scattered photons impinging the spectrometer sensor. Additionally, the measured spectra were corrected using a stripping algorithm (Santos and Costa, 2014; Costa et al., 2015). The radiation beams were generated by a tungsten-target x-ray machine (model Y.SMART 300HP, YXLON, Germany) using voltages of 60, 80, 100 and 120 kV. The x-ray tube focal spot to spectrometer distance was fixed in 1.2 m.

The samples were placed one by one between source and detector, according to the schematic experimental set-up illustrated in Fig. 2, under a sample-holder specially developed for this purpose. For each sample, six measurements were made superposing all samples of a given formulation. Thus, these spectra were transmitted by different thicknesses of samples A, B, C and D. In order to estimate the uncertainties of the mean linear attenuation coefficient of each sample, five measurements were performed for each thickness of each set of sample in each of the applied voltages.

3. Results and discussions

As an example of the measured spectra, Fig. 3 shows the primary x-ray spectrum and the spectra transmitted by different thicknesses of sample B using 60, 80, 100 and 120 kV. Fig. 4 shows the same data for the sample C, measured in the same values of applied voltage.

Fig. 5 presents the result of the application of Eq. (1) using the corresponding set of spectra transmitted through the slabs of sample A with thicknesses ranging from 12 to 74.6 mm. The figure also plots the linear attenuation coefficient of the water and are calculated using the mathematical model (Mariano, 2017), which adopts the NIST database (Berger et al., 2010). Figs. 6 and 7 presents similar result of the application of Eq. (1) considering the sample B with thickness ranging from 10.8 to 64.1 mm and sample C with thickness ranging from 10 to 60.7 mm, respectively. Finally, Fig. 7 shows the linear attenuation coefficients of sample D obtained from transmitted spectra through thickness ranging from 10.1 to 62.1 mm. (Fig. 8)

4. Conclusion

Linear attenuation coefficient of developed water equivalent materials were estimated by using primary and transmitted x-ray spectra. The sample formulas were designed using a previously developed Least Squares Method and a group of four water-equivalent combinations were produced. The measured linear attenuation coefficients were compared to corresponding coefficients form the water. For energies in the range of 20–60 keV, the comparative results demonstrated that the developed samples are compatible with the proposed target material

(water). It can be observed by the experimental results that, for higher energies in the range of 60–120 keV, the experimental the experimental set-up requires to be improved in order to reduce the scattered photons impinging the spectrometer sensor. It can be performed by adapting a more selective collimation system between the x-ray source and the CdTe detector. This improvement will also reduce the combined uncertainties.

The mean differences between the measured and the target μ(E) was lower than (7.0 ± 0.3) % in the range of energies from 20 to 80 keV. Therefore, the experimental method shows to be an adequate option for supporting the decision on the qualification of the developed material in comparison to the target material.

Acknowledgments

This work was partially supported by the São Paulo Research Foundation—FAPESP (grants 2017/23034-9 and 2010/12237-7) and by the National Council of Technological and Scientific Development—CNPq (grant 309745/2015-2), in addition to the joint CNPq/FAPESPINCT project—"Metrology of ionizing radiation in medicine" (grant 573659/2008-7). The authors also thanks to Capes (financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil - Finance Code 001)

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