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Feasibility Study of Transit Dosimetry (TD) with an Electronic Portal Imaging Device (EPID) in volumetric arc therapy (VMAT) for head and neck cancer (HNC)

Arvind Kumar[1,2]*, Kiran Sharma[1], C P Bhatt[3], Sangeeta Hazarika[2]

1. Graphic Era Deemed to be University, Dehradun, Uttarakhand, India.
2. All India Institute of Medical Sciences (AIIMS), Rishikesh, Uttarakhand, India.
3. Sarvodaya Hospital and Research Center, Faridabad, Haryana (Delhi NCR), India.

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ABSTRACT

Introduction: The progress in radiotherapy treatment modalities, such as Intensity Modulated Radiotherapy (IMRT) and Volumetric Arc Therapy (VMAT), introduces considerable complexity. Consequently, the precision of dose delivery in treatment becomes crucial. This dosimetric investigation aims to integrate transit dosimetry into routine clinical procedures and assess outcomes using the gamma analysis methodology.

Material and Methods: This dosimetric investigation selected a cohort comprising 30 patients diagnosed with head and neck cancer (HNC) and treated using Truebeam™ & Halcyon™ medical linear accelerators (Varian Medical Systems, Palo Alto, CA). Nine hundred forty-two treatment fluence maps were generated using transit dosimetry and evaluated with gamma analysis. The dosimetry was performed using amorphous silicon (a-Si 1000 and a-Si 1200) electronic portal imaging devices (EPIDs), with gamma analysis criteria of 2% dose difference (DD) and 2 mm distance to agreement (DTA), as well as 3% DD and 3 mm DTA.

Results: Daily treatment consistency was assessed by establishing the initial-day fluence as the reference for the entire treatment regimen. In all instances, it was observed that the area gamma value was <1, exceeding 95% compliance when applying the 2%, 2 mm, and 3%, 3 mm criteria. This indicates a favourable agreement between the fluence of the reference day and subsequent treatment sessions throughout the course of treatment.

Conclusion: The findings of this dosimetric investigation demonstrate the successful integration of transit dosimetry into routine clinical procedures, providing assurance in dose verification without imparting additional doses to patients. Consequently, this dosimetric approach exhibits potential efficacy for dose verification purposes within clinical settings.

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Introduction

The primary objective of radiotherapy is to optimize tumor control probability (TCP) while minimizing normal tissue complication probability (NTCP). Achieving this goal necessitates navigating a high level of procedural complexity, involving intricate treatment algorithms and dose-delivery systems. Emerging treatment modalities such as intensity-modulated radiotherapy (IMRT) and volumetric arc therapy (VMAT) have gained popularity due to their potential for precise dose modulation, albeit with increased complexity and the potential for undesired dose delivery outcomes.

Notably, in 2005, a fatal radiation overdose in New York due to linear accelerator (LINAC)/IMRT misadministration underscored the critical importance of stringent quality assurance (QA) measures and adherence to departmental standard operating procedures (SOPs) to mitigate such incidents [1].

Ensuring the accuracy of radiation dose delivery is paramount in radiotherapy, with image acquisition serving as a crucial step towards this end. Portal imaging, wherein an electronic portal imaging device (EPID) measures fluence passing through the patient during dose delivery, plays a pivotal role. Portal dosimetry (PD), involving the comparison of portal imaging with an expected fluence set, holds promise as an alternative to traditional in-vivo dosimetry. EPID, a key component of transit dosimetry, has evolved from video-based systems to liquid ionization chamber-based ones, culminating in the latest generation employing an amorphous silicon system. This modern EPID configuration utilizes a scintillator to convert radiation into visible light, which is then

*Corresponding Author: Tel: +91-8750498817; Email: arvinddiundi7@gmail.com

detected by an array of photodiodes integrated into an amorphous silicon panel [2,3].

In the context of radiotherapy, stringent dose verification is imperative, as deviations in dose delivery, whether systematic (Σ) or random (σ) errors, can have severe consequences. Transit dosimetry, a method utilizing EPID during treatment delivery, offers advantages in terms of efficiency and patient safety, as it does not entail additional dose exposure. It serves as a viable alternative to direct in-vivo dosimetry, capable of detecting real-time changes in anatomy, -such as volume shrinkage and setup variation, thereby facilitating adaptive radiotherapy [4,5]. Effective implementation of transit dosimetry for patient dose verification purposes in routine clinical practice is the focal point of this study.

Materials and Methods

Patient Selection

This study enrolled 30 patients diagnosed with head and neck cancer (HNC) who underwent treatment utilizing Truebeam™ and Halcyon™ medical linear accelerators, employing flattened (6 MV FF (flattening filter)) and unflattened (6 MV FFF (flattening filter free)) beams, respectively, via volumetric arc therapy (VMAT). The patient simulation was performed on a GE Optima 580 CT simulator with a 2.5 mm slice thickness. Image fusion, contouring, planning, and plan evaluation were performed on Eclipse treatment planning system (TPS) version 16.1.0 (Varian Medical System, Palo Alto, CA, USA). A total of 942 patient treatment field fluence maps were created through transit dosimetry and subsequently subjected to analysis using the gamma (γ) analysis method by comparing planned and delivered radiotherapy doses in Eclipse TPS.

The Planning Target Volume (PTV) is subdivided into three risk-stratified volumes: PTV HR (high-risk), PTV IR (intermediate-risk), and PTV LR (low-risk). The volumes vary with PTV HR ranging from 103.11 to 231.14 cc, PTV IR from 231.01 to 323.22 cc, and PTV LR from 49.98 to 151.53 cc. Mean volumes are 167.40 cc for PTV HR, 207.20 cc for PTV IR, and 114.52 cc for PTV LR. Prescribed doses of 69.96 Gy, 63 Gy, and 54 Gy are administered to PTV HR, PTV IR, and PTV LR, respectively, over 33 fractions.

Table 1. The dose-volume constraints of some normal tissues in head and neck cancer (HNC)

Structures	Dose-volume constraints
cochlea	D_{mean}<45 Gy
larynx	D_{mean}<45 Gy
parotid	D_{mean}<26 Gy
brainstem	D_{max}<54 Gy
lens	D_{max}<5 Gy
mandible	D_{max}<70 Gy
spinal cord	D_{max}<45 Gy

Dosimetric constraints recommended by Quantitative Analyses of Normal Tissue Effects in the Clinic (QUANTEC) govern the exposure limits for organs at risk (OARs). The details regarding the dose constraints for some normal tissues within the HNC plans are summarized in Table 1.

Equipments

Transit dosimetry studies were performed using Varian Medical Systems' C-arm Truebeam™ and O-ring Halcyon™ medical linear accelerators. The Truebeam™ 2.0 LINAC is equipped to handle a variety of photon and electron energies and includes a millennium-120 multileaf collimator (MLC) featuring 40 central leaf pairs, each 5 mm wide, and 20 outer leaf pairs, each 10 mm wide, at the isocenter. This system operates with a top MLC speed of 2.5 cm/s, adjustable dose rates, and a gantry rotation of one rotation per minute. It can deliver radiation to a maximum field size of 40 x 40 cm^2. The megavoltage (MV) and kilovoltage (kV) imaging panel includes an amorphous silicon (a-Si) 1000 detector panel with a 30 x 40 cm^2 active area.

The Halcyon™ version 3.0 bold model medical LA O-ring gantry system stands out with its unique 6MV flattening filter-free (FFF) beam and jawless design. It's designed for smooth patient flow, thanks to its innovative dual-layer stacked and staggered multi-leaf collimator (MLC), which has both proximal and distal layers. This MLC boasts reduced transmission and 114 leaves, with 29 pairs per bank on the proximal layer and 28 pairs per bank on the distal layer. This setup creates a 5 mm leaf effect at the isocenter, which is crucial for treating patients. The two banks are offset by 5 mm. The system offers a high dose rate of 800 cGy/min, a faster MLC speed of 5 cm/s, four gantry rotations per minute (RPM), and can treat a maximum field size of 28 x 28 cm^2, making it highly efficient for clinical use. Unlike typical linear accelerators, this one doesn't have a light field. The MV imager has an amorphous silicon (a-Si) 1200 detector panel that's set 154 cm away from the source. This panel is physically 43 × 43 cm^2, with an isocentric projection of 28 × 28 cm^2, and it provides imaging dose rates of 9 cGy/min and 15 cGy/min.

Imager's

The imager comprises three primary components: an image detection unit, a digitization unit, and an X-ray image system (XI system). Varian's high-energy detectors utilize an indirect detection method. Initially, incident photons are converted into electrons, which are then converted into light. Subsequently, this light generates an electron-hole pair. The detector accumulates this charge on the intrinsic capacitor of the photodiode. Figure 1 illustrates the process of image generation.

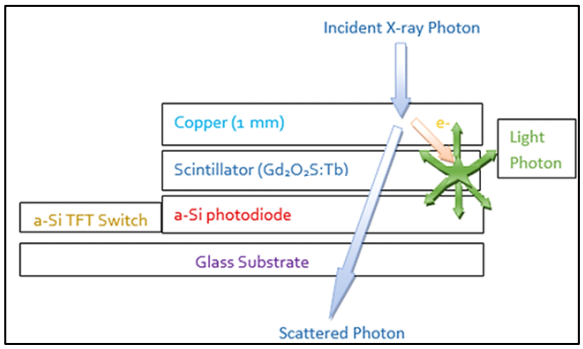

Figure 1. Image generation process

The a-Si 1200 detector exhibits non-saturation characteristics when employed for Free Form Factor beam applications across varying source-to-detector distances. Furthermore, it demonstrates reduced ghosting artifacts compared to its predecessor, the a-Si 1000 Electronic Portal Imaging Device [6,7,8]. Table 2 shows comparison between parameters of a-Si 1000 and a-Si 1200 detectors.

Setup and analysis

For the Truebeam™ linear accelerator, transit dosimetry images were captured using an Electronic Portal Imaging Device positioned laterally at 0 cm, longitudinally at 0 cm, and vertically at 50 cm. Conversely, for the Halcyon™ LINAC, the EPID was fixed at a distance of 154 cm from the radiation source. Portal dose estimation was executed utilizing a Portal Dose Image Prediction algorithm (PDIP) and an Anisotropic Analytic Algorithm (AAA_16.1.0) for Truebeam™ and Halcyon™ LINACs, respectively. Fluence validation was carried out using Eclipse® treatment planning system versions 13.5.0 and 16.1.0, respectively. The initial-day fluence served as the reference baseline, and the consistency of fluence throughout the treatment course was assessed. Furthermore, pre-treatment portal dosimetry was conducted for all selected cases.

Table 2. Comparison between parameters of a-Si 1000 and a-Si 1200 detectors

Parameters	a-Si 1000	a-Si 1200
Resolution (mm)	0.39	0.34
Maximum irradiation area (cm^2)	30*40	43*43
Sensitive area of the panel (cm^2)	30*40	40*40
Total pixel matrix	768*1024	1280*1280
Active dosimetry matrix	768*1024	1190*1190

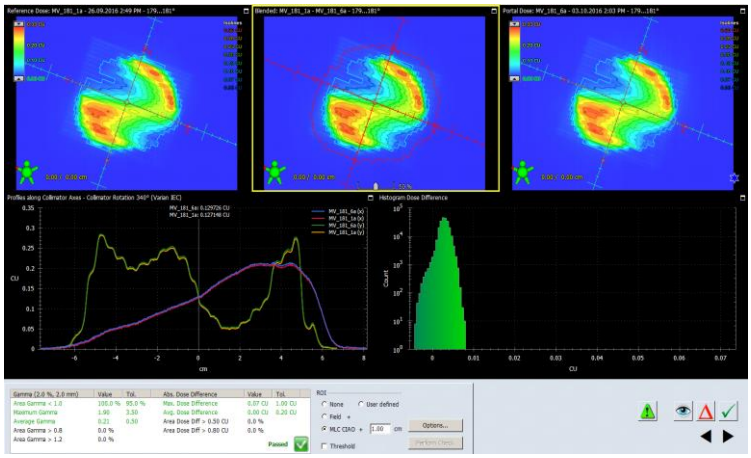

Figure 2. Gamma evaluation for a volumetric arc therapy (VMAT) case

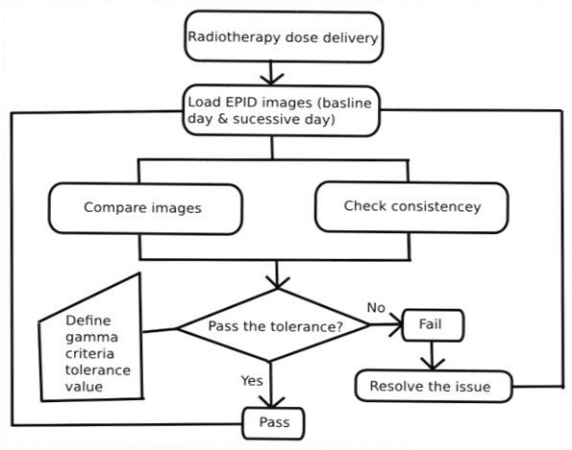

Figure 3. Flow chart for the transit dosimetry (TD) process

The gamma (γ) index analysis was conducted with criteria set at 2% and 2 mm for dose difference (DD) and distance to agreement (DTA), respectively, and at 3% and 3 mm for DD and DTA, respectively. A comprehensive consistency assessment was executed across all selected cases throughout the treatment course, involving analysis of 942 fluence maps. Figure 2 presents the gamma evaluation outcomes for a specific VMAT case, and Figure 3 shows a typical workflow for the transit dosimetry process.

Results

Area Gamma

The Gamma (γ) assessment of initial and subsequent measurements should adhere to acceptance criteria for more than 95% of portal images when applying gamma analysis criteria of 2%, 2 mm, and 3%, 3 mm. Across all instances, it was determined that the area gamma was greater than 95% when employing the 2%, 2mm, and 3%, 3mm criteria. The area gamma findings are detailed in Table 3, Table 4, Figure 4 and Figure 5.

Average Gamma

For each of the selected cases, the average gamma values were determined to be less than 0.5. The maximum values recorded were 0.30±0.03 and 0.17±0.02, while the minimum values were 0.04±0.01 and 0.02±0.00 for the 2%, 2 mm, and 3%, 3 mm criteria, respectively, as presented in Table 3, Table 4, Figure 6 and Figure 7.

Additionally, conventional EPID portal dosimetry was conducted for all cases, yielding results within the respective tolerance limits. Specifically, when utilizing the 3%, 3mm criteria, the area gamma was greater than 95%, and the average gamma values remained below 0.5.

Table 3. Gamma evaluation with criteria of 2%, 2 mm for transit dosimetry performed with amorphous silicon (a-Si) 1000 and amorphous silicon (a-Si) 1200 detectors in volumetric arc therapy (VMAT) for head and neck cancer (HNC)

	a-Si 1000			a-Si 1200		
No. of Patient	Area Gamma <1	Average Gamma	SD	Area Gamma <1	Average Gamma	SD
1	99.99 %	0.12	0.01	100.00 %	0.05	0.00
2	97.20 %	0.30	0.03	98.44 %	0.15	0.00
3	99.76 %	0.19	0.01	98.96 %	0.11	0.00
4	99.70 %	0.14	0.01	98.84 %	0.12	0.00
5	99.99 %	0.16	0.01	96.30 %	0.17	0.01
6	97.40 %	0.24	0.02	99.80 %	0.10	0.01
7	100.00 %	0.11	0.01	98.33 %	0.14	0.00
8	99.99 %	0.09	0.01	98.90 %	0.10	0.00
9	99.90 %	0.12	0.01	99.99 %	0.06	0.00
10	99.99 %	0.12	0.01	98.60 %	0.12	0.01
11	99.90 %	0.11	0.01	99.99 %	0.06	0.01
12	96.67 %	0.22	0.02	99.90 %	0.06	0.00
13	97.60 %	0.20	0.01	99.60 %	0.04	0.00
14	99.78 %	0.12	0.01	99.99 %	0.04	0.00
15	98.97 %	0.14	0.01	99.89 %	0.05	0.00

Table 4. Gamma evaluation with criteria of 3%, 3 mm for transit dosimetry performed with amorphous silicon (a-Si) 1000 and amorphous silicon (a-Si) 1200 detectors in volumetric arc therapy (VMAT) for head and neck cancer (HNC)

	a-Si 1000			a-Si 1200		
No. of Patient	Area Gamma <1	Average Gamma	SD	Area Gamma <1	Average Gamma	SD
1	100.00%	0.10	0.01	100.00 %	0.03	0.00
2	98.95%	0.17	0.02	99.99 %	0.07	0.00
3	99.96%	0.11	0.01	99.99 %	0.10	0.00
4	99.99%	0.12	0.01	99.54 %	0.09	0.00
5	100.00%	0.07	0.01	98.53 %	0.13	0.01
6	97.98%	0.20	0.02	100.00 %	0.10	0.00
7	100.00%	0.08	0.01	99.72%	0.11	0.00
8	100.00%	0.09	0.01	100.00 %	0.08	0.00
9	100.00%	0.12	0.01	100.00 %	0.07	0.00
10	100.00%	0.10	0.01	99.86 %	0.11	0.01
11	100.00%	0.11	0.01	100.00 %	0.05	0.00
12	98.25%	0.15	0.02	100.00 %	0.06	0.00
13	100.00%	0.09	0.01	99.99 %	0.04	0.00
14	100.00%	0.07	0.00	100.00 %	0.02	0.00
15	99.99%	0.12	0.01	100.00 %	0.04	0.00

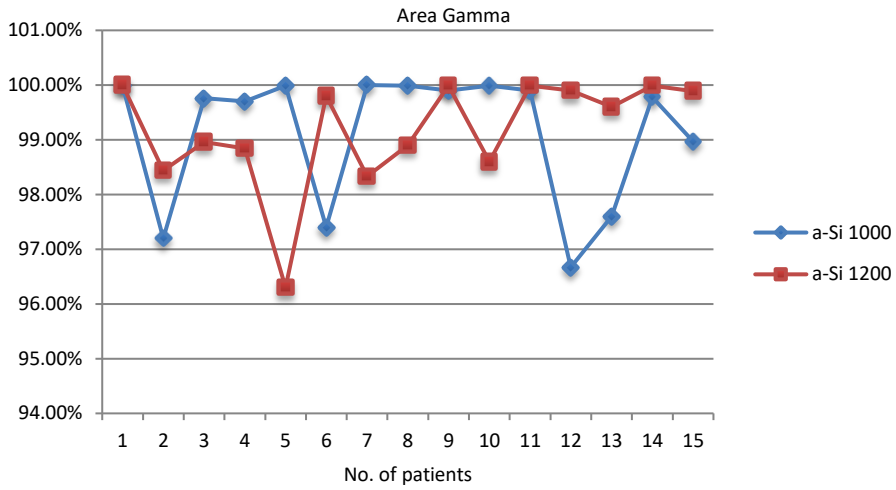

Figure 4. Area gamma evaluation performed with a-Si 1000 and a-Si 1200 detectors with 2%, 2 mm gamma (γ) evaluation criteria

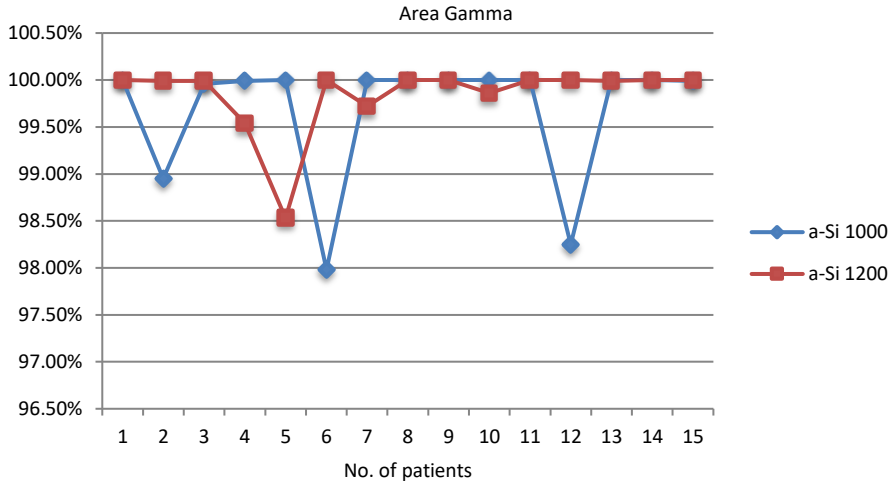

Figure 5. Area gamma evaluation performed with a-Si 1000 and a-Si 1200 detectors with 3%, 3 mm gamma (γ) evaluation criteria

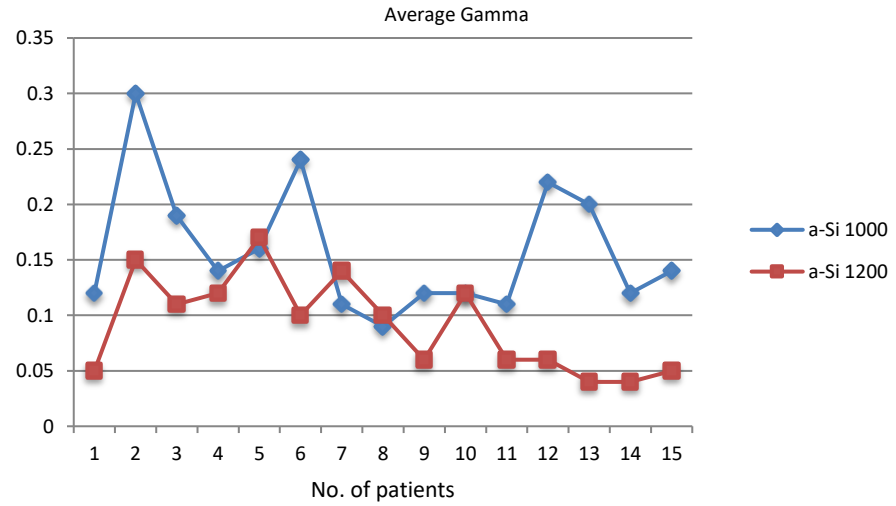

Figure 6. Average gamma evaluation performed with a-Si 1000 and a-Si 1200 detectors with 2%, 2 mm gamma (γ) evaluation criteria

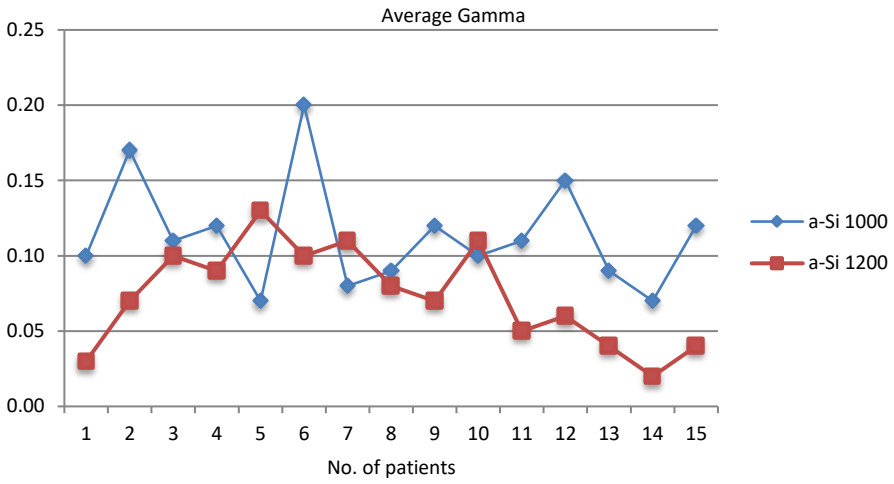

Figure 7. Average gamma evaluation performed with a-Si 1000 and a-Si 1200 detectors with 3%, 3 mm gamma (γ) evaluation criteria

Discussion

As treatment delivery techniques become more complex, thorough commissioning of treatment planning systems is essential. Low DA et al. [9] (1998) introduced an extension of isodose comparison tools that simultaneously integrates a method based on dose difference and distance to agreement. Evaluations of DD and DTA complement each other, enhancing the quality assessment of dose distribution calculations. In regions of low gradient, doses are directly compared by establishing acceptable gamma evaluation criteria. Conversely, in high-gradient regions, errors in either calculated or measured doses may result in significant dose differences.

Prior to commencing this study, all quality assurance procedures were conducted in accordance with recommendations from the American Association of Physicists in Medicine (AAPM) Task Group (TG)-142 report, with additional imager quality assurance performed as outlined by Sua et al. (2006) [10,11]. This study aims to evaluate the repetitive accuracy of dose delivery for head and neck cancer cases throughout the treatment course, involving analysis of 942 fluence maps.

In recent years, numerous investigations have explored the feasibility of transit dosimetry for intensity-modulated radiation therapy and volumetric-modulated arc therapy plans. Due to the complexity of these plans, such as beam modulation through varying multileaf collimator leaf positioning, dose rate, and gantry speed, it is imperative to develop comprehensive testing protocols for commissioning and quality assurance. Van Esch et al. [12] (2004) and Ling et al. [13] (2008) developed procedures to assess the synchronization of the monitor unit (MU) and MLC position with gantry angle. However, reliance solely on machine log files, as highlighted by Agnew et al. [14] (2014) and Pasler et al. [15] (2015), may not be sufficient to detect certain errors, necessitating alternative methods such as EPID-based in-vivo dosimetry.

A study was conducted on implementing Electronic Portal Imaging Device transit dosimetry to measure dose distributions at a plane behind the patient during radiotherapy treatment. The research addressed various dosimetric challenges, including artifacts caused by radiation backscatter. The study validated a transit dosimetry algorithm using both phantom and clinical studies, demonstrating high accuracy in dose measurements and significant potential for clinical application [16].

Another investigation focused on the use of EPID-based transit dosimetry for Volumetric Modulated Arc Therapy in a clinical setting. This research involved analyzing EPID transmission fluence maps to identify positional errors during treatment, demonstrating the utility of EPID for in vivo dosimetry in head and neck cancer treatments. The study emphasized the importance of EPID's real-time verification capabilities, which are crucial for ensuring accurate treatment delivery and detecting deviations from the planned dose [17].

Furthermore, the integration of machine learning techniques, such as convolutional neural networks (CNNs), has been explored to enhance the error detection capabilities of EPID-based dosimetry systems. These advanced models have shown promise in identifying treatment errors and improving the overall robustness of the dosimetry process [18].

Gamma (γ) analysis compares the delivered dose point-by-point to the TPS-calculated dose based on DD and DTA criteria. This method, commonly used for fluence verification, is particularly crucial for ensuring accurate dose delivery in advanced treatment techniques like VMAT. During treatment, neither image-guided radiotherapy nor any pre-treatment patient-specific quality assurance is effective in detecting these changes. Transit images acquired in every fraction were compared to those of the first fraction using the global gamma (γ) index with the portal dosimetry tool [19,20].

AAPM TG-119 recommends a γ index consisting of 3%, 3 mm criteria with a 90% passing rate, which is widely accepted [21]. AAPM TG-218 provides

comprehensive guidelines for the use of the γ index analysis method for patient-specific quality assurance (PSQA) [22]. According to the Eclipse® treatment planning system manual, after alignment, when applying gamma criteria of 4%, 4 mm for evaluation between portal dose calculation (PDC) and measurement, the results should be within the acceptance criteria for >95% [23].

Different pre-treatment QA systems can detect errors during complex dose delivery. EPID-based in-vivo dosimetry shows promise in identifying potential errors that may go undetected through pre-treatment verification processes [24,25]. Mijnheer et al. [26] (2018) demonstrated the potential benefits of EPID-based transit dosimetry for detecting errors during VMAT delivery.

Rasaei and Rooshenas (2018) [27] assessed a rapid EPID-based dosimetry technique for Intensity-Modulated Radiation Therapy and compared it with a 3D EPID-based dosimetry system. The study included a comparison with conventional two- and three-dimensional detectors for Volumetric Modulated Arc Therapy. The results indicated that the fast EPID-based dosimetry method provided accuracy and efficiency on par with the 3D EPID-based system, while offering the advantage of faster processing times. This suggests that the fast method could serve as a reliable alternative for routine dosimetric verification, potentially streamlining workflows in radiation therapy departments by reducing verification time without compromising precision.

Nigam, Kumar, and Singh (2022) [28] conducted a study comparing patient-specific quality assurance for 6 MV and 10 MV Volumetric Modulated Arc Therapy plans at the isocenter, utilizing an improved gamma evaluation algorithm. The results indicated that both 6 MV and 10 MV VMAT plans achieved clinically acceptable dosimetric accuracy using the improved gamma evaluation method. However, 6 MV plans generally exhibited slightly higher gamma passing rates compared to 10 MV plans. This suggests that while both energy levels are effective, 6 MV may offer slightly greater precision in certain patient-specific QA assessments when evaluated with the improved gamma algorithm.

In this study, we investigated the feasibility of transit dosimetry using a-Si 1000 and a-Si 1200 detectors, considering parameters such as MLC position, varying dose rate, and gantry speed. Gamma (γ) analysis was performed using stringent 2%, 2 mm, and 3%, 3 mm criteria for all patients. This approach is considered stringent because the first day's fluence was considered as the baseline value, incorporating uncertainty within the rest of the treatment course. A consistency check was performed for the remaining fraction of treatment, with values of area gamma <1 and average gamma with standard deviation (SD) evaluated for each treatment field (a total of 942 fluence maps) for all 30 patients. The results demonstrate agreement with specified tolerances throughout the treatment course. According to Tables 3 and 4, the Area Gamma for a-Si 1200 is higher than a-Si 1000, and the average gamma for a-Si 1200 is lesser than a-Si 1000.

Despite the limited number of cases in this study, this dosimetric strategy proves to be an effective means of tracking the accuracy of dose delivery, particularly in identifying errors that may occur during VMAT delivery. If anomalies are observed during treatment, investigations can be conducted promptly to correct them for possible reasons [29].

This study indicates that EPID-based transit dosimetry is a feasible and effective method for verifying dose delivery in VMAT for head and neck cancer, balancing accuracy and clinical efficiency. Future research and advancements in this area are expected to enhance its clinical applicability further and improve patient safety.

Conclusion

A feasibility study was conducted to assess transit dosimetry using electronic portal imaging devices in volumetric-modulated arc therapy for head and neck cancer treatment, employing two different detectors, namely a-Si 1000 and a-Si 1200 (utilizing C-arm and O-ring gantry linear accelerators). The aim was to detect errors in dose delivery throughout the entire treatment regimen. Gamma (γ) analysis was employed to compare the baseline and successive measured fluence maps, revealing no variation for either detector. This method of in-vivo dose verification offers simplicity in clinical application, instilling confidence in accurate dose delivery to patients without additional time consumption or increased patient dose.

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