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BALLISTIC GEL AS A TISSUE SUBSTITUTE: STUDIES AT LOW ENERGIES FOR PHYSICAL PHANTOMS IN IN VIVO MONITORING SYSTEMS CALIBRATION

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ABSTRACT

Ballistic Gel (BGel) is a well-established tissue substitute in ballistic research due to its ability to mimic the mechanical properties of human tissue, such as impact or penetration. Although extensively studied in this and other fields, the radiological characterization of ballistic gel as a tissue substitute remains poorly understood. Previous studies have shown a good correlation of the material at medium (> 186 keV) and high energies (up to 2204 keV). That results demonstrate BGel as a potential tissue substitute of human muscle and other soft tissues in the development of physical phantoms for calibration of whole-body counter systems. The aim of this study is to evaluate BGel as tissue substitute at low energies (5 keV to 70 keV). The tests were performed on the GE Isovolt 160 X-ray source and the AMPTEC XR-100T-CdTe spectrometer for X-ray and gamma analysis. The instruments have a wide detection range, allowing the analysis of X-rays and gamma rays at different energies. The spectrometer was aligned with the primary beam of the X-ray source. For comparison purposes, spectra were measured without any attenuation of the primary beam and then with four samples, individually or together, each 2 cm thick, resulting in thicknesses ranging from 2 to 8 cm. The linear attenuation coefficient of the ballistic gel was calculated from the radiation attenuation law equation using the spectra obtained for thicknesses of 0, 2, 4, 6, and 8 cm of the material. All spectra were corrected for radiation interactions and their values were normalized to the highest intensity value of the counts. Energies between 5 keV and 70 keV were evaluated and the ballistic gel was compared to human muscle and its expected results according to NIST XCOM database. The results showed a good correlation with muscle in the energy range from 25 keV, with differences below 7%, within the limits accepted by ICRU-44 for homogeneous calibration phantoms in *in vivo* monitoring systems. The energies lower than 25 keV showed low attenuation compared to the expected results according to NIST XCOM, which have values close to those of muscle. The ballistic gel has demonstrated good suitability for use as a tissue surrogate of human muscle in the development of physical calibration phantoms in a whole-body counter for low energies above 25 keV.

1. INTRODUCTION

In vivo monitoring systems, which are designed based on specific geometries for organs or for whole-body measurements, are of significant importance in the field of internal dosimetry, particularly for occupationally exposed workers (OEW) and members of the public affected by incorporations of radioactive material. These systems allow for the estimation of the activity incorporated by an individual due to radioactive contamination, thereby enabling the estimation of the committed effective dose [1,2]. To be used for this purpose, it is essential to calibrate these *in vivo* systems using physical phantoms, which are typically built with homogenously distributed radioactive sources with certified activities [3–7].

In order to achieve this objective, the development and utilization of tissue-equivalent materials, designed to mimic the radiological properties of human tissues, is a requisite. In accordance with the International Commission on Radiation Units and Measurements (ICRU), a tissue-equivalent material must exhibit a comparable elemental composition, density, and to be capable of simulating body tissue in terms of its interactions with ionizing radiation within the energy range relevant to its intended purpose [8]. A material is considered tissue-equivalent if its linear attenuation coefficients exhibit a high degree of similarity to those observed in human tissues within a specific energy range, in addition to other relevant parameters [8,9]. To determine material attenuation coefficients with precision, a variety of experimental techniques and theoretical approaches are employed. Experimental methods include transmission, scattering, and absorption measurements using radiation sources with well-defined energy spectra [10–12].

A variety of materials have been proposed and utilized as tissue-equivalent substances throughout history. These include water, gelatin, agarose, various plastics such as polymethyl methacrylate (PMMA), and proprietary mixtures like A-150 Tissue Equivalent Plastic [8,13]. These materials are selected based on their capability to replicate the radiation absorption and scattering characteristics of human tissues, thereby providing a reliable medium for calibrating dosimetry instrumentation. Water has often been regarded as the optimal choice due to its prevalence in biological tissues and well-understood radiological properties [8,13]. However, practical limitations, such as those pertaining to handling and mechanical stability, have led to the development and preference for solid tissue-equivalent materials in many applications.

Ballistic gel has found extensive application as a tissue equivalent in ballistic studies, primarily due to its ability to replicate the mechanical properties of human tissue when subjected to impact or penetration [14,15]. While widely studied in other contexts, the comprehensive characterization of BGel in terms of its radiological properties as a tissue substitute for interaction of ionizing radiation with matter is yet to be fully explored. Research in this area is important to improve the accuracy and reliability of this material to be used in dosimetry and calibration.

In previous studies, our research group conducted tests on BGel to evaluate its applicability as a tissue-equivalent material for the development of physical calibration phantoms for *in vivo* monitoring systems. These tests were performed experimentally, using discrete energy photons from Ra-226 radioactive source covering energies from 186 keV to 2204 keV, and computationally, through simulations with Monte Carlo method-based codes [16, submitted]. The results were promising and confirmed its tissue equivalence within the studied energy range. The aim of this study is to evaluate the ballistic gel as a potential tissue substitute for the construction of physical phantoms dedicated to the calibration of whole-body counter systems in low energies. The investigation aims to assess the material linear attenuation coefficients using x-rays up to 70 keV.

2. MATERIALS AND METHODS

Four samples (A1, A2, A3, and A4) of BGel were prepared by dissolving distilled water (68.5%), gelatin bloom-250 (27.4%), and glycerin (4.1%) in a solution. The resulting gel was then inserted into containers with internal dimensions of 10x10x2 cm^3. The measured density of the material, after gelification, was 1.11 g/cm^3. The sample containers were designed with an exposure hole, so that only the material under study was irradiated and attenuated the radiation beam, without influence of the container material. Fig. 1 shows an example of a BGel sample.

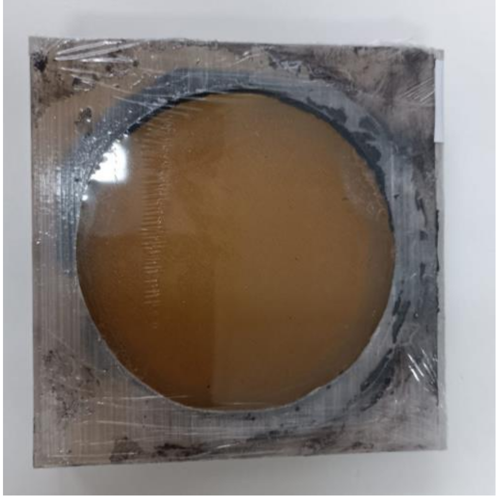
Fig. 1. Ballistic gel sample

The tests were conducted with a constant potential X-ray source, the GE X-Ray Isovolt 160 [17], and the AmpTec XR-100T-CdTe spectrometer [18], which is used for X-ray and gamma analysis. The equipment has a comprehensive detection range, allowing for photon analysis of various energies. However, for the purposes of this study, the maximum beam energy was fixed at 70 keV for all analyses. The detector was calibrated using radioactive sources of Ba-133 and Am-241, and only peaks with low uncertainty were considered.

Once the calibration process was complete, the spectrometer was aligned with the primary radiation beam emitted by the X-ray equipment. Initially, spectrum measurement was performed without any primary beam attenuation (I_0) and subsequently with samples A1, A2, A3, and A4 of the BGel. A new sample was added for each attenuation measurement, increasing the thickness, x, of the combined sample. This resulted in the acquisition of attenuated spectra in a range of 0 to 8 centimeters of ballistic gel material. The experimental arrangement is illustrated in Figure 2.

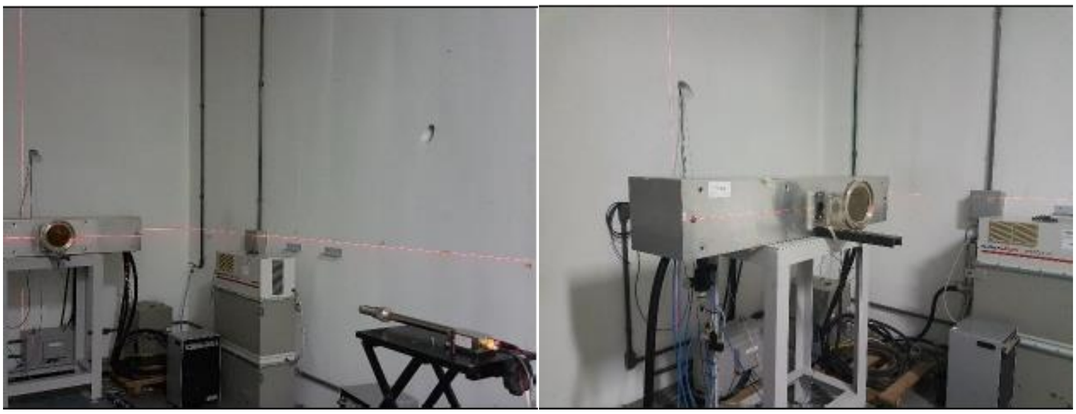
Fig. 2. Experimental setup of samples irradiation.

The dimensions of the radiation field were consistently larger than those of the detector's sensitive volume, and the low-scattering conditions recommended by the International Electrotechnical Commission [19] were taken into account. The stability of the radiation beam was verified through a monitor chamber positioned at the primary radiation beam outlet. The maximum variation observed between irradiations was consistently less than 0.5%. Thus, correction for instability of the beam was not needed. On the other hand, the spectra underwent a correction to account for the effects of scattered radiation and other products of radiation interaction with matter. This was performed using an in-house C^{++} program that applies the stripping method for spectra correction, described by Antunes (2021) [16]. Artifacts in the spectrum observed from 0 to approximately 5 keV were removed and not considered in this evaluation, and the spectrum was corrected from 5 keV to maximum energy.

The linear attenuation coefficient was calculated using the attenuation law, as represented by the following equation:

$$I = I_0 e^{-\mu x} \qquad \text{[Equation 1]}$$

where, I represents the final intensity of the photon beam after passing through a x thickness of the material, Io is the initial intensity of the beam, and μ is the linear attenuation coefficient. In this work, for each energy, Io, was considered the peak area without any sample and, I, the peak area obtained with a sample of thickness x. The μ was obtained for 10, 15, 20, 25, 30, 35, 40, 45, 60, 65 and 70 keV. Each peak analyzed corresponds to the specific channel of its referred energy on the spectra.

The mass attenuation coefficient of the muscle tissue was obtained from the XCOM NIST (*National Institute of Standards and Technology)* database based on the data of the muscle tissues composition from ICRP-110 [17]. The linear attenuation coefficient was obtained considering its density (1.05 g.cm^{-3}). Likewise, a comparable procedure was conducted for BGel, considering its elemental composition and density, experimentally calculated based on its compounds, and for water, commonly used material as a tissue substitute in development of dosimetry physical phantoms.

3. RESULTS

The uncorrected and corrected spectrum are shown in Fig. 3. The doted lines indicate the brute spectra and the continuous lines represented the corrected spectra.

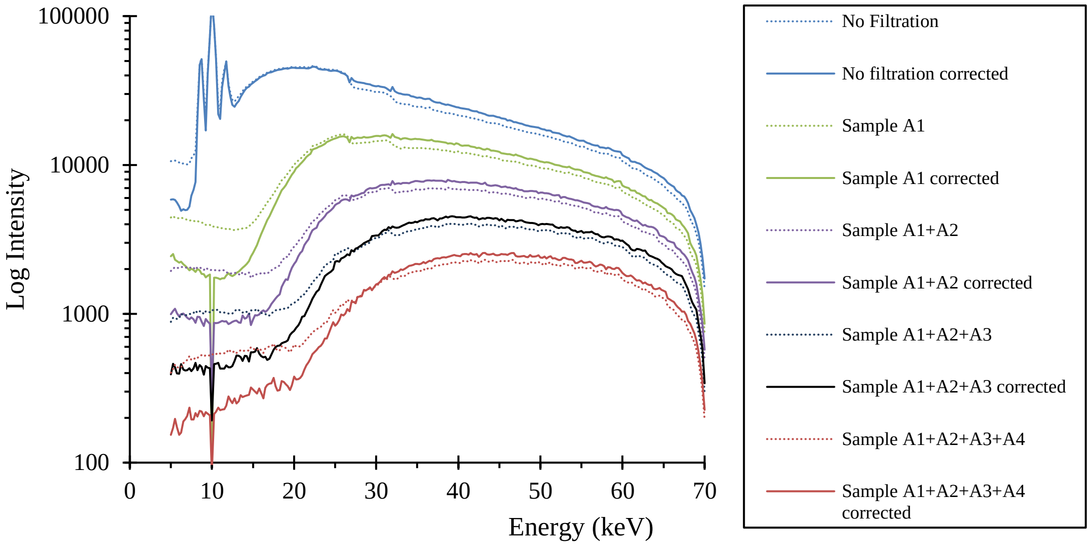

Fig. 3. Uncorrected and corrected spectrum

The calculated results of the linear attenuation coefficients in low energies, in the energy range of 10 keV to 70 keV, are presented in Table 1. Energies below 10 keV were disregarded due to the low efficiency of detection in this range.

Tab. 1. Linear attenuation coefficients obtained experimentally for the BGel and values calculated from NIST XCOM software. The muscle linear attenuation coefficients were considered as reference values.

Energy (keV)	**Muscle NIST XCOM***	**BGel Experimental**		**BGel NIST XCOM**		**Water NIST XCOM**	
	μ (cm^{-1})	**μ (cm^{-1})**	**Ref. Diff.**	**μ (cm^{-1})**	**Ref. Diff.**	**μ (cm^{-1})**	**Ref. Diff.**
10	5.228	0.881 ± 0.138	-83%	5.118	-2.1%	4.955	-5.2%
15	1.7766	0.691 ± 0.091	-61%	1.737	-2.2%	1.672	-5.9%
20	0.8612	0.650 ± 0.036	-25%	0.848	-1.5%	0.810	-6.0%
25	0.5393	0.498 ± 0.006	-7.7%	0.538	-0.3%	0.508	-5.8%
30	0.3972	0.385 ± 0.002	-3.0%	0.401	0.9%	0.376	-5.4%
35	0.3241	0.321 ± 0.001	-0.8%	0.330	1.9%	0.308	-5.1%
40	0.282	0.286 ± 0.001	1.4%	0.290	2.8%	0.268	-4.9%
45	0.2556	0.266 ±0.001	4.2%	0.264	3.4%	0.244	-4.7%
50	0.2376	0.249 ± 0.001	4.6%	0.247	3.9%	0.227	-4.5%
55	0.2248	0.232 ± 0.001	3.3%	0.234	4.2%	0.215	-4.4%
60	0.2151	0.227 ± 0.002	5.3%	0.225	4.5%	0.206	-4.3%
65	0.2075	0.221± 0.002	6.3%	0.217	4.6%	0.199	-4.2%
70	0.2013	0.265 ± 0.011	31.6%	0.211	4.8%	0.193	-4.2%

When compared to the theoretical values of the linear attenuation coefficients of the BGel obtained in the XCOM NIST database and those of human muscle tissue, the expected results are differences ≤ 5% for all analyzed energies. Thus, BGel performance was better or equal to the water in the 10 keV to 70 keV range (see Table 1).

Experimentally, in the range from 25 to 65 keV, the difference of these values varied from 1% to 8%. Energies below 25 keV showed differences from -83 % to -25 % (20 keV). For the energy of 70 keV, this difference was -32%. High differences obtained from experimental calculation for lower energies indicate that the corrections performed in the spectra was not sufficient to remove all counts resulting from partial energy deposition. For 70 keV energy, a hypothesis for this difference may arise from pile-up effect since the count rate was higher without any attenuation and the in-house correction program does not correct this effect. In addition, the number of counts in this region of the spectra is inherently lower and the counting statistics was poorer.

The comparison between experimental values of linear attenuation coefficients of the BGel and the values calculated in NIST XCOM based in BGel elemental composition and density, this difference varied from 1% to 7% in the energy range of 25 keV to 60 keV. In the energies below 25 keV, the differences range from -83% to 23%. For the highest energy, 70 keV, this difference was 26%. These results were consistent with the differences observed in the comparison of experimental values and the NIST XCOM values calculated for the reference muscle tissue. Fig. 4 shows the data from Tab. 1 plotted in a chart.

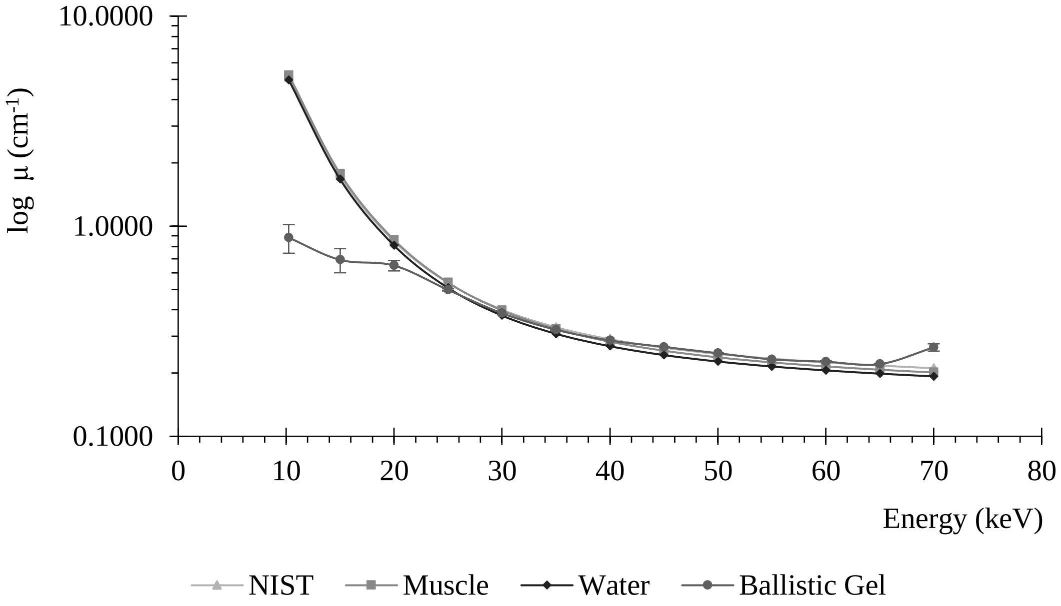

Fig. 4. Graphic of ballistic gel, muscle and water linear attenuation coefficients.

For *in vivo* monitoring systems calibration phantoms, the International Commission on Radiation Units and Measurements (ICRU), in Report-44 [8], accepts a difference of up to 10% between the tissue coefficients and the tissue surrogate. Thus, theoretical data demonstrated the BGel can be used as tissue substitute for energies above 10 keV. Experimental data proved BGel applicability in the range of 25 keV to 65 keV. Differences in experimental results in the range of 10 keV to 25 keV and for 70 keV should be evaluated in the future.

4. CONCLUSION

The calculation of the linear attenuation coefficient of BGel at various energies was conducted using X-ray spectra data ranging from 10 to 70 keV, both unfiltered and filtered through 2 to 8 cm of material. The spectra were corrected for interaction products such as scattered radiation. The results demonstrated a good correlation between the experimental data and muscle tissue in the energy range of 25 to 65 keV, with discrepancies below 8%. However, energies below 25 keV showed significant differences compared to muscle tissue and the theoretical expected value (up to -83%), indicating that the applied correction was not fully effective in this energy range. The energy of 70 keV could influenced by the pile-up effect, which was also not corrected in the applied program, resulting in a larger difference of -32%.

Theoretically, in the range of 10 to 70 keV, BGel showed better or equivalent correlation with human muscle tissue when compared with the water, which is commonly used as a tissue-equivalent material in the development of phantoms. This study found experimental evidence of the applicability of ballistic gel as a muscle substitute material at low energies (25 to 65 keV) for the development of calibration phantoms for *in vivo* monitoring systems, in accordance with ICRU-44 report. The study suggests the development of new methods and correction matrices to obtain results more consistent with the expected theoretical values.

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