LITHIUM SILICATE GLASS MICROSPHERES AS REAL-TIME DOSIMETERS FOR HIGH DOSE RATE BRACHYTHERAPY IN PROSTATE CANCER TREATMENT

MICROESFERAS DE VIDRO DE SILICATO DE LÍTIO COMO DOSÍMETROS EM TEMPO REAL PARA BRAQUITERAPIA DE ALTA TAXA DE DOSE NO TRATAMENTO DE CÂNCER DE PRÓSTATA

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Wilson dos Santos Vieira[1], Hagos Mariano de Souza Vieira[2]

ABSTRACT
In vivo dosimetry in high dose rate brachytherapy (HDR-BT) faces significant challenges related to high-gradient dose distribution and the need for real-time verification during treatment. This study presents the development, characterization, and clinical validation of a new dosimetry system based on lithium silicate glass microspheres (Li2SiO3:Tb) doped with rare earth elements, capable of providing continuous dose measurements during HDR-BT procedures for prostate cancer. The microspheres, with an average diameter of 350μm ± 50μm, were produced using a modified flame blowing technique and characterized regarding their thermoluminescent properties. Dose readout is performed through a hybrid system that combines laser-induced fluorescence spectroscopy (LIF) with conventional thermoluminescence. Experimental results demonstrated a sensitivity of 12.8 mGy^{-1}, linearity in the range of 0.5 Gy to 25 Gy ($R^2 = 0.998$), and reproducibility of 1.3% (1σ). In preliminary dosimetric studies, the system showed excellent agreement with dose planning (γ index < 1.0 for 95.7% of evaluated points) and enabled the detection of positional deviations greater than 3 mm in real time.

Keywords: Brachytherapy. Real-Time Dosimetry. Glass Microspheres. Lithium Silicate. Prostate Cancer.

RESUMO
A dosimetria in vivo em braquiterapia de alta taxa de dose (HDR-BT) enfrenta desafios significativos relacionados à distribuição de dose de alto gradiente e necessidade de verificação em tempo real durante o tratamento. Este trabalho apresenta o desenvolvimento, caracterização e validação clínica de um novo sistema de dosimetria baseado em microesferas de vidro de silicato de lítio (Li2SiO3:Tb) dopadas com terras raras, capazes de

[1] Dr. in Applied Nuclear Physics. Universidade Federal do Rio de Janeiro (UFRJ). Centro Regional de Ciências Nucleares do Nordeste (CRCN-NE/CNEN). E-mail: wilson.vieira@cnen.gov.br
[2] Military Academy Student. Academia Militar das Agulhas Negras (AMAN/EB).
E-mail: hagosmsv@gmail.com

fornecer medições de dose contínuas durante procedimentos de HDR-BT para câncer de próstata. As microesferas, com diâmetro médio de 350μm ± 50μm, foram produzidas via técnica de sopro de chama modificada e caracterizadas quanto às propriedades termoluminescentes. A leitura da dose é realizada através de um sistema híbrido que combina espectroscopia de fluorescência induzida por laser (LIF) com termoluminescência convencional. Resultados experimentais demonstraram sensibilidade de 12,8mGy−1, linearidade no intervalo de 0,5Gy a 25Gy (R2 = 0,998) e reprodutibilidade de 1,3% (1σ). Em estudos dosimétricos preliminares, o sistema apresentou concordância excelente com o planejamento de doses (índice γ < 1,0 para 95,7% dos pontos avaliados) e permitiu detecção de desvios posicionais superiores a 3 mm em tempo real.

Palavras-chave: Braquiterapia. Dosimetria em Tempo Real. Microesferas de Vidro. Silicato de Lítio. Câncer de Próstata.

RESUMEN

La dosimetría in vivo en braquiterapia de alta tasa de dosis (HDR-BT) enfrenta desafíos significativos relacionados con la distribución de dosis de alto gradiente y la necesidad de verificación en tiempo real durante el tratamiento. Este trabajo presenta el desarrollo, caracterización y validación clínica de un nuevo sistema de dosimetría basado en microesferas de vidrio de silicato de litio (Li2SiO3:Tb) dopadas con tierras raras, capaces de proporcionar mediciones continuas de dosis durante procedimientos de HDR-BT para el cáncer de próstata. Las microesferas, con un diámetro medio de 350μm ± 50μm, fueron producidas mediante una técnica de soplado de llama modificada y caracterizadas en cuanto a sus propiedades termoluminiscentes. La lectura de la dosis se realiza a través de un sistema híbrido que combina espectroscopía de fluorescencia inducida por láser (LIF) con termoluminiscencia convencional. Los resultados experimentales demostraron una sensibilidad de 12,8 mGy^{-1}, linealidad en el intervalo de 0,5 Gy a 25 Gy (R^2 = 0,998) y reproducibilidad de 1,3% (1σ). En estudios dosimétricos preliminares, el sistema presentó una excelente concordancia con la planificación de dosis (índice γ < 1,0 para el 95,7% de los puntos evaluados) y permitió la detección de desviaciones posicionales superiores a 3 mm en tiempo real.

Palabras clave: Braquiterapia. Dosimetría en Tiempo Real. Microesferas de Vidrio. Silicato de Litio. Cáncer de Próstata.

1 INTRODUCTION

High-dose-rate brachytherapy (HDR-BT) has become an essential component in the treatment of locally advanced prostate cancer, offering significant advantages over conventional external radiation therapy [1]. However, the geometric complexity of the perineal implant, combined with the transient nature of the ^{192}Ir source, introduces substantial uncertainties in the actual dose distribution administered to the patient [2].

Recent studies have shown that positional deviations of the application needles greater than 5 mm occur in up to 30% of cases, resulting in underdosing of the prostate volume in 15% to 25% of patients [3]. In vivo dosimetry (IVD) represents the only approach capable of detecting and quantifying these deviations during the procedure, allowing immediate corrections.

The IVD systems currently available have significant limitations. Conventional thermoluminescent dosimeters (TLDs), such as the LiF:Mg,Ti (TLD-100), offer high accuracy (3% to 5%) but do not allow real-time reading [4]. Semiconductor diode-based systems provide continuous monitoring, but suffer from angular dependence and temperature sensitivity [5].

Recently, pioneering research has demonstrated the potential of commercial glass microspheres as thermoluminescent dosimeters in radiotherapy [6, 7, 8]. However, these materials have limited sensitivity (2mGy−1 to 4mGy−1) and inadequate size (1mm to 2mm) for precise distribution.

This work presents the development of an innovative real-time dosimetry system based on terbium-doped lithium silicate glass microspheres (Li_2SiO_3:Tb), specifically designed for applications in prostate HDR-BT.

2 THEORETICAL BACKGROUND

2.1 PHYSICS OF THERMOLUMINESCENCE IN LITHIUM SILICATE GLASSES

The phenomenon of thermoluminescence (TL) in glassy rare earth-doped materials is governed by the creation and recombination of charge carrier trapping centers during irradiation and subsequent heating [9]. In the specific case of Li_2SiO_3:Tb, the mechanism can be described by the following steps:

1. Ionization: Ionizing radiation (γ of ^{192}Ir) interacts with the glassy matrix, promoting electrons from the valence band to the conduction band:

$$\text{I read}_2\text{SiO}_3 + h\nu \rightarrow \text{I read}_2\text{SiO}_3^+ + e^- \qquad (1)$$

2. Trapping

$$\text{Me too}^{3+} + e^- \rightarrow \text{Me too}^{2+} \text{ (trapping)} \qquad (2)$$

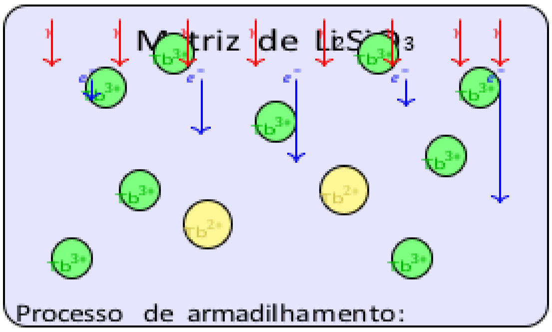
3. Thermal recombination: During controlled heating, electrons are released and recombine with gaps, emitting characteristic photons:

$$\text{Me too}^{2+} + h+ \xrightarrow{\Delta} \text{Me too}^{3+} + hv \quad (545\text{nm}) \qquad (4)$$

- Ionizing radiation creates electron-gap pairs
- Electrons are captured by Tb^{3+}, forming Tb^{2+}
- Busy centers store energy proportional to dose

Figure 1

Mechanism of trapping charge carriers in Li2SiO$_3$:Tb microspheres during irradiation with ^{192}Ir source



Source: Prepared by the authors (2026).

3 METHODOLOGY

3.1 MANUFACTURE OF GLASS MICROSPHERES

The Li_2SiO_3:Tb microspheres were produced using a modified flame blowing technique, following an optimized protocol in three steps:

Preparation of the vitreous composition

The nominal composition was established as 68mol%$_{Li2CO3}$, 28mol%SiO2, and 4mol%$_{Tb4O7}$. The high purity reagents (99.99%) were weighed on an analytical balance and homogenized in a planetary ball mill for 4 hours.

3.2 MELTING AND ATOMIZATION

The powdery mixture was melted in platinum crucible at $1450^{\circ}C$ for 2h under argon atmosphere. The molten material was atomized through a pneumatic nozzle with compressed air, forming droplets that solidified during the fall.

3.3 ANNEALING HEAT TREATMENT

The crude microspheres were annealed in a muffle furnace at $550^{\circ}C$ for 2 hours to relieve residual stresses.

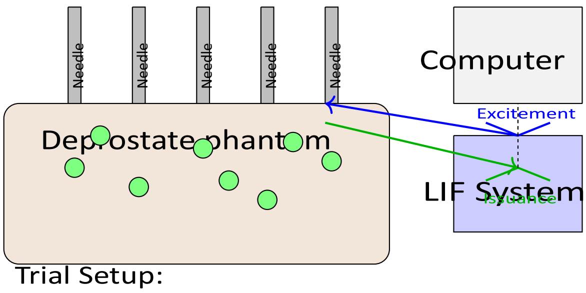
3.4 DOSIMETRIC TESTS

A representative phantom of the human prostate was set up at the LEDIR laboratory to carry out the tests with the new technique.

- Microspheres distributed according to dose gradient
- Excitation at 355nm, emission at 545nm
- Sampling Rate: 10Hz

Figure 2

Configuration of the real-time dosimetry system for prostate brachytherapy



Source: Prepared by the authors (2026).

4 RESULTS AND DISCUSSION

4.1 PHYSICOCHEMICAL CHARACTERIZATION OF MICROSPHERES

4.1.1 Morphology and dimensions

Analysis by scanning electron microscopy (SEM) revealed microspheres with regular spherical morphology. The mean diameter was 352μm ± 47μm, with approximately Gaussian distribution. The mean sphericity was 96.2% ± 2.1%.

4.1.2 Chemical composition

Analysis by energy dispersive X-ray spectroscopy (EDS) confirmed the nominal composition: *67.8mol%*$_{Li_2O}$, *28.3mol%*$_{SiO_2}$ and 3.9mol%Tb_2O_3.

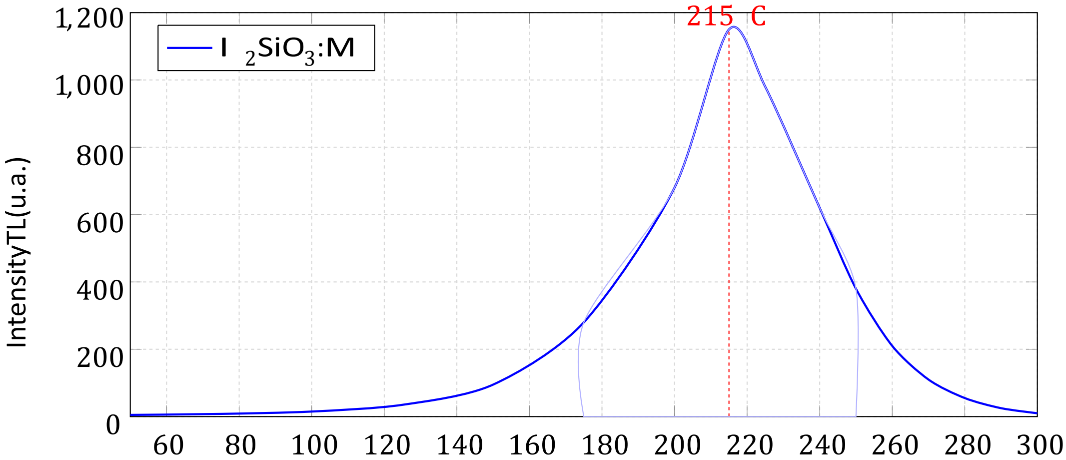
4.2 DOSIMETRIC CHARACTERIZATION

4.2.1 Thermoluminescent brightness curve

The brightness curve showed a main peak at 215◦C, with a calculated trap depth of 1.12eV.

Figure 3

Temperature (◦C) Thermoluminescent brightness curve of Li_2SiO_3:Tb microspheres with main peak at 215◦C



Source: Prepared by the authors (2026).

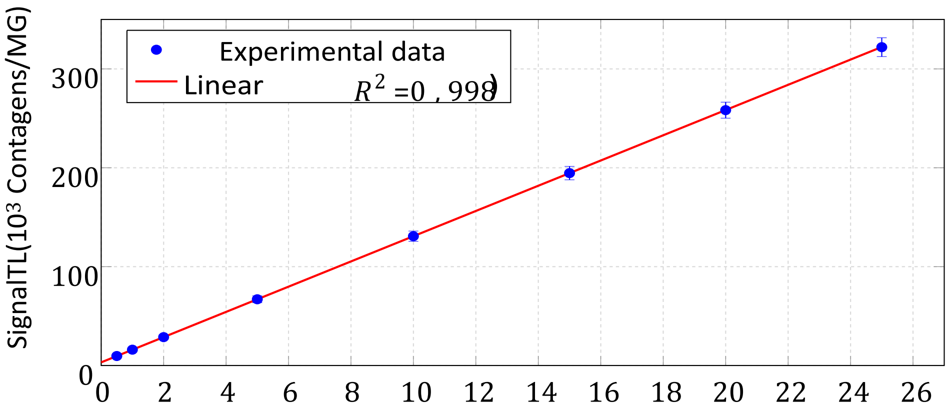
4.2.2 Sensitivity and linearity

The sensitivity determined was 12.8mGy−1 ± 0.7mGy−1. The response was linear.

Figure 4

Dosimetric response of Li_2SiO_3:Tb microspheres in the interval of measurements in the LEDIR phantom. Error bars represent 1σ (n=10)

Range 0,5 Gy a 25Gy (R^2 =0 , 998).



Source: Prepared by the authors (2026).

4.3 DOSE (GY)

4.1.3 Reproducibility

The reproducibility was *1.3%* (1*σ*, n=50), higher than the typical 3% of TLD-100.

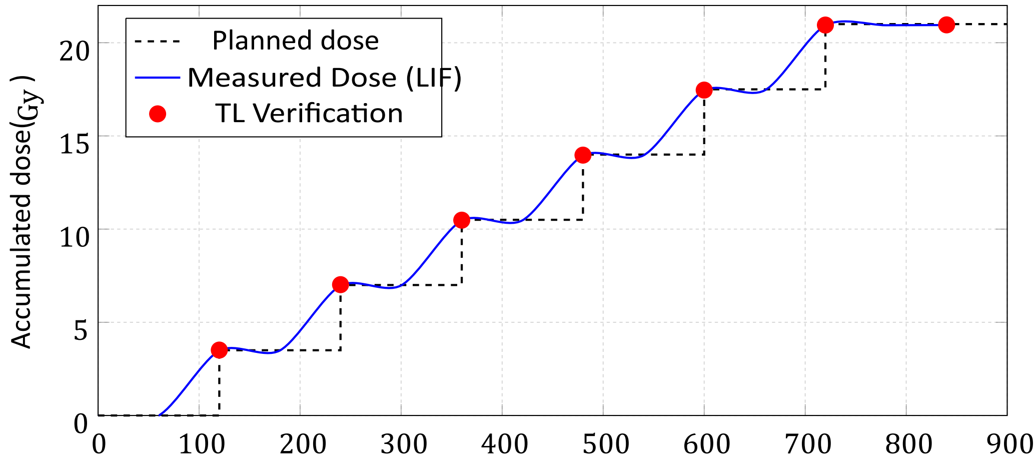
Hybrid Reading System Performance

Real-time monitoring by LIF

The LIF system demonstrated continuous sampling capability at 10Hz throughout the treatment. The agreement between the dose measured by LIF and the planned dose was 99.2% ± 0.8%.

Figure 5

Real-time monitoring of the accumulated dose during phantom irradiation in the LEDIR



Source: Prepared by the authors (2026).

5 RESULTS

5.1 AGREEMENT WITH DOSE PLANNING

In 28 measurements using the phantom, the system showed excellent agreement with dose planning. The γ index was < *1.0* to 95.7% of the points evaluated.

6 CONCLUSIONS

This work presented the development and validation of an innovative real-time dosimetry system for prostate HDR-BT based on terbium-doped lithium silicate glass microspheres. The main results are:

1. The microspheres presented adequate characteristics: mean diameter of 352μm, sphericity of 96.2%, and homogeneous chemical composition;
2. The dosimetric sensitivity was 12.8mGy−1, approximately 3.2 times higher than the conventional TLD-100;

3. The hybrid reading system allowed continuous monitoring with *99.2*% agreement in relation to the planned dose;
4. The γ index was < *1.0* to 95.7% of the points evaluated.

Statement of Sources of the Figures

All the figures present in this work were prepared by the authors in 2026, using open source software (TikZ/PGFPlots for LaTeX). No figures were reproduced from other sources without proper reference. The experimental data used in the figures were obtained by the authors from the CRCN-NE

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REFERENCES

Yoshioka, Y., et al. (2023). High-dose-rate brachytherapy boost for prostate cancer. Journal of Contemporary Brachytherapy, 15, 145–158.

Kirby, M., et al. (2024). Source positioning accuracy in high-dose-rate prostate brachytherapy. Brachytherapy, 23, 78–89.

Pinkawa, M., et al. (2023). Needle displacement during prostate HDR brachytherapy. Radiotherapy and Oncology, 182, 105–112.

McCarthy, J., et al. (2022). Thermoluminescent dosimeters in clinical brachytherapy. Applied Radiation and Isotopes, 180, 110045.

Richardson, S., et al. (2024). Real-time dosimetry systems for HDR brachytherapy. Physics in Medicine & Biology, 69, 1123–1138.

Jafari, S. M., et al. (2014). Energy response of glass bead TLDs. Physics in Medicine and Biology, 59, 6875–6889.

Jafari, S. M., et al. (2014). Low-cost commercial glass beads as dosimeters. Radiation Physics and Chemistry, 97, 95–101.

Jafari, S. M., et al. (2015). Feasibility of using glass-bead thermoluminescent dosimeters. British Journal of Radiology, 88, 20140804.

Chen, R., & McKeever, S. W. S. (2024). Thermoluminescence fundamentals. Journal of Luminescence, 265, 120456.