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Characterization of applicator material for treatment of superficial lesions in brachytherapy

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Abstract: The treatment of superficial lesions by brachytherapy is performed using radioactive sources positioned inside tumors or at a short distance from them, to deposit the prescribed dose in the target volume. In the case of treating skin lesions, due to the proximity between the source and the patient's surface, it is important to use applicators that conduct the radiation source to the region to be treated, ensuring the safety and hygiene of the process. The treatment of keloids, for example, can be performed by brachytherapy. Considering that the applicators must undergo rigorous quality control, this study presents an evaluation of an applicator developed for the treatment of skin lesions, consisting of fifteen spheres of synthetic material, for use in High dose rate brachytherapy (HDR) equipment, model Nucletron Digital V3, equipped with an Ir-192 source. It was considered important to determine whether the spheres are suitable for medical use, direct contact with the patient's skin and sterilization methods. Furthermore, it was necessary to consider the material's resistance to the irradiation process, since the spheres must be used in multiple applications. In this sense, it was necessary to define the material of the spheres and, through this characterization, consider their suitability for the proposed use. Since the spheres were acquired with generic specifications, this study aimed to perform analyses to characterize the material, defining its composition. Consequently, the focus was to evaluate their safe use in the brachytherapy applicator.

Keywords: Brachytherapy, superficial lesions, dimethyl polysiloxane, applicator.

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Caracterização do material de aplicador para tratamento de lesões superficiais em braquiterapia

Resumo: O tratamento de lesões superficiais por braquiterapia é realizado utilizando fontes radioativas posicionadas no interior de tumores ou a uma curta distância destes, para deposição da dose prescrita no volume alvo. No caso de tratamento de lesões na pele, em função da proximidade entre a fonte e a superfície do paciente, é importante o uso de aplicadores que conduzem a fonte de radiação até a região a ser tratada, garantindo a segurança e a higiene do processo. O tratamento de queloides, por exemplo, pode ser conduzido por braquiterapia. Considerando que os aplicadores devem passar por um rigoroso controle de qualidade, este trabalho apresenta uma avaliação de um aplicador desenvolvido para o tratamento de lesões de pele, constituído de quinze esferas de material sintético, para uso em equipamento High dose rate brachytherapy (HDR), modelo Nucletron Digital V3, dotado de uma fonte de Ir-192. Considerou-se importante determinar se as esferas são adequadas para uso médico, contato direto com a pele do paciente e métodos de esterilização. Além disso, se fez necessário considerar a resistência do material ao processo de irradiação, uma vez que as esferas devem ser utilizadas em múltiplas aplicações. Neste sentido, estabeleceu-se a necessidade de definir de que material as esferas são constituídas e, através dessa caracterização, considerar sua adequação ao uso proposto. Como as esferas foram adquiridas com especificações genéricas, este trabalho teve por objetivo realizar análises para caracterização do material, definindo sua composição. Por consequência, teve como foco avaliar seu uso seguro para compor o aplicador de braquiterapia.

Palavras-chave: Braquiterapia, lesões superficiais, dimetil polissiloxano, aplicador.

1. INTRODUCTION

Skin cancer is the most common type of tumor, accounting for more than half of the malignant tumors diagnosed annually worldwide. Because the skin is the largest and most extensive organ in the human body, the appearance of lesions is quickly noticed by the patient in the early stages. Due to their history, staging and treatment, malignant skin tumors are divided into two types: melanomas and non-melanomas. Melanoma has a lower incidence when compared to non-melanoma skin cancer, but it is more aggressive and has a high associated mortality rate. In the case of non-melanoma cancer, its early diagnosis and treatment are responsible for avoiding physical deformities and functional changes due to the aggressive treatment in controlling more advanced tumors [1]. In the treatment of skin cancer, surgery can be mutilating, or require complex plastic reconstruction techniques under general anesthesia. Thus, radiotherapy has been used for treatment for more than 50 years, with different techniques that include: superficial X-rays; orthovoltage X-rays; megavoltage photons; electron beam irradiation and high-dose rate (HDR) brachytherapy. Radiotherapy, in particular well-planned brachytherapy, is often the treatment of choice in cases of skin cancer that cannot be treated via surgical excision without serious damage [2, 3].

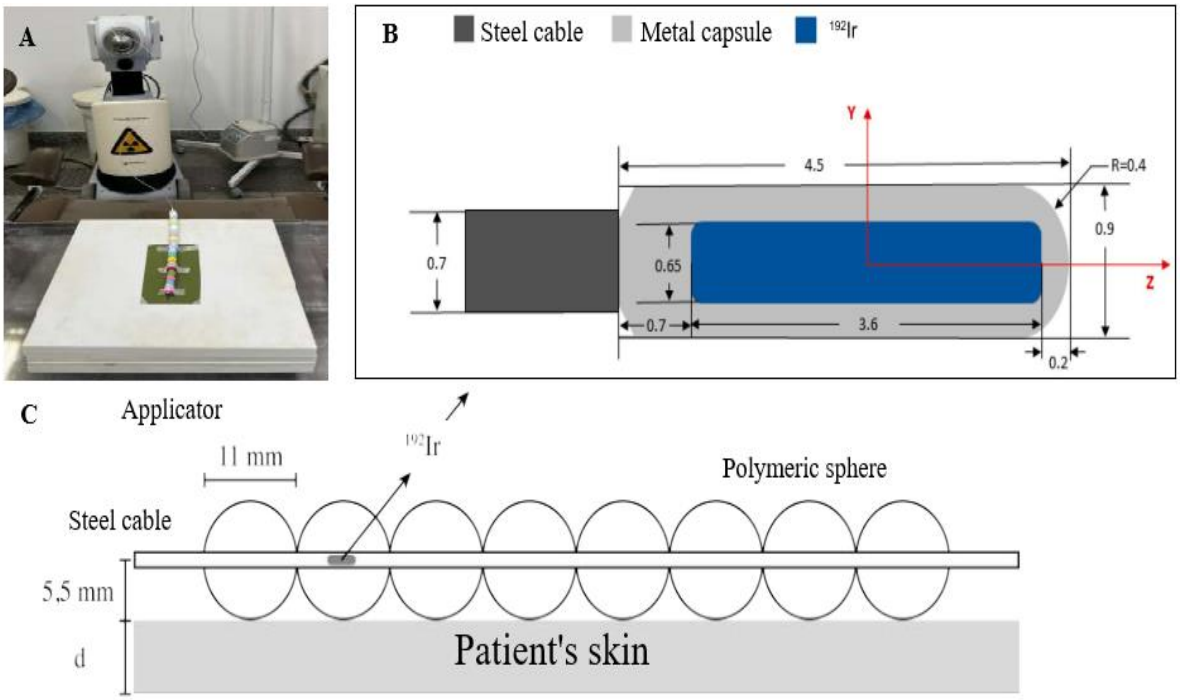
Keloids are formed as a result of excessive tissue growth in the dermis, occurring beyond the extension of a skin lesion, such as an area of inflammation, a burn or a surgical incision [4]. Although they are benign tumors of the dermis, because they extend beyond the edges of the wound, they end up being associated with cosmetic deformities. They cause symptoms such as pain, itching or a burning sensation, negatively impacting the patient's quality of life from an aesthetic, psychological and functional point of view, thus justifying their treatment [5]. Surgical excision to remove keloids is commonly provided as a treatment. However, this procedure alone shows recurrence rates of between 50–80% of treated cases.

Surgical excision combined with postoperative radiotherapy ends up being the best choice to prevent recurrence. The brachytherapy modality has been described for several years as a treatment for keloid scars and is considered one of the most effective treatments combined with surgery [6].

Considering the issues that have arisen regarding the use of radiotherapy, specifically in HDR brachytherapy modality for treating skin lesions in the form of both malignant tumors (melanoma and non-melanoma) and benign tumors (keloids), an applicator was designed and developed to protect the source used in HDR from contact with the patient's skin. Thus, this work was motivated by the need to characterize the spherical material chosen to compose the applicator, which has the additional function of ensuring treatment hygiene. The HDR equipment consists of a remote post-loading system containing a single high-activity source, with an activity of approximately 10 Ci (370 GBq). Although ^{60}Co or ^{137}Cs are commonly used, ^{192}Ir is currently the most widely used isotope. Its choice in this treatment modality becomes more appropriate due to its greater specific activity and because it has photons with energies that allow for less robust shielding.

Treatment using an afterloader is performed by moving the radioactive source through one or more available channels. The source can be positioned precisely at any point on the catheters or applicators. The position and dwell time of the source are programmed through the treatment planning system (TPS), obtaining the desired isodose curves. Afterloaders can be used for interstitial, interluminal and intracavitary implants [7]. The source used in HDR is presented as a small "seed" welded to the end of a flexible steel cable. The cable with the source connected to the end is also called the source wire. The source dimensions vary between 0.3 and 1 mm in diameter and 3.5 and 10 mm in length, depending on the model. The HDR unit (afterloader) is equipped with several channels and an indexing system to direct the source to each channel. In some models such as the microSelectron® Digital (Figure 1), the channels are provided on a rotating turret in which any channel can be aligned with the path of the source wire.

Figure 1: A) Afterloader system for HDR microSelectron® Digital (Nucletron-Elekta, Stockholm, Sweden) belonging to the Luxemburgo Hospital. and; applicator placed on a solid water body simulator. B) Schematic diagram of Nucletron HDR 192Ir model mHDR-v2r high dose rate sources. Dimensions are in millimeters. C) Schematic drawing of the positioning of the applicator on the patient's skin.



Source: Adapted by the authors with their own photo and schematic drawing by Wen *et al.* (2022) [8].

The applicators or catheters are connected to the channels by so-called transfer tubes or transfer guides. Before the radioactive source wire is extended for treatment, a dummy wire with a false source is extended to check for obstructions in the source path. The source is positioned in the programmed stop positions in precise increments by stepper motors [7]. In cases where the source will have direct contact with the patient's skin, it is important that the skin is protected. In this case, the original applicator must undergo adaptation. For this work, protection using synthetic polymeric spheres was considered, since polymers are widely used for biomedical applications. However, it became necessary to characterize the selected material to ensure the expected radioresistance and compatibility qualities for medical use.

Recently, several studies have been carried out on the biomedical use of silicone rubber materials and their interaction with radiation. Dimethyl polysiloxane (DMPS), for example, has been especially cited in the development of composites for use as radiation shielding, such as the studies by Almuqrina *et al.* (2024) who propose DMPS as a matrix with Bi_2O_3 loading [9]. Gouda and Zard (2024) propose the use of DMPS modified with SnO_2 and CdO particles for gamma radiation shielding [10]. The studies suggest application of the materials in both the nuclear and medical industries. Gouda *et al.* (2023) contextualized the use of DMPS in radiotherapy, highlighting its properties that make it suitable: stable material after long exposure to radiation, heat resistance, low cost, high melting point, moldability, mechanical strength [11].

2. MATERIALS AND METHODS

The applicator was developed for the ^{192}Ir brachytherapy source with the HDR microSelectron® Digital afterloader system owned by Hospital Luxemburgo. It consisted of 15 spheres of synthetic material (low cost) with a diameter of 11 mm (Figure 1), with a perforation through the center of the sphere and run through a plastic tube (catheter) for application produced by Elekta (with an external radius of 2 mm). The material of the spheres has a low density (close to that of water), as determined by measuring the apparent density. The distal end of the tube is closed, restricting the movement of the source to a maximum distance of 1118 mm. The catheter tube was fitted to the original Nucletron microSelectron applicator, type F14.

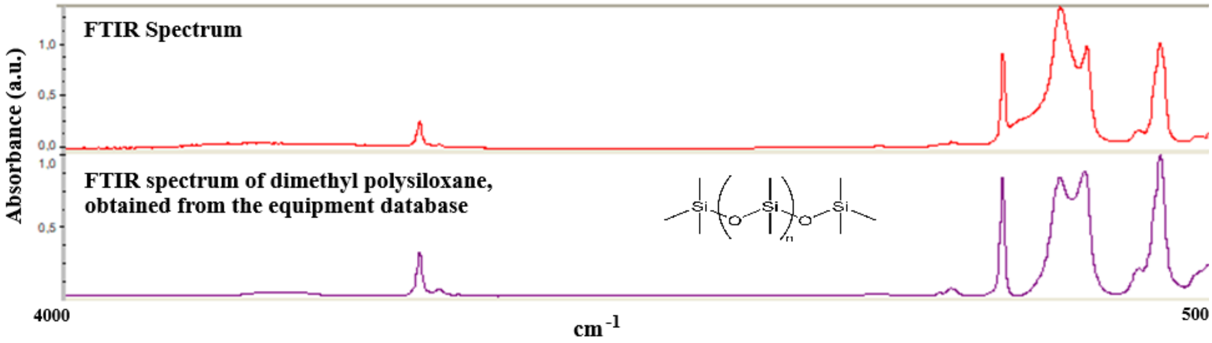
Fourier Transform Infrared Spectroscopy (FTIR) and thermogravimetric analysis (TGA) were used to characterize the sphere material. FTIR characterization was performed with a Thermo Fisher Scientific equipment (Nicolet 6700 model), in ATR mode, with 64 scans, resolution of 4 cm-1 (Ge crystal) and in the range of 4000 cm^{-1} to 675 cm^{-1}. In the Thermogravimetric analysis (TGA) characterization, a Shimadzu equipment, model TGA-50, was used with the following experimental conditions: heating rate of 10 °C min^{-1} from room temperature to 800 °C, nitrogen as carrier gas with a flow rate of 50 mL min^{-1}, platinum sample holder and sample mass of 4.89 mg. The analyses were conducted with one of the white spheres to avoid interference of dyes in the characterization of the material.

FTIR analysis was repeated on the sphere after irradiation, during which the material was exposed to a total gamma dose of 180 mGy. This dose was administered in nine increments of 20 mGy each. The objective was to evaluate the posible material radiodegradation. This dose is approximately equivalent to twelve sessions of keloid treatment by brachytherapy. The irradiation was performed as part of using the sphere in the developed applicator. Consequently, it was irradiated with 192Ir brachytherapy source from the HDR microSelectron® Digital afterloader.

3. RESULTS AND DISCUSSIONS

A white sphere sample (to avoid interference from possible dye) was analyzed by FTIR; the results are shown in Fig. 2. The spectrum of the analyzed sample was subjected to a comparison with the equipment database for material identification, indicating a similarity of 95.9% with the thermoplastic elastomer dimethyl polysiloxane. Siloxane or polysiloxane is a polymer with chemical formula $[R_2SiO]n$, where R is an organic radical, such as methyl, ethyl, phenyl or fluoroalkyl. Dimethyl polysiloxane (DMPS), which contains methyl radicals, is popularly known as silicone rubber, a material widely used in medicine in a safe manner [12].

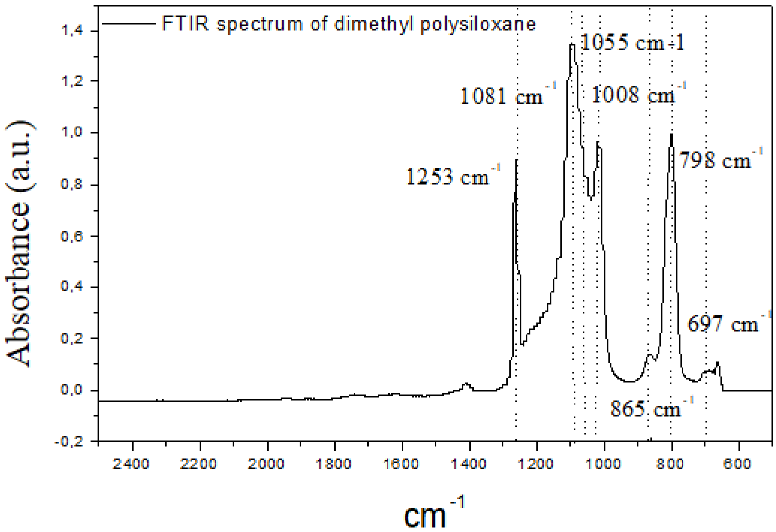
Figure 2: FTIR spectrum obtained from the white sphere and similar spectrum obtained through the comparison function with information from the equipment database.



Source: Research data.

To better detail the FTIR results that allow the identification of the sphere material, Fig. 3 shows absorption bands characteristic of dimethyl polysiloxane.

Figure 3: FTIR spectrum obtained from the white sphere.



Source: Research data.

The assignments of the main bands in the spectra were based on the literature data [13, 14]. The sharp peak at 1253 cm^{-1} was assigned to -Si$(CH_3)_3$ groups. Si-CH_3 group vibrations were assigned to the absorbance signal at 865 cm^{-1}. The broad peak around 1081–1055 cm^{-1} was attributed to the asymmetric stretching -Si–O–Si– vibration with different polymerization degrees [13]. The peak assignments are summarized in Table 1.

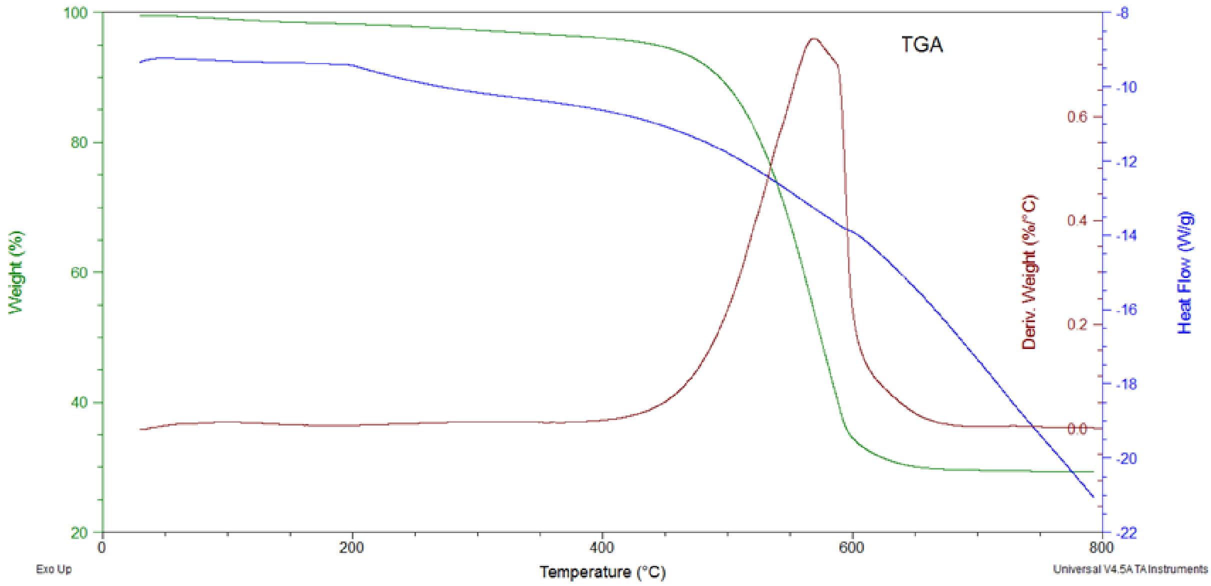
Table 1 : Positions and assignments of the main bands in the FTIR spectrum of dimethyl polysiloxane [13, 14].

Band position [cm^{-1}]	Band assignment
1253	$–Si(CH_3)_3$
1081	–Si–O–Si– asymmetric stretching (high crosslinking degree)
1055	–Si–O–Si– asymmetric stretching (surface groups, low crosslinking degree)
1008	double bond CH_2, double bond CH asymmetric bending
865	$–Si–CH_3$
798	SiC symmetric bending
697	SiC stretching

Based on result of FTIR, which resulted in the identification of the dimethyl polysiloxane, a TGA analysis was performed considering the expected thermal degradation temperature for this material between 200°C to 600°C. The residual mass as a function of temperature upon heating for the white sphere is presented in Fig. 4. Thermogravimetric analysis has been commonly utilized to investigate the thermal stability and thermal degradation kinetics of materials, and can also be used to characterize a polymeric material, knowing its thermal properties in advance.

Evaluation of Fig. 4 indicates that the polymer exhibited measurable mass loss beginning at about 200 °C. The rate of mass loss was fairly constant up to about 400 °C where the rate of loss increased rapidly. According previously shown to literature that the dimethyl polysiloxane produces significant quantities of benzene under pyrolysis at 250 °C. This occurs with minimal cyclic siloxane oligomers evolution. The small initial mass loss could be due to the de-benzylation reaction while the more rapid mass loss at elevated temperatures is most likely due to the formation of cyclic siloxane trimers [15].

Figure 4: The residual mass of polysiloxanes as a function of temperature upon heating rate of 10 °C min^{-1}.

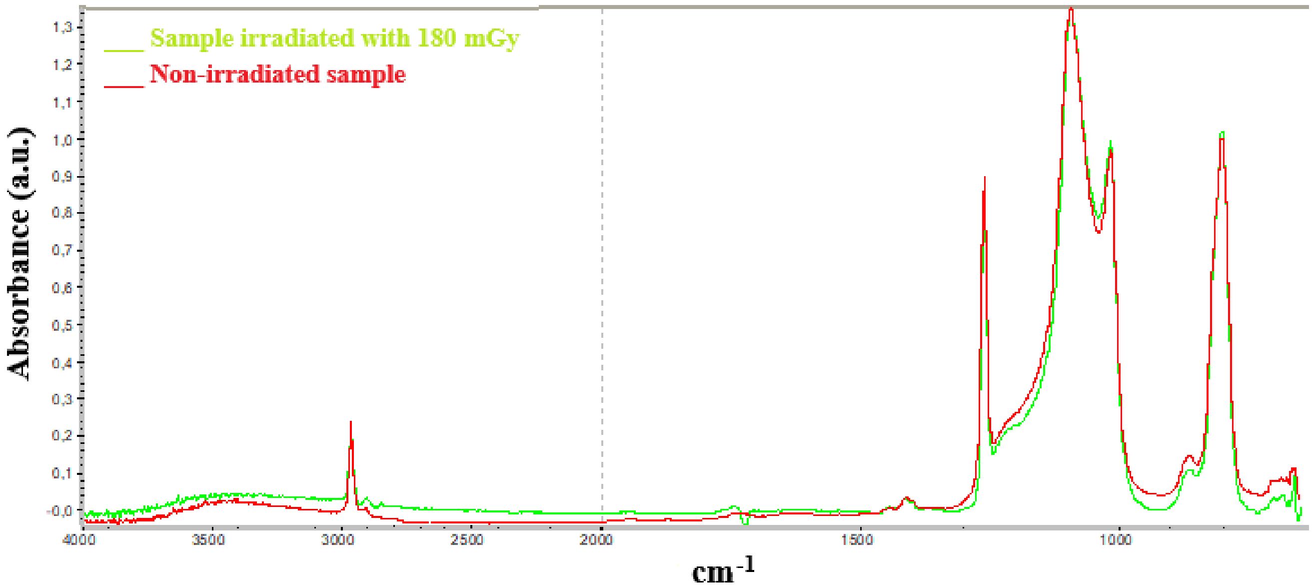


Source: Research data.

In Fig. 4, it can be observed that the TGA curve where the dimethyl polysiloxane matrix presented good thermal stability, with an initial mass loss temperature above 200 °C, compatible with what is known in the literature for this material [16]. As expected for the thermal degradation of linear silicones, under an inert atmosphere, it occurs mainly by the thermo-depolymerization mechanism involving the breaking of Si-O bonds of the siloxane skeleton of the silicone main chain, with its reorganization [17]. The residual masses of the polymer once degradation had ended was than 20% as expected because the literature reports of residual masses ranging from zero to 29% [15].

Dimethyl polysiloxane is a material widely used in medicine, which provides peace of mind regarding its use in the brachytherapy applicator. It demonstrates thermal stability and can be subjected to thermal sterilization processes. To assess the potential radiodegradation of the material under the conditions studied in this work, FTIR analysis was performed on a sphere irradiated with a total gamma dose of 180 mGy. The results are shown in Fig. 5.

Figure 4: FTIR spectrum of non-irradiated sample and sample irradiated with 180 mGy.



Source: Research data.

Fig. 5 presents the FTIR spectrum obtained from the DMPS sample before and after irradiation with 180 mGy. The absence of new peaks in the spectrum, which could indicate the radioinduced formation of new bonds in the material, can be observed. Thus, it demonstrates the absence of radio-induced degradation processes assessable by the FTIR technique in the sample for this radiation dose. In the fact, regarding radioresistance, studies demonstrate the integrity of the material for high doses of gamma radiation (up to 500 kGy) [14], and it has even been studied in the composition of copolymers, forming the matrix of a composite aimed at shielding against gamma and neutron radiation [18].

Studies have indicated several applications of DMPS in the context of radiotherapy, dosimetry and medical imaging. In the context of radiotherapy, DMPS has been used as one of the main components in flexible dosimeters. Dosimeters containing compounds such as dihydrorhodamine 6G are sensitive to radiation and exhibit a linear increase in fluorescence with the absorbed dose, allowing monitoring of dose distribution in tissues that move or deform during treatment. Because these dosimeters are moldable, they allow conformity to the surface of the body, providing dosimetric accuracy in difficult-to-access regions [19].

Another example is the development of DMPS scintillators, capable of emitting visible light when irradiated. This characteristic is exploited in prototypes of radiation sensors and medical imaging, where rapid response and the ability to detect various radiation energies are essential. Studies have shown that DMPS scintillators can achieve light emission efficiencies similar to conventional plastic scintillators, offering a more versatile alternative for medical environments that require precision and adaptability [20].

4. CONCLUSIONS

The characterization work of the polymeric spheres of a brachytherapy applicator was carried out using FTIR and TGA techniques. It was determined that the material of the spheres is made of the thermoplastic elastomer dimethyl polysiloxane, known for its frequent use in medicine and for its resistance to gamma irradiation. TGA analysis also indicates the thermal resistance of the material, which favors thermal sterilization processes for multiple uses of the applicator. Thus, it is concluded that the material of the sphere is suitable for the proposed use, that is, to compose a brachytherapy applicator for the treatment of superficial lesions.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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