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X-ray spectrometry applied for determination of linear attenuation coefficient of polymer-based samples as radiologically tissue-equivalent materials

Boiset[a*], G. R.; Rosinelli[a], R. R.; Freire[a], G.; Moura[a], R. A. S.;
Moratta[a], R.; Yoshimura[a], E. M.; Costa[a], P. R.

[a] *Dep. of Nuclear Physics, University of São Paulo, Rua do Matão, 1371, 05508-090, São Paulo, Brazil*
**gisell@if.usp.br*

ABSTRACT

In this work we obtained experimental linear attenuation coefficients of polymer-based samples at diagnostic imaging energy range (15-150 keV) for eleven formulations candidates for tissue-equivalent materials (TEMs). TEMs is any material that simulates a human body part or human tissue in its interaction with radiation. In diagnostic radiology, the maximum difference between the linear attenuation coefficient of the TEMs and the target material should be no more than 5% in the energy range of interest. A polienergetic narrow beam was obtained using a tungsten target x-ray tube and CdTe detector. The densities of the samples were determined and compared with reference materials obtaining a maximum difference of 17%. The comparisons between the linear attenuation coefficient of the formulations and the respective reference materials for which they were initially designed, has demonstrated good correspondence over a wide energy range. Energy ranges in which the developed samples simulate other human tissues in addition to those initially considered were found, taken into account the criterion that the maximum difference between the linear attenuation coefficients does not exceed 5% is met. The results emphasize the possibility of production and characterization of TEMs to be used in the construction of imaging and dosimetry phantoms.

Keywords: **attenuation coefficient, X-ray spectrometry, tissue-equivalent material, polymer**

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1. INTRODUCTION

According to Report 44 of the International Commission on Radiation Units and Measurements (ICRU), tissue-equivalent materials (TEMs) is any material that simulates a human body part or human tissue in its interaction with radiation [1]. Any volume of TEM used to simulate these interactions is called phantom.

Phantoms are used in research laboratories and clinical field for quality assurance, dosimetry and radiation protection [2]. They are mostly imported and expensive. For a material to be considered a human tissue simulator, it must mimic the physical properties and present a behavior of radiation transmission as a function of thickness, very similar to that of the reference material [3]. The radiation attenuation as a function of the photon's energy and the medium in which they interact can be expressed in terms of the linear attenuation coefficient μ(E). For image quality assessments in diagnostic radiology, ICRU recommends that the maximum difference between μ(E) of the TEMs and the target material should be no more than 5% in the energy range of interest [1]. The linear attenuation coefficient of a sample can be obtained experimentally using radioactive sources, synchrotron radiation, or polyenergetic beams [4].

Water, due to its abundance in the human body, is often used as a reference material to simulate tissues [5]. Other materials have been used to mimic specific physical properties of human tissues[6]. Currently, the growing need for radiologically tissue-equivalent materials is justified by the diversity in modality and the high demand for imaging exams. The production and characterization of materials like those studied in this work are of interest for constructing phantoms for diagnostic radiology applications. With the development and production of phantoms from national materials, it will be possible to reduce the costs and time of acquisition of these devices.

The aim of the present work was to estimate the linear attenuation coefficient of polymer-based samples applying X-ray spectrometry techniques in the energy range used in diagnostic imaging (15-150 keV). The formulations were produced using national technology, with substances found commercially. The results obtained for each sample were compared with the attenuation coefficient of the reference material in order to evaluate the formulation that best represents it.

2. MATERIALS AND METHODS

2.1. Design and production of the samples

Eleven formulations for TEMs, identified from A to K, obtained using the Mariano&Costa method [7] were analyzed. They were produced to be radiologically equivalent to reference materials liquid water (formulations A-E), soft tissue (formulations F-I), and commercial materials CIRS 30/70 and CIRS 50/50 (CIRS, inc, Norfolk, VA, USA) (formulations J and K). All formulations had polypropylene (C_3H_6) as the main substance with one or two additives, such as calcium carbonate ($CaCO_3$), titanium dioxide (TiO_2), sodium chloride (NaCl), calcium difluoride (CaF_2) and magnesium oxide (MgO). Table 1 shows elemental compositions used to produce the samples studied together with the acronyms for their identification, thickness and additives used. The thickness of each sample was measured five times at different positions using a precision caliper. The samples were produced in with cylindrical shape. Figure 1 shows four of the samples identified from A to D. Their densities were determined by direct measurement of mass and volume.

Figure 1: *Tissue equivalent samples tagged as A, B, C and D produced with polypropylene as main substance*

Table 1: Elemental compositions of the substitute materials produced with polypropylene as main substance.

Samples	Thickness (mm)	Additive (in mass)	Elemental composition (fraction by weight)								
			H	C	O	F	Na	Mg	Cl	Ca	Ti
A	24.15 ± 0.08	NaCl (8%)	0.132	0.788	-	-	0.031	-	0.049	-	-
B	21.30 ± 0.07	$CaCO_3$ (4%) MgO (10%)	0.124	0.741	0.059	-	-	0.060	-	0.016	-
C	24.03 ± 0.05	CaF_2 (7%)	0.134	0.796	-	0.034	-	-	-	0.036	-
D	22.13 ± 0.06	MgO (19%)	0.116	0.694	0.075	-	-	0.115	-	-	-
E	23.65 ± 0.17	$CaCO_3$ (9%)	0.131	0.790	0.043	-	-	-	-	0.036	-
F	22.85 ± 0.06	NaCl (5%)	0.137	0.813	-	-	0.020	-	0.030	-	-
G	21.90 ± 0.24	CaF_2 (9%)	0.131	0.779	-	0.044	-	-	-	0.046	-
H	21.70 ± 0.07	MgO (23%)	0.111	0.659	0.091	-	-	0.139	-	-	-
I	24.06 ± 0.07	TiO_2 (7%)	0.134	0.796	0.028	-	-	-	-	-	0.042
J	22.85 ± 0.06	NaCl (3%)	0.139	0.831	-	-	0.012	-	0.018	-	-
K	21.93 ± 0.05	NaCl (4%)	0.138	0.822	-	-	0.016	-	0.024	-	-

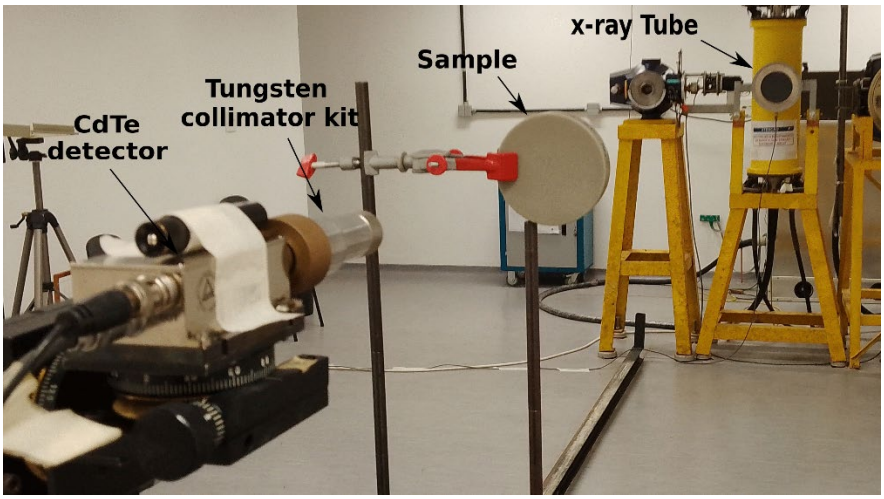
2.2. Experimental set-up

The linear attenuation coefficients μ(E) were experimentally determined according to the exponential attenuation law using a polyenergetic narrow beam [8]. All x-ray measurements were performed using Philips MCN 421 x-ray tube with tungsten target (W) and a beryllium window (Be) of 2.2 mm. The narrow beam was obtained using a cylindrical lead (Pb) collimator with a thickness of 28 mm and a diameter of 1.5 mm positioned 14 cm from the focal point of the X-ray tube, and a collimator kit from Amptek. Samples were positioned one by one between the X-ray tube and the detection system to measure the transmitted spectrum. A sampleless measurement was made to obtain the primary spectrum. The voltage applied to the tube determines the maximum energy of the spectrum. As the spectrum contains fewer counts at higher energies, to ensure a high count of photons within the range of interest (15 - 150 keV), thereby reducing the uncertainty in our measurements, we used 180 kV as tube max potential. Figure 2 illustrate the experimental setup for primary and transmitted spectra measurements.

The detection system consisted on 3 x 3 x 1 mm^3 Cadmium Telluride (CdTe) spectrometer (model XR-100T, Amptek, Inc, EUA) with the PX4 digital pulse processor. A collimator kit

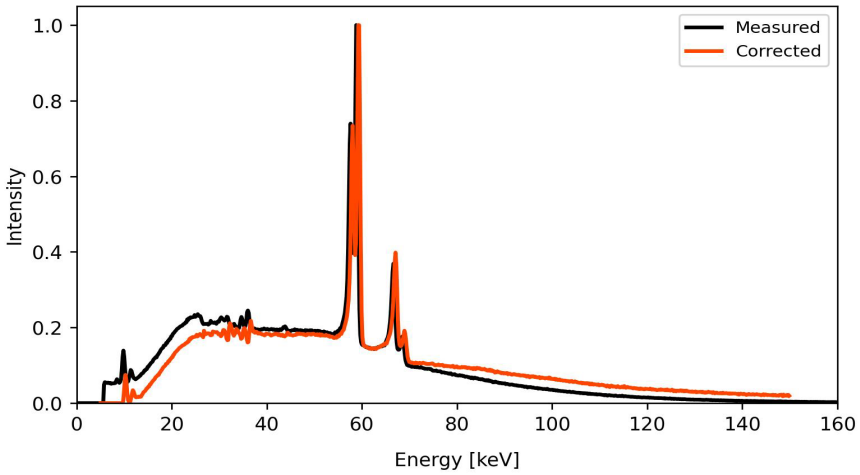
composed by stainless steel collimator housing, a brass spacer, a laser pointer and two tungsten alloy collimator disks was used, in order to reduce the scattered photons impinging the detector sensor. The diameter of the collimator disk proximal to sensor was 1 mm. To avoid damage to the detector and to reduce the dead time, a distance of 5.80 m was considered between the CdTe detector and the X-ray source. The detector was aligned using a device designed in PMMA with the same external dimensions as the spectrometer assembly coupled to a precision mechanical system [9]. After conclusion of the alignment procedure the device was carefully replace by the spectrometer. The measured spectra were corrected for the detector efficiency, Compton distortion and fluorescent escape fraction using a stripping algorithm [10,11]. Figure 3 compares the measured and corrected X-ray spectra obtained with the CdTe detector and demonstrates how the correction procedure eliminates spectral distortions caused by varying physical effects observed in the response functions at different energy ranges.

Figure 2: *Experimental setup used to measure primary and transmitted x-ray spectra*



The energy calibration of the spectrometry system was performed with γ rays from radionuclide calibration sources of ^{241}Am,^{152}Eu and ^{133}Ba.

Figure 3: *Measured and corrected x-ray spectra obtained with CdTe detector.*



2.3. Linear attenuation coefficient calculation

The linear attenuation coefficients, μ(E), of the materials were determined experimentally through measurements of incident, $I_0(E)$, and transmitted spectra, I(E), through a thickness, x, of the samples, using the experimental setup described in section 2.2. These μ(E) were calculated according to the exponential attenuation law by equation 1:

$$\mu(E) = -\frac{1}{x}\ln\left[\frac{I(E) - I_{bg}(E)}{I_0(E) - I_{bg}(E)}\right] + \mu_{air} \qquad (1)$$

where μ_{air} accounts for the air attenuation and I_{bg} is the background radiation. The attenuation coefficients of the reference tissues were obtained using the XCOM database [12].

The experimental uncertainty of μ(E) was estimated by error propagation in equation 1, and can be attributed to photon statistics in the spectroscopy measurements and to errors in the measured value of the thickness:

$$\left(\frac{\sigma_\mu}{\mu}\right)^2=\left(\frac{\sigma_x}{x}\right)^2+\left(\frac{\sigma_{I_0}}{I_0}\right)^2\frac{1}{(\mu x)^2}\left(e^{\mu x}+1\right) \quad (2)$$

where σ_μ, σ_x, and σ_{I0} are the uncertainties of $\mu(E)$, x and I_0 respectively.

The spectra contain fewer counts measured at higher energies contributing to the relative errors increasing as energy increases. In order to have better counting statistics and reduce errors, for each sample, spectra acquisition was made using two parameter sets. For energies below 80 keV, a voltage of 180 kV, a current of 0.2 mA and an acquisition time of 600 s were used without additional filtration. These ensure a high photon counts at the beginning of the energy spectrum. For higher energies we used voltage of 180 kV, a current of 1.8 mA and acquisition time of 3600 s, with additional filtration of 3.5 cm of aluminum plus 0.5 cm of copper. These reduce low energy photons, ensuring high photon counts at the end of the energy spectrum reducing the uncertainty in our measurements. For the construction of the graphs, we combine the two measures.

3. RESULTS AND DISCUSSION

Sample mass density

The experimental mass densities of the samples radiologically equivalent to human tissues determined by direct measurement of mass and volume are shown in Table 2. Their percentage differences with the mass densities of the reference materials liquid water, soft tissue, commercial CIRS 70/30 and CIRS 50/50 are also presented. As expected, the density results are lower than the density of liquid water [13] since these materials are mainly composed of polypropylene, whose density is 0.89 g/cm^3.

The mass densities of samples radiologically equivalent to water (samples A-E) presented differences between 2 and 17%. For the attenuation factor of these materials to be the same, a greater thickness of the material is required than the reference material. This consideration is also important for samples of materials radiologically equivalent to soft tissue (samples F-I) that showed differences in relation to soft tissue density between 6 and 14%. For samples J and K radiologically equivalent to materials CIRS 70/30 and CIRS 50/50, the differences were 9 and 11%, respectively.

Table 2: Experimental densities of samples radiologically equivalent to human tissues and their difference with respect to the reference material.

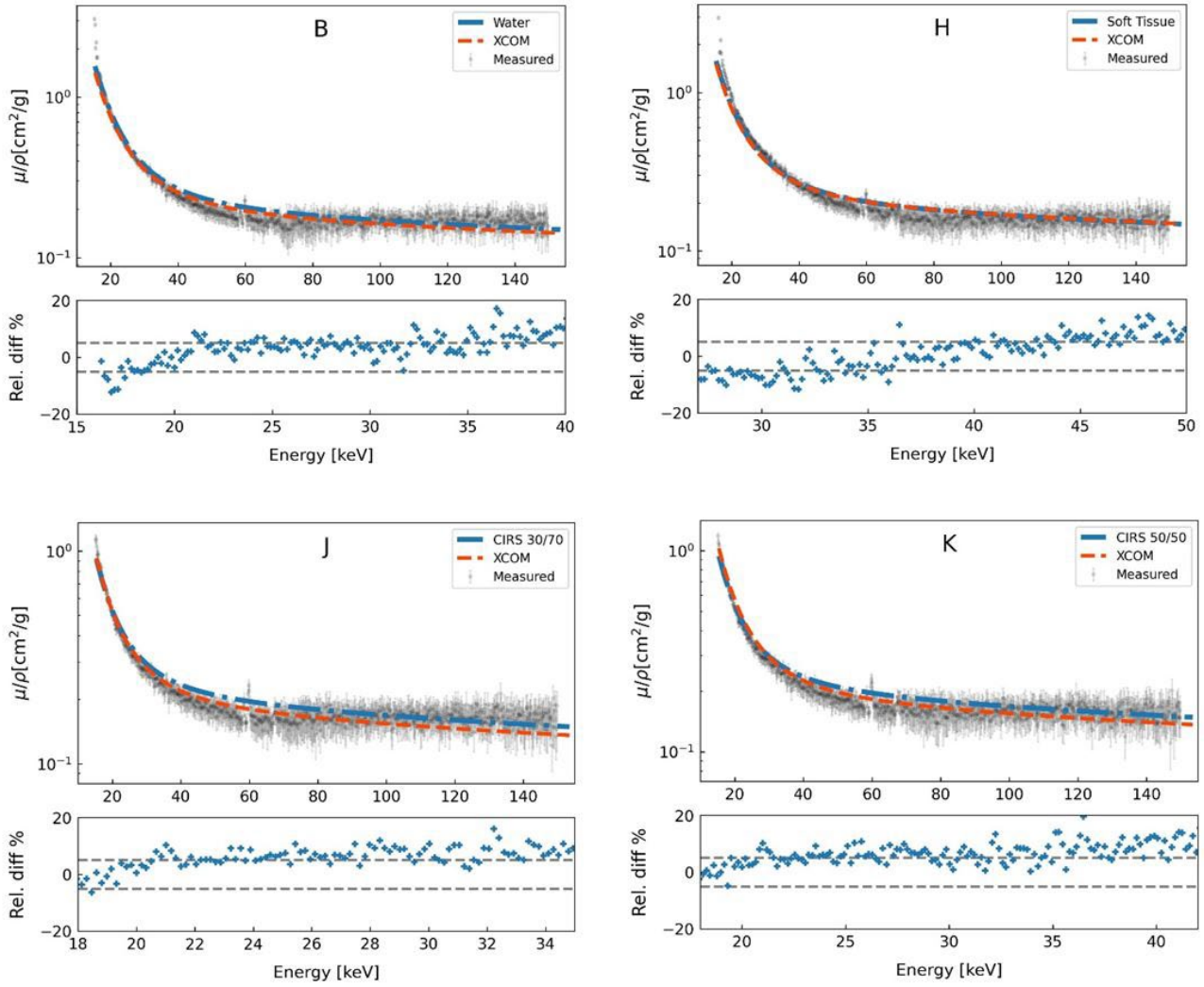
Samples	Density (g/cm^3)	Reference density (g/cm^3)	Difference (%)
A	0.877 ± 0.001		17
B	0.944 ± 0.001		6
C	0.878 ± 0.001	1.00[a]	17
D	0.983 ± 0.003		2
E	0.912 ± 0.001		9
F	0.909 ± 0.001		14
G	0.932 ± 0.001	1.06[b]	7
H	0.999 ± 0.003		6
I	0.886 ± 0.001		11
J	0.896 ± 0.002	0.97[c]	7
K	0.898 ± 0.002	0.98[d]	11

[a] Liquid water density from Hubbell and Seltzer [13]
[b] Soft tissue density from White et al. [14]
[c] CIRS 30/70 density from Poletti et al. [15]
[d] CIRS 50/50 density from Poletti et al. [15]

Linear attenuation coefficient

As an example of the eleven formulations analyzed, Figure 4 shows the experimentally determined mass attenuation coefficients as the result of applying the attenuation law using the corresponding set of primary and transmitted spectra through samples B, H, J and K in the energy range between 15 and 150 keV. These samples were the ones with the best compatibility with the reference materials. In addition, the attenuation coefficient values for the samples calculated using the XCOM database [12] are also presented. Below each chart, it is possible see an area between two dashed lines, representing where the percentage difference between attenuation coefficients of measured sample and the reference material was less than ± 5%, allowing us to determine an energy range that the total difference between the tissue and the measured material is consistent with that required by ICRU.

Figure 4: *Attenuation coefficient of the reference material (dashed blue line), calculated using XCOM database (dashed orange line) and measured using the x-ray spectrometer for samples B, H, J and K (gray points). The relative percentage difference of the measured data against the reference material is shown below each graph (blue points), with the horizontal dashed lines corresponding to ±5%.*



The mass attenuation coefficient values of the B sample are compatible with water in the range 20 to 40 keV with a difference about ± 5%. The compatibility range with soft tissue for the H sample is between 28 and 45 keV. Samples J and K, developed as radiologically equivalent to commercial materials CIRS 30/70 and CIRS 50/50, presented better compatibility between 18 and 35 keV.

Comparison with other tissues

The linear attenuation coefficients for the eleven samples were compared with other tissues in addition to those initially considered. Figure 5 presents the samples that showed good compatibility with adipose tissue, skin, glandular tissue, and commercial material BR 12, in the energy range used in mammography.

Figure 5: *Linear attenuation coefficient of the reference material (dashed blue line), calculated using XCOM database (dashed orange line) and measured spectrometrically for samples E, H, G and D (gray points). The relative percentage difference of the measured data against the reference material is shown below each graph (blue points), with the horizontal dashed lines corresponding to ±5%.*

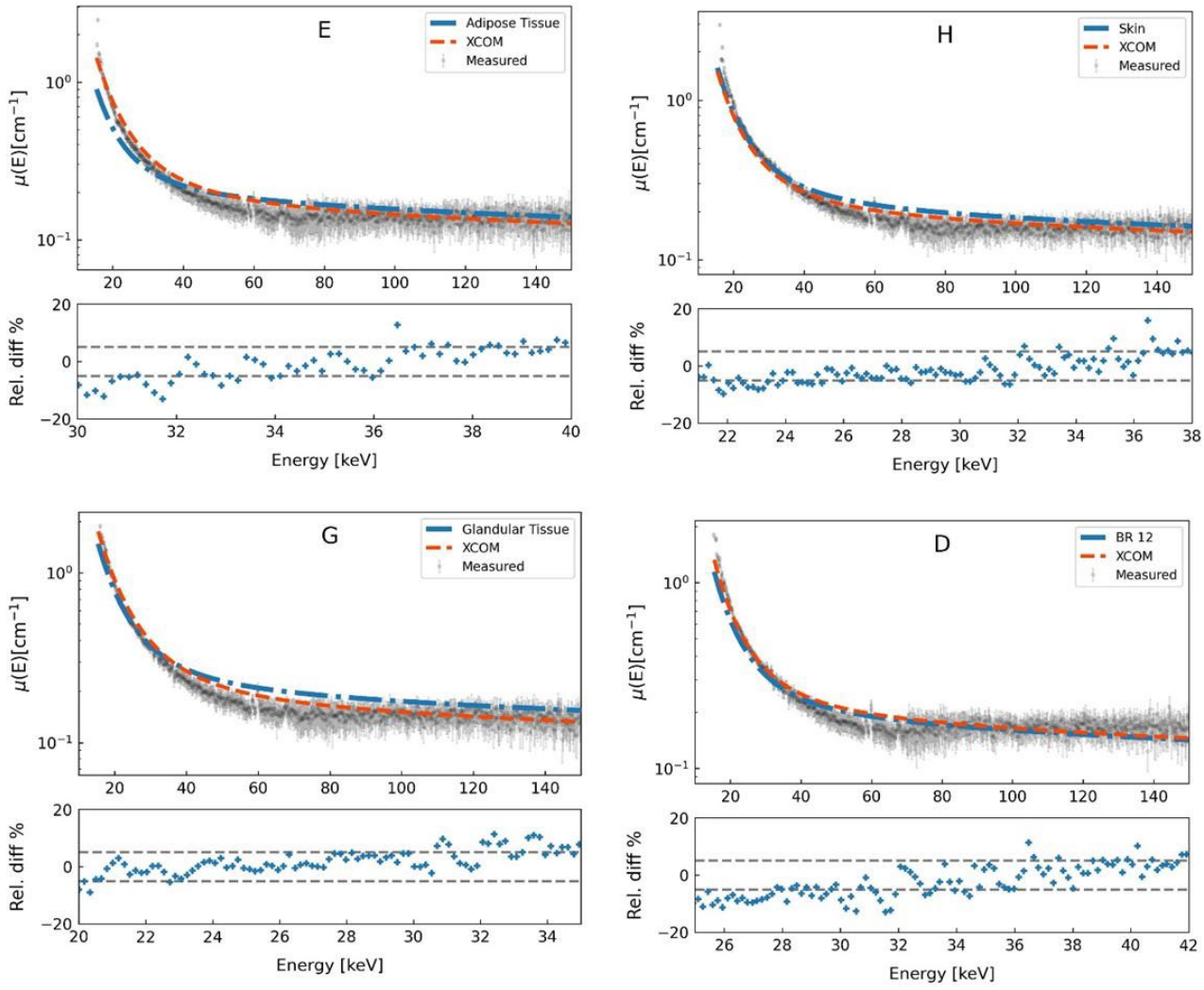


Table 3 presents range of energies in which the developed formulations meet the criteria that the maximum difference of the measured μ(E) against reference materials obtained with XCOM were within ±5%, as recommended by ICRU. The results showed that there are energy ranges in which the developed samples are suitable simulators of other tissues in addition to those initially considered.

Table 3: Polypropylene-based formulations and range of energies in which their linear attenuation coefficient difference with respect to reference material meet the ICRU ±5% criterion.

Samples	**Reference Material**	**Energy Range (keV)**
A	Adipose Tissue	25 - 35
B	Adipose Tissue	35 - 50, 80 - 120
	Glandular Tissue	15 - 22
	Skin	110 - 150
	Thyroid	110 - 150
C	Adipose Tissue	25 - 35
D	Adipose Tissue	35 - 50, 80 - 110
	Glandular Tissue	20 - 30
	Skin	110 - 150
	Thyroid	110 - 150
E	Adipose Tissue	30 - 40
F	Adipose Tissue	20 - 35
G	Adipose Tissue	38 - 50
	Glandular Tissue	20 - 35
H	Adipose Tissue	20 - 38
	Glandular Tissue	30 - 40
	Skin	45 - 70
	Soft Tissue	20 - 40
	Brain	25 - 40
I	Adipose Tissue	35 - 45
	Glandular Tissue	20 - 30
J	Adipose Tissue	100 - 150
K	Adipose Tissue	110 - 150
	Soft Tissue	120 - 150

Adipose tissue was simulated by all samples, being sample J better at the high energies (100 – 150 keV), while F and H are good substitutes at low energy range (20 – 38 keV), which means that in the future, the use of each material will depend on the protocol to be applied. Samples B, D, G, H and I are good candidates to mimic glandular tissue in the energy range of interest in mammography (15 – 40 keV). For skin, sample H proved to be a good candidate for energies between 45 and 70 keV. For energies higher than 110 keV, samples B and D were the ones that presented the best results for this tissue. On the other hand, brain was simulated only by sample H, in an energy range of 25 to 40 keV, making it more difficult to use in medical practice, needing for further study in the future, looking for a sample with better compatibility.

With these results, we have viable candidates for the construction of both, geometric and anthropomorphic phantoms for use in quality control of equipment used in mammography and diagnostic imaging, using low-cost materials.

4. CONCLUSION

The experimental methodology used in this work allowed the determination of linear attenuation coefficient from X-ray spectroscopy for developed polymer-based formulations in the energy range used in diagnostic imaging. The results obtained were compared with μ(E) from water, soft tissue, and commercial materials using XCOM database. With the application of the Mariano&Costa method, formulations were elaborated, finding equivalence to some of the reference materials used. The results also showed that there are energy ranges in which the developed samples are good mimics of adipose, glandular breast, skin, soft tissue, thyroid and brain, with compatibility within ±5%. The findings highlight the possibility of elaboration and validation of tissue-equivalents samples for constructing anthropomorphic phantoms with national and accessible materials that simulate human tissues of interest in the energy range of diagnostic imaging.

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