doi.org/10.15392/2319-0612.2026.3022
Braz. J. Radiat. Sci., Rio de Janeiro
2026, 14(2) | 01-27 | e3022
Editor: Prof. Dr. Bernardo Maranhão Dantas
Editor: Prof. Dr. Alfredo Lopes Ferreira Filho
Submitted: 2025-10-26
Accepted: 2026-01-21

Original Article

Patient-Specific Quality Control (PSQA) of stereotactic treatments in radiotherapy: a study of the sensitivity of a commercial in-vivo dosimetry system

Silva[a*], M. S.; Cardoso[a], S. C.

[a] Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil.

*Correspondence: mardeysantana@oncomedoncologia.com.br

Abstract: This study evaluates a commercial automated in-vivo dosimetry software for stereotactic radiotherapy, focusing on its sensitivity to variations and accuracy in dose prediction. **Development:** The system's sensitivity was assessed through linear accelerator performance tests, detecting both natural and intentionally introduced errors. **Methods:** The research was divided into two parts. In Part A, the system's sensitivity was tested by assessing output constancy and linearity for different field sizes. A homogeneous phantom simulated static fields, allowing the introduction of controlled discrepancies, including geometric shifts, multileaf collimator (MLC) deviations, and energy variations. Part B used a heterogeneous phantom replicating human head and neck anatomy to simulate realistic stereotactic radiotherapy plans with varying targets and doses. These plans were intentionally modified before irradiation and delivered to an electronic portal imaging device. Planned and delivered dose distributions were compared using gamma index criteria. **Results:** Output linearity tests showed improved gamma passing rates with higher dose deliveries, while larger fields exhibited degraded rates due to steep dose falloff at field borders. The 3%/3mm criterion was ineffective for low-dose segments. For output constancy, gamma passing rates improved with stricter 2%/2mm and 1%/1mm criteria as dose decreased, whereas the 3%/3mm criteria remained insensitive. The system effectively detected intentional output variations, though sensitivity dropped for dose differences below 5%. It identified field size variations up to 1 mm and collimator rotations up to 5°, with MLC discrepancies detectable up to 1 mm. Among the tested criteria, 3%/3mm proved least robust. Energy variations were accurately detected. Tests with the heterogeneous phantom confirmed the platform's ability to verify planned treatment parameters and dose metrics accurately. **Conclusion:** The study provided a comprehensive assessment of stereotactic treatment plan quality. The evaluated platform demonstrated strong capability to detect performance variations, geometric and MLC errors, and energy discrepancies, ensuring confidence in the quality assurance process. The findings support avoiding the use of permissive gamma criteria such as 3%/3mm in stereotactic treatments, as they provide limited insight into plan quality.

Keywords: quality control; stereotactic radiotherapy; sensibility; gamma analysis.

doi.org/10.15392/2319-0612.2026.3022
Braz. J. Radiat. Sci., Rio de Janeiro
2026, 14(2) | 01-27 | e3022
Editor: Prof. Dr. Bernardo Maranhão Dantas
Editor: Prof. Dr. Alfredo Lopes Ferreira Filho
Submitted: 2025-10-26
Accepted: 2026-01-21

Controle de Qualidade Paciente Específico (PSQA) de tratamentos estereotáxicos em radioterapia: um estudo da sensibilidade de um sistema comercial de dosimetria *in-vivo*

Resumo: Este estudo avalia a sensibilidade de uma solução comercial de *software* automatizado para dosimetria *in-vivo* voltada a tratamentos estereotáxicos. **Desenvolvimento:** A sensibilidade do sistema é avaliada por meio de testes de desempenho do acelerador linear, detectando variações no desempenho e erros intencionalmente introduzidos. **Métodos:** O estudo foi dividido em duas partes. Parte A testou a constância e linearidade do rendimento para diferentes tamanhos de campo, bem como utilizou de um fantoma homogêneo para introduzir e medir discrepâncias intencionais, como variações geométricas, do colimador multilâminas e de energia do feixe. Parte B utilizou um fantoma heterogêneo que simula a anatomia de cabeça e pescoço humana para planos de radioterapia estereotáxica, modificados antes da irradiação e comparados com as distribuições planejadas usando o índice gama para diferentes critérios. **Resultados:** Testes de linearidade do rendimento mostraram que as taxas de aprovação gama melhoraram com o aumento da entrega de dose, mas campos maiores tiveram taxas degradadas devido à rápida queda de dose nas bordas do campo. O critério 3%/3mm foi ineficaz para segmentos de baixa dose. Para a consistência de rendimento, as taxas de aprovação gama melhoraram com os critérios 2%/2mm e 1%/1mm à medida que a entrega de dose diminuiu, enquanto o critério 3%/3mm permaneceu insensível. O sistema detectou eficazmente variações e distorções intencionais de rendimento, embora o critério 3%/3mm tenha sido pouco sensível a discrepâncias de dose abaixo de 5%. Testes mostraram boa sensibilidade para certos critérios gama, detectando variações de tamanho de campo até 1mm e rotações de colimador até 5º, enquanto discrepâncias no MLC foram detectáveis até 1mm, com o critério 3%/3mm sendo o menos robusto. Variações de energia do feixe foram bem identificadas. Testes com o fantoma heterogêneo confirmaram a capacidade do sistema para verificar os índices de tratamento planejados. **Conclusão:** Este estudo abordou diversos testes para entender a dinâmica do planejamento estereotáxico e, principalmente, a avaliação da qualidade desses planos. A plataforma testada, juntamente com a avaliação de vários critérios, justifica o não uso do critério mais permissivo como padrão em tratamentos estereotáxicos, já que este fornece pouca informação sobre a qualidade dos tratamentos planejados. Além disso, a plataforma garante boa confiança no processo de garantia da qualidade devido à sua forte capacidade de detectar variações de desempenho, discrepâncias geométricas, erros de posicionamento do MLC e discrepâncias na qualidade do feixe.

Palavras-chave: controle de qualidade; radioterapia estereotáctica; sensibilidade; análise gama.

1. INTRODUCTION

Radiotherapy is a medical therapy modality using ionizing radiation to control the uncontrolled growth of neoplastic cells. This cancer treatment approach relies on the principle that external agents, such as radiation, can damage the DNA of a cell, inducing biological damage through physicochemical processes. When a cell cannot repair these mutations, it undergoes programmed cell death (apoptosis), which is also true for neoplastic cells. Most conventional radiotherapy treatments use this strategy, delivering daily radiation doses over several days to promote tumor cell death through their cell cycles [1,2].

An alternative to conventional radiotherapy is ablative stereotactic radiotherapy, also known as stereotactic radiotherapy. The term "stereotactic" refers to the precise three-dimensional positioning of the target and precise dose delivery. "Ablative" implies the removal or destruction of tissue without surgery; a term often used in neurosurgery. However, this term is less used now due to its implication of a radiobiological mechanism of action through high radiation doses. Stereotactic treatments are characterized by precise dose delivery, millimetric target volumes, fewer treatment days (usually less than five), and high doses per fraction (over 5 Gy) [3-5].

Quality control in ablative stereotactic radiotherapy presents significant challenges for medical physicists responsible for safe radiation delivery. There is no scientific consensus on the methodology for implementation and execution. The Brazilian National Nuclear Energy Commission (CNEN) mandates the use of dosimeters adapted to the techniques performed but leaves quality assurance programs to be established by each service according to national and international protocols.

In-vivo transit dosimetry systems, which measure the delivered dose during treatment and verify it against the calculated dose by a Treatment Planning System (TPS), are considered the safest barriers in radiotherapy practice risk analyses. Traditionally,

radiotherapy treatments are monitored using radiation measuring devices (dosimeters) placed on the patient's surface, measuring the entry dose. However, these devices do not provide three-dimensional dose distribution information, only entry dose. They also require prior calibration and complex reading [6].

Radiographic films, when placed on the patient's surface, can provide planar dose distribution information but require prior calibration, careful handling, and difficult processing [7-8].

With advancements in solid-state technology, photodiode arrays embedded in amorphous silicon (aSi), known as electronic portals, have been developed and integrated into linear accelerators for rapid image processing [6-8]. These arrays are now used to measure the planar dose map transmitted through the patient during radiotherapy. This distribution is then compared with a predicted distribution in terms of dose differences and spatial displacements.

Specialized oncology solution companies have developed softwares to process these transmitted dose maps, reconstructing the three-dimensional dose distribution delivered to the patient using back-projection algorithms. However, implementing this in-vivo transit dosimetry methodology raises questions about its sensitivity to variations and absolute dose calculation accuracy.

This study proposes testing a commercial automated in-vivo transit dosimetry software solution. The research aims to develop a sensitivity study of the SunCHECK™ Patient platform (Sun Nuclear Corporation, Version 3.2.1) in detecting variations and its accuracy in dose prediction. Initially, the study evaluates the electronic portal device's linearity and consistency regarding dose using a comparative mathematical analysis tool. Additionally, it examines the system's ability to detect output variations (output factors) based on administered dose. The study also tests the commercial in-vivo system's capability to identify systematically introduced errors in a homogeneous phantom representing stereotactic treatments. Finally, it assesses the system's effectiveness in

identifying systematically introduced variations in a heterogeneous phantom simulating a real stereotactic plan.

2. MATERIALS AND METHODS

For this work, an Elekta Synergy Platform linear accelerator (Elekta, Crawley, UK) with nominal photon energies of 6 and 15 MV, equipped with kV electronic imaging panels (Elekta XVI) and MV (Elekta iView GT) and an Agility multi-leaf collimator (Elekta Agility MLC) was used. The radiotherapy fields were planned on the Monaco® system, version 5.11.02. The configured treatment fields were verified and managed via the MOSAIQ® system, version 2.64. Verifications were conducted on the SunCHECK™ Patient platform from Sun Nuclear Corporation, version 3.2.1. This work was divided into two parts. An overview of each part is presented in Table 1.

Table 1. Description of the methods developed in each of the two phases of this work.

A	Output constancy and linearity;
	Output factor variations;
	Sensibility in a homogeneous phantom from static fields;
B	Sensitivity in a Head and Neck Phantom for stereotactic treatments, Steev from CIRS, by using manually modified clinical radiotherapy treatment plans.

2.1. Part A

Phase A of this work involves testing and quantifying the sensitivity of the SunCHECK™ Patient Platform for different scenarios using only its pre-treatment module, called Fraction 0. Various fields were configured in Monaco®, Elekta's planning system. These fields were then exported to the SunCHECK™ Patient Platform as well as the R&V system (MOSAIQ®), where they were configured and/or modified before beam delivery. Therefore, the SunCHECK™ Platform is expected to be able to detect, in some way,

manually inserted discrepancies between planned and delivered (measured) fields. To compare these two planar distributions, the Gamma Index Analysis has been used for different criteria.

2.1.1. Output linearity

To test the linearity of output as a function of delivered dose, various fields with different monitor units (MU), namely 10, 20, 30, 50, 100, and 200 MU, were prepared for subsequent irradiation. Linearity was also tested as a function of field size for fields measuring 5×5, 3×3, and 1×1 cm². The dose rate of irradiation was fixed at the linear accelerator's maximum nominal operational value (approximately 600 MU/min). The fields were irradiated three times per day on three different days (nine measurements in total) and analyzed using gamma analysis with global normalization for three different evaluation criteria: standard, 2% and 2 mm; permissive, 3% and 3 mm; and restrictive, 1% and 1 mm.

2.1.2. Output constancy

To test constancy as a function of dose rate, various fields with a fixed dose of 200 MU were prepared for subsequent irradiation. The dose rates were then varied to values of 600, 300, 150, 75, and 37 MU/min (the dose rate is discretized as a geometric progression with a ratio of ½ based on the maximum dose rate). Constancy was also tested as a function of field size for fields measuring 5×5, 3×3, and 1×1 cm². The fields were irradiated three times per day over three different days and analyzed using gamma analysis with global normalization for the three predefined evaluation criteria: standard, permissive and restrictive.

2.1.3. Output fluctuations

This test aims to identify the system's ability to detect variations in machine output or even a linear relationship of these variations as a function of the delivered dose. Several fields with different monitor units, namely 10, 50, and 100 MU, were prepared for subsequent irradiation. The fields were created in triplicate for each mentioned dose to allow for later modification. In the treatment management system (R&V system), MOSAIQ®, the planned

fields were modified in terms of the delivered dose. Relative variations from the planned dose, with amplitudes of ±1%, ±2%, ±3%, and ±5%, were applied to the original fields. Of the three fields created for each described dose, one was kept unchanged with the nominal dose value, and the other two had their original dose values modified by the same magnitude but in opposite directions (simulating underdosing and overdosing). The fields were irradiated three times on different days and analyzed using gamma analysis with global normalization for three predefined evaluation criteria.

2.1.4. Sensitivity in a homogeneous phantom using static fields

More extensively, these tests aim to evaluate the system's ability to detect different variations that are part of the clinical routine of a radiotherapy treatment, initially in a homogeneous phantom, using static fields.

2.1.4.1. Geometric Discrepancies

These are defined in the context of divergences between planned fields and irradiated fields due to variations in irradiation geometry, such as gantry, collimator, table rotations, and field sizes. Here, gantry and table rotations could not be tested due to geometric limitations. While the gantry rotates along with the detector array, the table does not influence pre-treatment irradiation.

Various fields, with a fixed dose, nominally 100 MU, and a fixed field size of 3×3 cm^2, were prepared for subsequent irradiation. The fields were created in sextuplicate for each discrepancy to be tested to allow for later modification. In the treatment management system (R&V system), MOSAIQ®, the planned fields were modified in terms of the geometry to be analyzed. All fields were irradiated three times on different days and analyzed using gamma analysis, global normalization, for the three predefined evaluation criteria.

Collimator (C): for the evaluated dose, six fields were generated. One field was kept unchanged, while the remaining five had their original collimatot rotation modified to 1°, 2°, 3°, 4°, and 5° relative to the deffault value, 0°.

Field size variations (MLC and jaws): for the evaluated dose, six fields were generated. One field was kept unchanged, while the remaining five had their original field size asymmetrically modified by 1, 2, 3, 4, and 5 mm relative to the nominal value, either in the X direction using the multileaf collimator (MLC) or in the Y direction using the jaws.

2.1.4.2. MLC Discrepancies

These discrepancies are defined as divergences between the planned leaf positions and the irradiation positions. Several fields were prepared with a fixed dose, nominally 100 MU, and a fixed field size of 3 × 3 cm² for subsequent irradiation. For each discrepancy to be evaluated, the fields were created in sextuplicate to allow for later modification.

In the treatment management system, the planned fields were modified in terms of leaf positioning. Tests were performed considering modifications involving **one**, **two**, or **three adjacent leaves**. For each case, of the six fields created, one was irradiated without any modification, while the remaining five had the positions of the corresponding number of leaves modified, reducing the field by 1, 2, 3, 4, and 5 mm. All fields were irradiated three times on different days and analyzed using gamma analysis with global normalization, according to the three predefined evaluation criteria.

2.1.4.3. Beam Energy Discrepancies

These are defined in the context of divergences between the beam energy used during planning and the energy delivered. Since the linear accelerator has two available photon energies, the aim is to test the software's ability to recognize that the irradiated field was delivered with a different energy than planned, in terms of gamma analysis.

Two fields for the 6 MV energy with a fixed dose nominally at 100 MU, and a fixed field size of 3×3 cm², were prepared for subsequent irradiation.

Beam Energy 6 MV: Of the two fields created, one was kept as planned and the other had its energy modified to 15 MV. The configurations used are summarized in Table

11. The fields were irradiated three times on different days and analyzed using gamma analysis, global criterion, for the three predefined evaluation criteria.

2.2. Part B

Parte B of this work consists of testing and quantifying the sensitivity of the SunCHECK™ Patient Platform using a heterogeneous phantom with clinical treatment plans for radiosurgery. Different scenarios were tested using the Fraction 0 module. The main objective of the tests in this phase is to evaluate the system's ability to detect different variations that are part of the clinical routine of stereotactic radiotherapy treatment.

Three stereotactic treatment plans, based on the number and size of lesions, were conducted to assess the system's ability to detect dose (output) variations intentionally introduced during dose delivery. Concurrently, we used the metrics provided by the platform during the secondary dose calculation phase, DOSECHECK^{TM}, to compare the planned doses against doses measured in a secondary detector (PinPoint 3D chamber).

2.2.1. One lesion

A lesion (CTV) with a volume of 5.01 cm³ was outlined, centered at the intersection of the phantom's fiducial markers, which coincides with the center of positioning of a PinPoint 3D ionization chamber.

Subsequently, 20 Gy was prescribed in a single fraction to be delivered to the PTV, created from a 2 mm symmetric expansion of the CTV, resulting in a volume of 8.48 cm³. The plan consisted of a VMAT dose delivery, with two full coplanar arcs, ensuring beam coplanarity for simplification of measurement geometry. The dose was restricted to adjacent volumes to create a rapid dose gradient. Five identical copies of the treatment plan were generated, which were then fully exported to the SunCHECK™ Patient platform and the R&V MOSAIQ® system, where four plans had their monitor units (MU) modified by 1%, 3%, 5%, and 10%. The plans were then delivered over 3 consecutive days, resulting in three measurements, and evaluated using gamma analysis, global normalization, for the three

predefined evaluation criteria. Additionally, the plans were delivered directly to the phantom with a PinPoint 3D chamber properly positioned to measure the absolute dose delivered at the planning isocenter (center of the largest lesion).

2.2.2. Two leasions

A lesion (CTV) with a volume of 5.01 cm³ was outlined, centered at the intersection of the phantom's fiducial markers, which coincides with the center of positioning of a PinPoint 3D ionization chamber. A second lesion (CTV) with a volume of 2.12 cm³ was added later to the first one, coplanar in the sagittal plane, with a separation of about 9 cm between their centers of mass.

Subsequently, 18 Gy was prescribed in a single fraction to be delivered to the PTVs, created from a 2 mm symmetric expansion of the CTVs, resulting in a volume of 8.48 cm³ for the central lesion and 3.90 cm³ for the posterior lesion. The plan consisted of a VMAT dose delivery, with two full coplanar arcs and a single isocenter. The dose was restricted to adjacent volumes to create a rapid dose gradient. Five identical copies of the treatment plan were generated, which were then fully exported to the SunCHECK™ Patient platform and the R&V MOSAIQ® system, where four plans had their monitor units (MU) modified by 1%, 3%, 5%, and 10%. The plans were then delivered over 3 consecutive days, resulting in three measurements, and evaluated using gamma analysis, global normalization, for the three predefined evaluation criteria. Additionally, the plans were delivered directly to the phantom with a PinPoint 3D chamber properly positioned to measure the absolute dose delivered at the planning isocenter (center of the largest lesion).

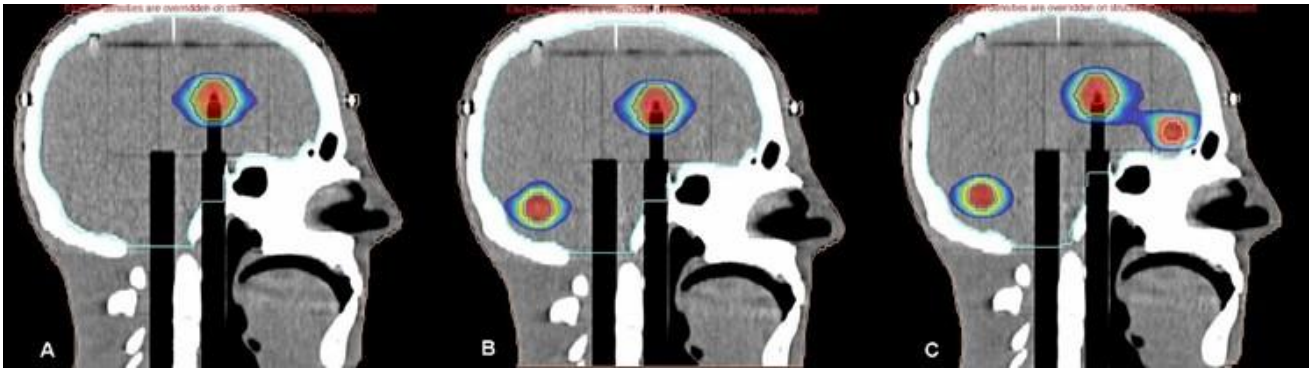
2.2.3. Three Lesions

A lesion (CTV) with a volume of 5.01 cm³ was outlined, centered at the intersection of the phantom's fiducial markers, which coincides with the center of positioning of a PinPoint 3D ionization chamber. A second lesion (CTV) with a volume of 2.12 cm³ was added later to the first one, with a separation of about 9 cm between their centers of mass.

A third lesion (CTV) with a volume of 0.89 cm³ was then added anterior to the first two, located 5 cm from the first lesion and 12 cm from the second one, from their respective centers of mass. All three lesions are coplanar in the sagittal plane generated at the intersection of the fiducial markers.

Subsequently, 16 Gy was prescribed in a single fraction to be delivered to the PTVs, created from a 2 mm symmetric expansion of the CTVs, resulting in a volume of 8.48 cm³ for the central lesion, 3.90 cm³ for the posterior lesion, and 2.49 cm³ for the anterior lesion. The plan consisted of a VMAT dose delivery, with two full coplanar arcs and a single isocenter. The dose was restricted to adjacent volumes to create a rapid dose gradient. Five identical copies of the treatment plan were generated, which were then fully exported to the SunCHECK™ Patient platform and the R&V MOSAIQ® system, where four plans had their monitor units (MU) modified by 1%, 3%, 5%, and 10%. The plans were then delivered over 3 consecutive days, resulting in three measurements, and evaluated using gamma analysis, global criterion, for the three predefined evaluation criteria. Additionally, the plans were delivered directly to the phantom with a PinPoint 3D chamber properly positioned to measure the absolute dose delivered at the planning isocenter (center of the largest lesion). The 50% isodoses of the prescribed dose for the three plans can be seen in Figure 1.

Figure 1: Representation of the 10 Gy isodoses for the single lesion planning (A), 9 Gy in SRS of two lesions (B), and 8 Gy in SRS of three lesions.



2.3. Statistical Treatment of Data

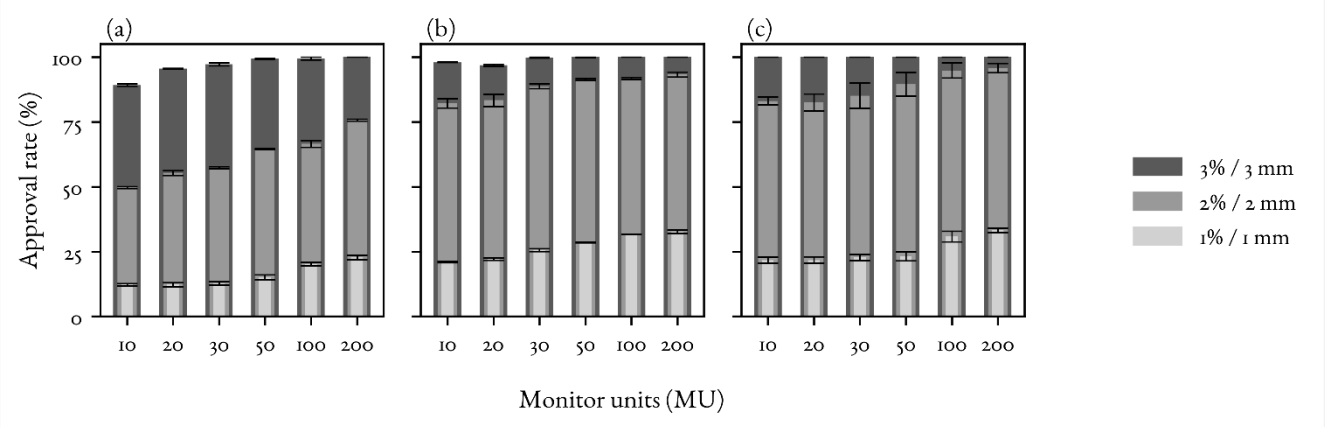
Given the methodology used and the triplicate data collection for various tested scenarios, the data are presented as the simple arithmetic mean of measurements taken at different times. Error bars indicate the corresponding standard deviations for each set of measurements.

3. RESULTS AND DISCUSSIONS

3.1. Output linearity

The gamma passing rates as a function of the delivered dose (in MU) for fields sizes of (a) 5×5 cm², (b) 3×3 cm² and (c) 1×1 cm² are shown in Figure 2 (a-c).

Figure 2(a-c): Gamma passing rate as a function of the dose delivered (MU) for field sizes of (a) 5×5 cm², (b) 3×3 cm² and (c) 1×1 cm².



A consistent trend of increasing gamma passing rates with increasing delivered dose was observed, regardless of the selected evaluation criterion, for a given field size. This behavior is expected, since higher-dose segments are less affected by relative dosimetric and statistical uncertainties.

However, a comparison among different field sizes revealed a systematic degradation of gamma passing rates for larger fields, even under equivalent irradiation conditions. In

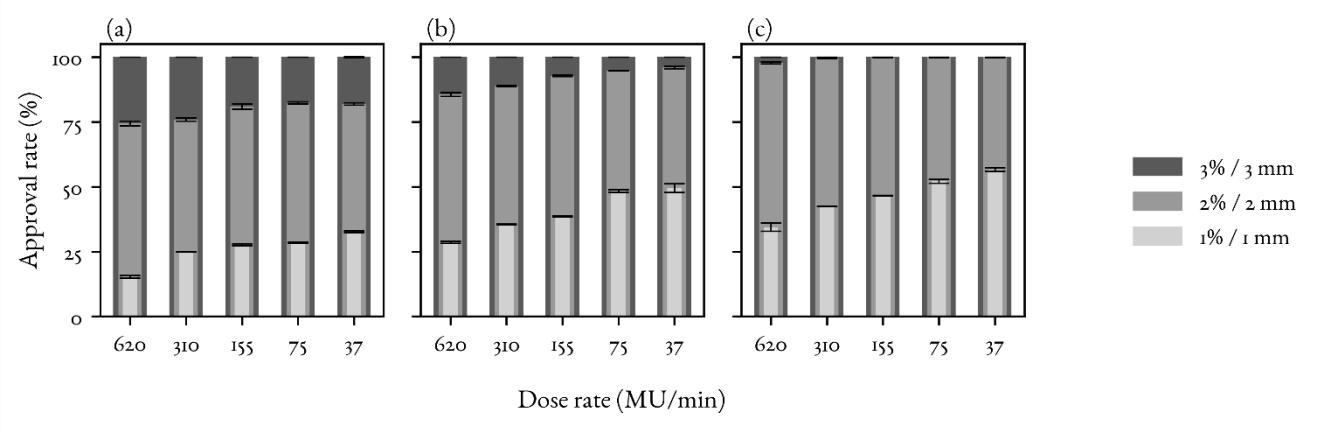
other words, for the same delivered dose and evaluation criterion, larger fields exhibited lower gamma agreement than smaller fields. This effect can be primarily attributed to the increased influence of beam symmetry and flatness variations, which become progressively more relevant as the field size increases.

For small fields, the 3%/3 mm criterion proved unable to detect variations in the delivery of low-dose segments, indicating a low sensitivity of gamma analysis under this criterion. This limitation reinforces the inadequacy of the 3%/3 mm criterion for quality assessment of stereotactic treatment plans, in which small dosimetric deviations may lead to clinically significant impacts.

3.2. Output constancy

The gamma passing rates as a function of the dose rate (MU/min) for fields sizes of (a) 5×5 cm², (b) 3×3 cm² and (c) 1×1 cm² are shown in Figure 3 (a-c).

Figure 3(a-c): Gamma passing rate as a function of the dose rate (MU/min) for field sizes of (a) 5×5 cm², (b) 3×3 cm² and (c) 1×1 cm².



The gamma passing rates obtained using the 2%/2 mm and 1%/1 mm criteria showed improved agreement as the delivery dose rate decreased during the delivery of 100 MU. In contrast, the 3%/3 mm criterion again demonstrated low sensitivity to dose rate variations, failing to adequately capture changes in delivery conditions.

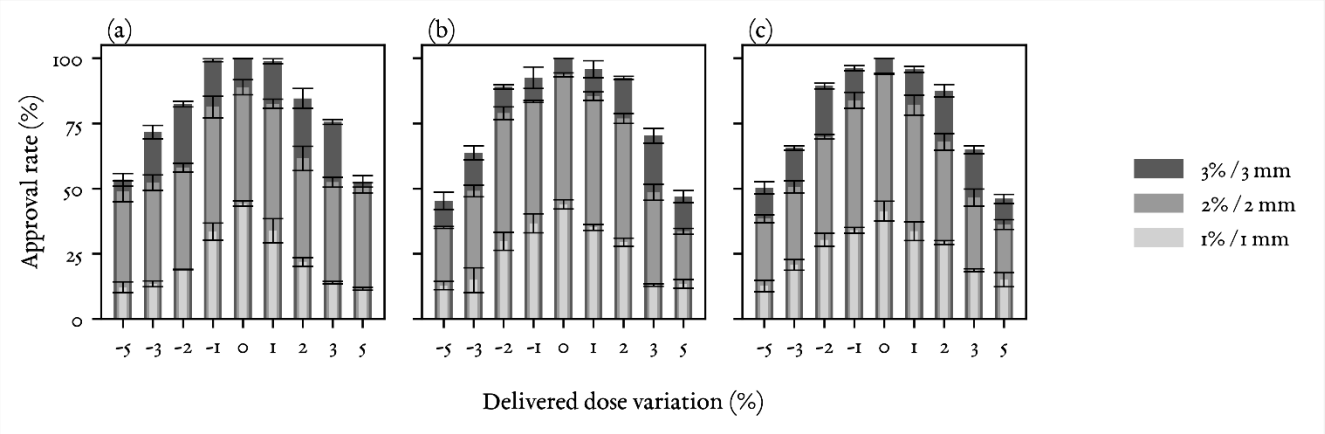
The analysis of gamma passing rates across different field sizes further allowed the identification of field edge effects, which became increasingly pronounced as the field size

increased. This behavior highlights the growing influence of beam characteristics at the field periphery for larger fields, reinforcing the dependence of gamma agreement on field size under varying delivery conditions.

3.3. Output fluctuations

The gamma passing rates as a function of the difference between the delivered dose and the planned doses of 10 MU, 50 MU, and 100 MU are shown in Figure 4 (a-c), respectively. Field sizes were set at 3×3 cm² with a dose delivery rate of 320 MU/min.

Figure 4(a-c): Gamma passing rate as a function of the dose difference delivered for a 3×3 cm² field with (a) 10, (b) 50 and (c) 100 MU.



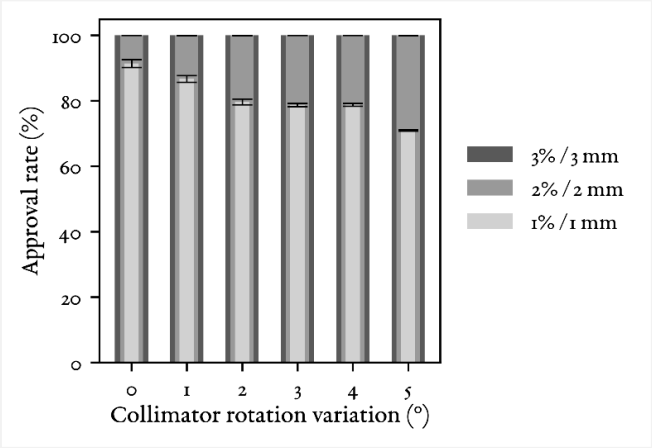
All dose delivery configurations show that gamma passing rates decrease with greater discrepancies between delivered and predicted doses. Discrepancies of 1% cause a slight drop in passing rates with the 3%/3mm criterion. Discrepancies of 5% halve the number of approved points for all criteria compared to an unaltered dose field. The system effectively detects both underdosing and overdosing.

3.4. Geometric discrepancies

3.4.1. Collimator

The gamma passing rates as a function of introduced discrepancies for collimator rotation are shown in Figure 5.

Figure 5: Gamma passing rate as a function of introduced collimator rotation discrepancies at the time of dose delivery.



Results indicate that detecting collimator rotation discrepancies up to 5° is difficult with the 3%/3mm and 2%/2mm criteria. The 1%/1mm criterion shows a linear decrease in passing rates with increased discrepancies but is influenced by other beam parameters. It is important to assess if collimator rotations impact clinical treatment quality and if they are crucial for meeting clinical goals.

3.4.2. Field Size in X (MLC)

The gamma passing rates as a function of introduced discrepancies for field size in the multileaf collimator (X) axis are shown in Figure 6.

Figure 6: Gamma passing rate as a function of introduced field size discrepancies (in X) at the time of dose delivery.

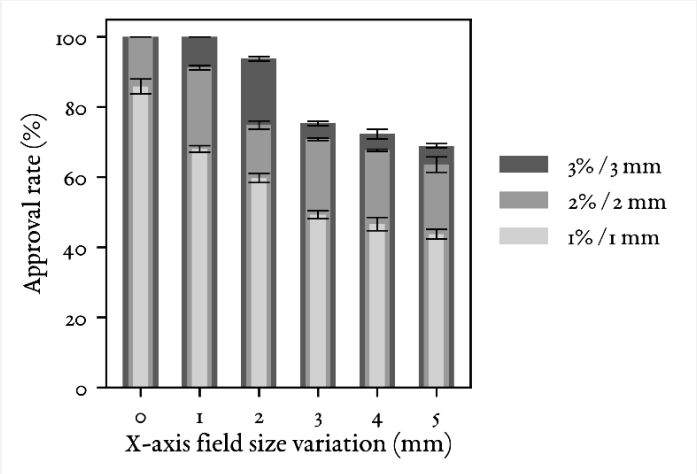
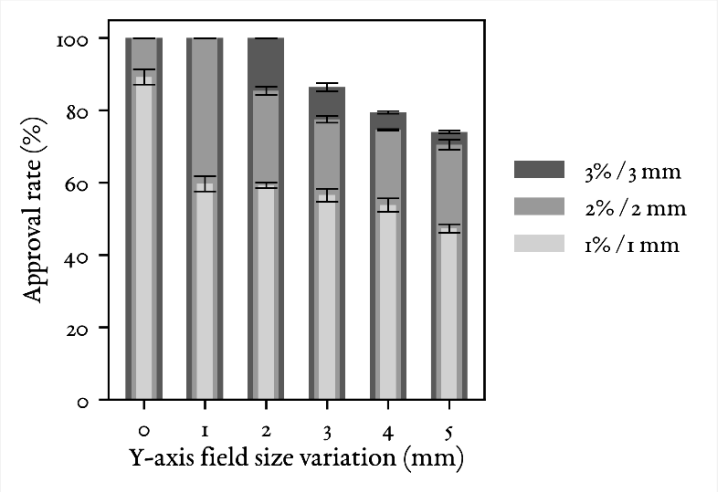


Figure 6 shows that the system detects discrepancies in field size during dose delivery, except for the 3%/3mm criterion with 1 mm changes. The 2%/2mm criterion effectively identifies variations, making it suitable for quality assurance. A saturation region is observed for discrepancies of 3–5 mm, where the system struggles to differentiate between values, though this range poses the highest risk for clinical outcomes. Further investigation into larger discrepancies is not needed since the system successfully detected variations starting from 1 mm.

3.4.3. Field Size in Y (jaws)

The gamma pass rate values for field size discrepancies along the primary collimator axis (Y) are shown in Figure 7.

Figure 7: Gamma pass rate as a function of field size discrepancies (in Y) introduced during dose delivery.

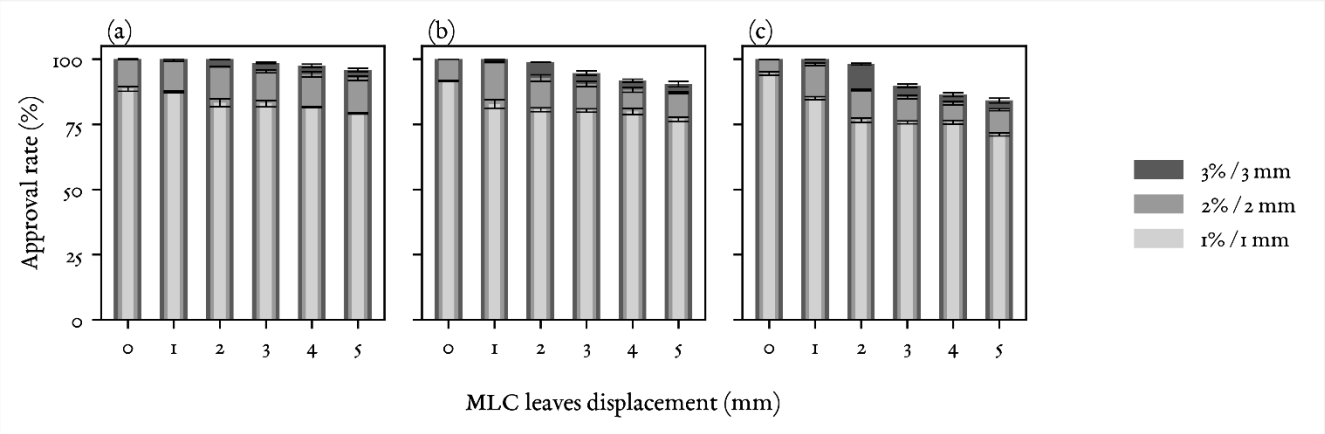


The passing rates shown in Figure 7 follow the same pattern as the X-axis field size discrepancies. However, in this scenario, the 2%/2mm criterion did not detect the 1mm intentional variation in the Y-axis field size. For other introduced discrepancies, all criteria showed reduced passing rates.

3.4.4. MLC discrepancies

The approval rate values for the gamma index as a function of the discrepancies introduced for the position of one, two, and three MLC leaves are presented in Figure 8(a-c).

Figure 8: Gamma pass rate as a function of variations in the position of (a) one MLC leaf, (b) two MLC leaves and (c) three MLC leaves introduced at the time of dose delivery.

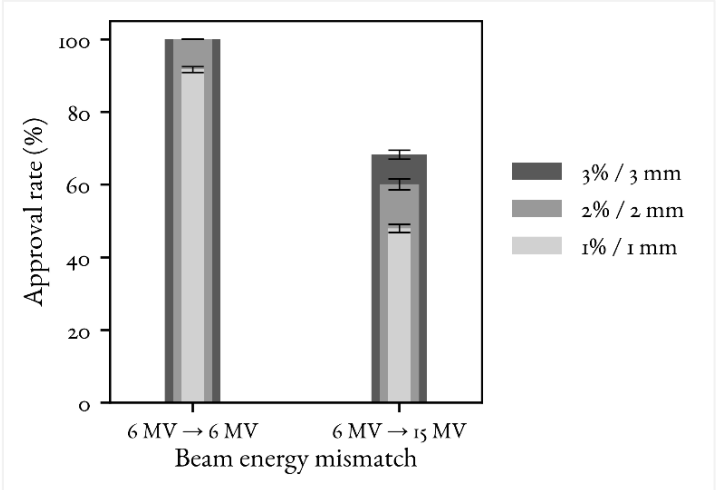


Again, the approval rates displayed in Figure 8(a-c) show the expected behavior for the situations tested on the SunCHECK™ platform. The discrepancies intentionally introduced in the treatment fields at the time of dose delivery were detected for almost all tested criteria, being imperceptible only for the 3%/3mm criterion when the position of the leaves was modified by only 1mm prior to dose delivery. The percentage of approved points decreases as the variation in leaf position increases, as well as the number of modified leaves.

3.4.5. Beam energy discrepancy

The gamma passing rates as a function of the beam energy mismatch are presented in Figure 9.

Figure 9: Gamma passing rates as a function of variations in the 6 MV beam energy introduced at the time of dose delivery.



The system has shown good capability of detecting an intentionally introduced beam energy mismatch for any evalution criteria.

3.5. Sensitivity in a Head and Neck Phantom for stereotactic treatments

3.5.1. One lesion

The radiosurgery planning conducted to deliver 20 Gy to a single lesion was transferred to the SunCHECK™ platform for secondary plan verification. Some metrics from the treatment planning system (TPS) were compared with their equivalents obtained through independent calculation using the DOSECHECK™ mode and are shown in Table 2.

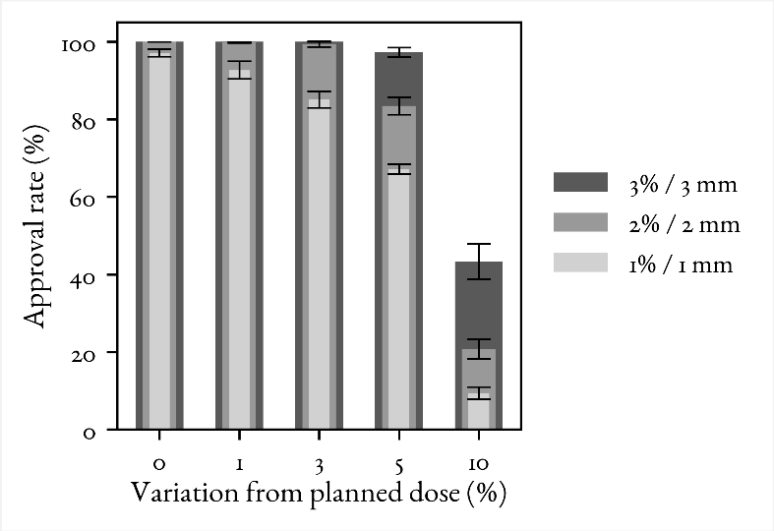
Table 2. Comparison of dosimetric parameters obtained from the SRS planning for PTV 20 Gy performed in the TPS versus their equivalents obtained through secondary calculation by the SunCHECK™ platform.

	TPS (Gy)	DOSECHECK™ (Gy)	Variation (Gy)	Variation (%)
D95	20,51	20,20	0,31	1,54
D90	20,85	20,53	0,32	1,52
Mean dose	22,25	22,05	0,20	0,92
Isocenter dose	22,88	22,77	0,11	0,40

As can be seen in the table above, there is good agreement between the dosimetric quantities from the TPS when compared to those obtained using the DOSECHECK™ mode, as the variations between any of them are less than 2%. These variations are justified by the difference in the calculation algorithms between the two platforms. While the TPS uses the Monte Carlo algorithm, the DOSECHECK™ mode employs the Collapsed Cone algorithm.

For Fraction 0 mode, the values of the gamma passing rates as a function of the intentionally introduced variations in the prescribed dose in an SRS planning with a single lesion are presented in Figure 10.

Figure 10: Gamma passing rates as a function of the planned dose variation for SRS planning of a single lesion.



As expected, the passing rates degrade as the variations introduced in the delivered dose increase, across all applied analysis criteria. It is also important to note that the 3%/3 mm criterion proves to be less efficient at identifying variations of up to 5% in the planned dose. The measurements obtained with the ionization chamber for the five delivered plans are presented in Table 3 below.

Table 3. Relationship between the TPS planned dose for the volume of a 0.03 cc PinPoint chamber and the dose measured by the same chamber.

Intentionally added variation	Planned dose (Gy)	Delivered dose (Gy)	Difference (%)
0 %	22,91	23,25	1,5
1 %	23,14	23,41	2,2
3 %	23,60	23,86	4,1
5 %	24,05	24,36	6,3
10 %	25,20	25,50	11,3

The measurements above obtained with the ionization chamber correlate well with the intentionally introduced variations, with discrepancies of less than 2% relative to the reference dose.

3.5.2. Two lesions

The radiosurgery plan designed to deliver 18 Gy to two lesions was transferred to the SunCHECK™ platform for secondary verification of the plan. Some metrics from the TPS were compared with their equivalents obtained through independent calculation in the DOSECHECK™ mode and are displayed in Table 4 below for the central PTV, and in Table 5 for the posterior PTV.

Table 4. Comparison of dosimetric parameters obtained from the SRS planning for the central PTV 18 Gy performed in the TPS versus their equivalents obtained through secondary calculation by the SunCHECK™ platform.

	TPS (Gy)	DOSECHECK™ (Gy)	Variation (Gy)	Variation (%)
D95	18,42	18,14	0,28	1,53
D90	18,74	18,41	0,33	1,76
Mean dose	20,01	19,73	0,28	1,42
Isocenter dose	20,43	20,25	0,18	0,80

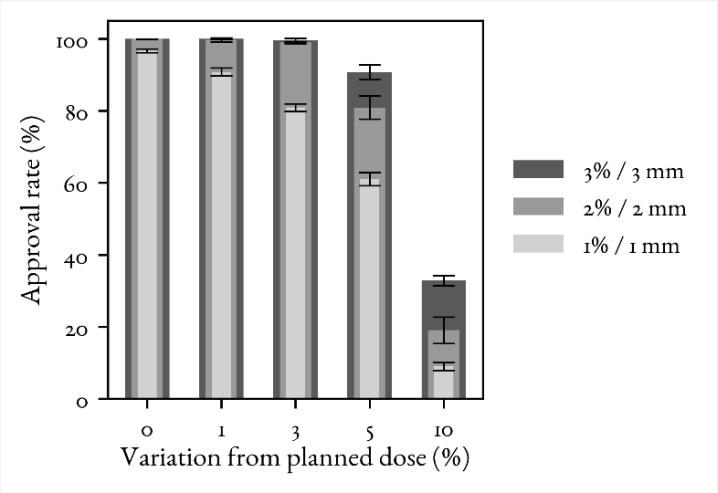
Table 5. Comparison of dosimetric parameters obtained from the SRS planning for posterior PTV 18 Gy performed in the TPS versus their equivalents obtained through secondary calculation by the SunCHECK™ platform.

	TPS (Gy)	DOSECHECK™ (Gy)	Variation (Gy)	Variation (%)
D95	18,01	17,56	0,45	2,52
D90	18,38	17,94	0,44	2,37
Mean dose	19,66	19,32	0,34	1,73
Isocenter dose	20,43	20,25	0,18	0,80

A greater variation is observed in the dosimetric parameters evaluated for the lesion volume farther from the isocenter (posterior PTV).

For Fraction 0 mode, the values of the gamma passing rates as a function of the intentionally introduced variations in the prescribed dose in an SRS planning with two lesions are presented in Figure 11.

Figure 11: Gamma passing rates as a function of the planned dose variation for SRS planning for two lesions.



Once again, the passing rates degrade as the variations introduced in the delivered dose increase, across all applied analysis criteria. The 3%/3 mm criterion continues to be a less robust criterion for identifying variations of up to 5% of the planned dose. There is also a greater overall degradation in the passing rates compared to the single lesion plan. This can be explained by increased modulation of the treatment in this second case, due to the number of planned lesions.

The measurements obtained with the ionization chamber for the five delivered plans are presented in Table 6.

Table 6. Relationship between the TPS planned dose for the volume of a 0.03 cc PinPoint chamber and the dose measured by the same chamber.

Intentionally added variation	Planned dose (Gy)	Delivered dose (Gy)	Difference (%)
0 %	20,63	20,79	0,8
1 %	20,83	20,88	1,2
3 %	21,24	21,34	3,4
5 %	21,66	22,00	6,6
10 %	22,69	23,05	11,7

Again, the measurements obtained with the ionization chamber correlate well with the intentionally introduced variations, with discrepancies of less than 2% relative to the reference dose.

3.5.3. Three lesions

The radiosurgery plan designed to deliver 16 Gy to three lesions was transferred to the SunCHECK™ platform for secondary verification of the plan. Some metrics from the TPS were compared with their equivalents obtained through independent calculation in the DOSECHECK™ mode and are displayed in Table 7 below for the central PTV, in Table 8 for the posterior PTV, and in Table 9 for the anterior PTV.

Table 7. Comparison of dosimetric parameters obtained in the 16 Gy delivery plan for the central PTV executed in the TPS versus their equivalents obtained through secondary calculation by the SunCHECK™ platform.

	TPS (Gy)	DOSECHECK™ (Gy)	Variation (Gy)	Variation (%)
D95	16,49	16,12	0,37	2,24
D90	16,75	16,39	0,36	2,13
Mean dose	17,98	17,62	0,36	2,00
Isocenter dose	17,74	17,83	0,09	0,50

Table 8. Comparison of dosimetric parameters obtained in the 16 Gy delivery plan for the posterior PTV executed in the TPS versus their equivalents obtained through secondary calculation by the SunCHECK™ platform.

	TPS (Gy)	DOSECHECK™ (Gy)	Variation (Gy)	Variation (%)
D95	16,34	16,02	0,32	1,93
D90	16,63	16,32	0,31	1,86
Mean dose	17,83	17,62	0,21	1,22
Isocenter dose	17,74	17,83	0,09	0,50

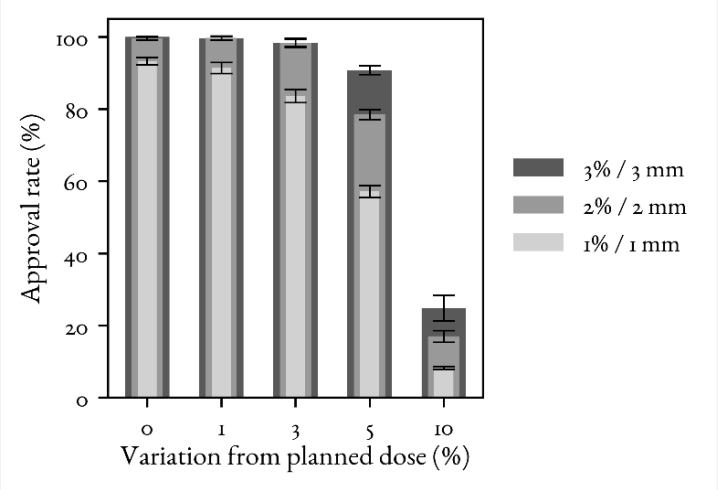
Table 9. Comparison of dosimetric parameters obtained in the 16 Gy delivery plan for the anterior PTV executed in the TPS versus their equivalents obtained through secondary calculation by the SunCHECK™ platform.

	TPS (Gy)	DOSECHECK™ (Gy)	Variation (Gy)	Variation (%)
D95	16,13	15,74	0,39	2,42
D90	16,5	16,08	0,42	2,53
Mean dose	17,69	17,32	0,37	2,05
Isocenter dose	17,74	17,83	0,09	0,50

The results displayed above show good agreement between the plans executed in the TPS and those independently and secondarily verified by the SunCHECK™ platform in DOSECHECK™ mode, with dosimetric quantities differing by less than 3% between the compared values.

For Fraction 0 mode, the values of the gamma passing rates as a function of the intentionally introduced variations in the prescribed dose in an SRS plan with three lesions are presented in Figure 12.

Figure 12: Gamma passing rates as a function of the planned dose variation for SRS planning for three lesions.



As with the other planning scenarios evaluated, the passing rates degrade as the variations introduced in the delivered dose increase, across all applied analysis criteria. Again, the 3%/3 mm criterion fails to identify variations of up to 5% of the planned dose. The degradation of the passing rates is generally more evident when compared to the single and

two-lesion plans, reinforcing the hypothesis that greater modulation in the treatment, indicative of higher delivery complexity, reduces the agreement rates between the planned and delivered doses.

Finally, the measurements obtained with the ionization chamber for the five delivered plans are presented in Table 10.

Table 10. Relationship between the TPS planned dose for the volume of a 0.03 cc PinPoint chamber and the dose measured by the same chamber.

Intentionally added variation	Planned dose (Gy)	Delivered dose (Gy)	Difference (%)
0 %	18,64	18,91	1,4
1 %	18,82	19,10	2,5
3 %	19,2	19,49	4,6
5 %	19,57	19,83	6,4
10 %	20,50	20,89	12,1

As we can see, there is again good agreement between the doses measured with the ionization chamber and the intentionally introduced variations in the plans before dose delivery, with discrepancies of less than 2% relative to the reference dose. The PinPoint 3D chamber proves to be a good auxiliary device for absolute dose verification at specific points during the quality assessment of a stereotactic treatment plan.

4. CONCLUSIONS

This study tested a commercial in-vivo dosimetry system for stereotactic radiotherapy. When testing output fluctuations, it showed good sensitivity to intentional dose delivery variations, but the 3%/3mm criterion was less effective for discrepancies under 5%.

Despite its widespread use, the 3%/3 mm criterion has notable limitations, particularly in highly modulated treatments such as stereotactic radiosurgery or IMRT/VMAT. A key limitation is its relative insensitivity to small but clinically relevant dose deviations. The

tolerances of 3% dose difference and 3 mm distance are relatively generous, which means that deviations in critical regions may not significantly reduce the gamma index, as most points may still pass. In highly modulated plans, dose distributions frequently include small high-dose regions and steep gradients. When deviations occur in these localized regions, the global passing rate can remain near 100%, effectively masking clinically significant errors. The gamma index evaluates each point independently and does not account for the clinical relevance or relative importance of individual points. As a result, highly modulated plans may exhibit localized failures that are relevant from a clinical perspective but remain undetected by the overall passing rate. Comparisons across plans with varying levels of modulation also indicate that the 3%/3 mm criterion often fails to discriminate plans with subtle yet meaningful differences in dose distributions. More stringent criteria, such as 2%/2 mm or dose-weighted gamma analyses, are inherently more sensitive to such variations.

Even when deliberate dose variations of up to 5% are introduced, the 3%/3 mm criterion frequently approves nearly all plans, whereas stricter criteria would reveal reductions in passing rates. This demonstrates that the insensitivity of the 3%/3 mm criterion is intrinsic to the metric itself, rather than resulting from experimental implementation or measurement errors.

In homogeneous phantom tests, the system effectively detected field size variations from 1 mm with the 2%/2mm criterion, but not collimator rotations up to 5º. MLC discrepancies were identified for displacements from 1 mm across various criteria, with 3%/3 mm being the least robust. Energy variations from 6 MV to 15 MV were well detected by all criteria.

Heterogeneous phantom tests showed the system's ability to verify treatment plan quality metrics. Small differences between TPS and DoseCHECK™ calculations were due to different dose calculation algorithms. In Fraction 0 mode, gamma pass rates decreased with increasing intentional yield variations, with 3%/3mm unable to detect variations under 5%. All tested variations were well detected by a PinPoint 3D ionization chamber. Higher

treatment plan complexity resulted in lower gamma pass rates due to high beam modulation and small low-dose segments.

In summary, the study highlights the importance of not using the most permissive criterion for stereotactic treatments, as it provides limited information on treatment quality. The platform ensures reliable quality assurance, detecting yield variations, geometric discrepancies, MLC positioning, and energy variations.

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the results of this study are available in the article. Derived data supporting the conclusions of this study are available upon request from the corresponding author.

REFERENCES

[1] Hall, Eric J. and Giaccia, Amato J. 2019. Radiobiology for the Radiologist. 8ª. Philadelphia: Wolters Kluwer, 2019.

[2] Symonds, Paul, Mills, John A. and Duxbury, Angela, [ed.]. 2019. Walter and Miller's Textbook of Radiotherapy: Radiation Physics, Therapy and Oncology. 8ª. s.l.: Elsevier, 2019.

[3] Nagata, Yasushi, [ed.]. 2015. Stereotactic Body Radiation Therapy: Principles and Practices. 1ª. s.l. : Springer, 2015.

[4] Trifiletti, Daniel M., et al., [ed.]. 2019. Stereotactic Radiosurgery and Stereotactic Body Radiation Therapy: A Comprehensive Guide. 1ª. s.l. : Springer, 2019.

[5] Heron, Dwight E. and Huq, M. Saiful. 2019. Stereotactic Radiosurgery and Stereotactic Body Radiation Therapy (SBRT). [ed.] Dwight E. Heron, M. Saiful Huq e Joseph M. Herman. 1ª. s.l. : demosMedical, Springer, 2019.

[6] Hansen, V. N., Evans, P. M. and Swindell, W. 1996. The application of transit dosimetry to precision radiotherapy. Maio de 1996, Vol. 23, 5ª, pp. 713-721.

[7] Devic, Slobodan, Tomic, Nada and Lewis, David. 2016. Reference radiochromic film dosimetry: Review of technical aspects. 2016, Vol. 32, 4ª, pp. 541-556..

[8] Esposito, Marco, et al. 2020. Estimating dose delivery accuracy in stereotactic body radiation therapy: A review of in-vivo measurement methods. Maio de 2020, Vol. 149, pp. 158–167.

LICENSE