ORIGINAL ARTICLE

Feasibility of Patient Quality Assurance Method Based on Log File and Onboard Detector in Helical Tomotherapy Technique

Ghazal Etemadi [1], Ahmad Mostaar [1,2*], Payam Azadeh [3], Niloofar Yousefi Moteghaed [1]

[1] *Department of Medical Physics and Biomedical Engineering, Shahid Beheshti University of Medical Sciences, Tehran, Iran*

[2] *Radiation Biology Research Center, Iran University of Medical Sciences, Tehran, Iran*

[3] *Department of Radiation Oncology, School of Medicine, Shahid Beheshti University of Medical Sciences, Tehran, Iran*

*Corresponding Author: Ahmad Mostaar

Email: mostaar@sbmu.ac.ir

Received: 25 May 2024 / Accepted: 15 October 2024

Abstract

Purpose: The phantom-less Patient-Specific Quality Assurance (PSQA) for Intensity-Modulated Radiotherapy (IMRT) plan verification has been exploited recently. This study aimed to evaluate the feasibility of PSQA based on log files and onboard detectors for prostate patients in helical tomotherapy.

Materials and Methods: For 15 prostate patients, the Quality Assurance (QA) of the helical tomotherapy plan was performed using the Delta4 phantom and Cheese phantom to evaluate the spatial dose distribution and point dose, respectively. These parameters were also reconstructed by Delivery Analysis (DA) software using measured Leaf Open Times (LOTs). Gamma analysis and relative dose difference were used to compare the measured and reconstructed doses with the calculated values. Then, using the relative discrepancy, the log file and onboard detector data were compared to the expected data to assess machine performance.

Results: The mean relative dose difference was within 1.3% among the measurement, reconstruction, and calculation. Statistical analysis and p-value results indicated that there was no statistically significant difference in the dose difference between the DA-based and conventional QA methods. The gamma values for the DA-based QA method were similar to the measurement QA method for the criteria 3%/3mm, 3%/2mm, 2%/3mm, 2%/2mm, 2%/1mm, and 1%/1mm. However, the gamma values for the criteria 3%/1mm, 1%/3mm, and 1%/2mm were comparable. The mean percentage difference in LOTs was 0.07%, with most discrepancies occurring in very low and some high LOTs. The relative difference between the log file and expected data was lower than 2.30% for the couch speed, couch movement, monitor unit, and gantry rotation per minute.

Conclusion: The DA software is an efficient alternative to measurement-based PSQA methods. However, the accuracy of the DA software requires further investigation for gamma analysis with strict criteria. The very low and high LOTs may lead to the dose discrepancy. The tomotherapy machine can accurately implement the planned parameters.

Keywords: Tomotherapy; Patient-Specific Quality Assurance; Prostate Cancer; Log File; Onboard Detector; Delivery Analysis Software.

DOI:

1. Introduction

Intensity-Modulated Radiation Therapy (IMRT), as one of the modern radiotherapy techniques, offers higher dose adaptation to target volumes while decreasing the dose to Organs At Risk (OAR) [1]. Patient-Specific Treatment Quality Assurance (PSQA) is an essential component of the treatment process, ensuring that the delivered dose aligns with the treatment plan [2, 3].

Because tomotherapy devices include various continuously moving parts during treatment, such as the gantry, treatment couch, binary Multileaf Collimator (MLC), and jaws, PSQA plays an even more significant role in this modality [4, 5].

Conventionally, phantom-based PSQA is performed before the patient using phantoms such as Mapcheck, Octavius, Delta4, Electronic Portal Iimaging Device (EPID), and Cheese phantom with arrays of dosimeters, ion chambers, or films [6-10]. Gamma analysis is used as a standard parameter for evaluating differences between the calculated and measured dose distributions. If the gamma pass rate is unacceptable, a new treatment plan should be planned and the PSQA procedure should be repeated [10, 11]. These methods have some drawbacks, such as being time-consuming, requiring accurate phantom setup, and requiring access to the treatment machine.

Additionally, they cannot accurately identify the cause of errors, transfer plan errors, beam delivery errors, or dose calculation errors within the Treatment Planning System (TPS).

Also, some errors related to the detector array may occur owing to inhomogeneous response and calibration issues. One of the essential limitations is the treatment plan evaluation using homogeneous phantoms whereas the heterogeneity of the patient is not considered. The phantom-based methods only evaluate the dose within a limited area or plate where measurement instruments are located.

As an alternative method, utilizing log file data produced by the treatment machine has recently been proposed [12-16]. This file contains data including output, gantry angles, and couch positions, as well as pressure and temperature values.

Using this data, the accurate dose delivery and proper machine performance can be verified, and the actual delivered dose can be reconstructed. This method offers more accurate and detailed information on device performance and the actual dose distribution in patients, overcoming the limitations of conventional methods. Owing to the rapid opening and closing of the leaves, any malfunction can result in errors in the delivered dose. Therefore, MLC verification is essential. Unlike the log file of the linear accelerators, the tomotherapy log files do not store the MLC positions and the Leaf Open Times (LOTs) sinograms [17-20]. These data can be extracted from a Megavoltage Computed Tomography (MVCT) detector and sent to the Delivery Analysis (DA) software workstation through an integrated Data Management System (iDMS). The DA software can retrieve actual LOTs and assess any differences in MLC performance. Furthermore, the dose distribution can be reconstructed based on the measured LOTs in the primary patient CT [21, 22]. Prostate cancer is one of the most common cancers in men, and with its timely and early diagnosis, it is possible to get a higher treatment gain. External radiotherapy with advanced techniques such as tomotherapy is one of the suitable methods for prostate cancer treatment. In this study, the capability of the DA software to reconstruct dose distribution for prostate treatment plans was assessed using gamma pass rates at various tolerance levels that other authors have not verified. The reconstructed dose distribution and point dose were compared with the Delta4 and Cheese phantom measurements. Additionally, the measured LOTs and log file data were verified.

2. Materials and Methods

2.1. Treatment Unit

In this study, all patients were treated with the Radixact X9 tomotherapy system (Accuray, Sunnyvale, CA, USA), which produced a 6 MV flattening filter-free (FFF) beam at a dose rate of 1025 cGy/min. Figure 1a shows the tomotherapy machine used in this study. Tomotherapy has an MLC with 64 binary, pneumatically driven leaves. For 15 prostate patients, helical tomotherapy (HT) plans were generated using the Accuray Precision treatment planning system (version 2.0.1.1) with a dose

prescription of 70 Gy in 28 fractions. The plans were set with a pitch of 0.35, a Modulation Factor (MF) of 2, and a field width of 2.5 cm in dynamic jaw mode.

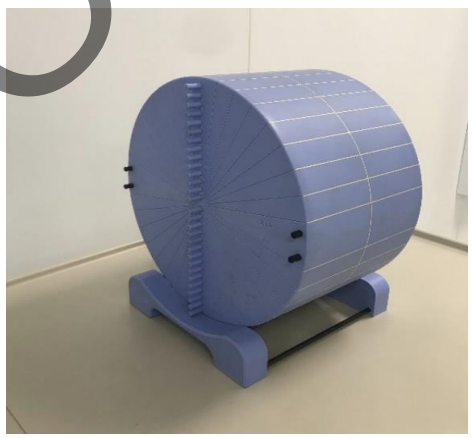
2.2. Point Dose Measurement

The Cheese phantom (Accuracy, Inc., Sunnyvale, USA), a cylindrical virtual water phantom, was used for the point dose measurement using a calibrated 0.053 cc Exradin A1SL ion chamber (Standard Imaging, Inc. Middleton, WI, USA) and a Tomoelectrometer (Standard Imaging, Inc. Middleton, WI, USA). Figures 1b and 1c show the devices used for the point-dose measurement in this study. To evaluate the accuracy of the delivered dose on a point-by-point basis, the dose at a specified point in the treatment plan was compared with that at a corresponding point in the Cheese Phantom. This point was selected within the high-dose region of the Planning Target Volume (PTV). To avoid error occurrence, due to sensitivity to positioning and the volume averaging effect, the selected point should not be located in the regions with high dose gradients.

2.3. Dose Distribution Measurement

A Delta4 phantom (ScandiDos, Madison, WI, USA) was used to measure the dose distribution (Figure 1d). It comprises 1069 p-type diodes with a 0.4 cm resolution at the center, arranged in a matrix along two orthogonal planes. To evaluate the accuracy of the delivered dose as a three-dimensional distribution, the Quality Assurance (QA) plan was delivered to the Delta4 phantom. The measured dose distribution was then compared with the calculated dose distribution based on the gamma passing rate.

(a)



(b)

(c)

(d)

Figure 1. A picture of the tomotherapy machine, phantom, and dosimetry equipment used in this study, including (a) Tomotherapy Radixact X9, (b) Chesse phantom, (C) Tomoelectrometer and A1SL chamber, and (d) Delta4 phantom

2.4. MVCT Detectors

The tomotherapy machine includes an array of parallel plate ionization chambers with pressurized xenon-filled cavities, separated by stainless steel septa, and housed in an aluminum case. The detectors are single slices consisting of 640 channels, providing an imaging Field Of View (FOV) of 39.4 cm at the isocenter. In addition, these detectors were connected to a data acquisition system.

2.5. Delivery Analysis (DA) Software

This software can be used for both pretreatment and treatment evaluation. In pretreatment assessment, the software can verify the accuracy of MLC performance and independently reconstruct the dose distribution based on the measured LOTs sinogram. Additionally, during the treatment, the software can identify variations in patient setup and anatomy between treatment fractions.

2.6. Methods

To verify the delivered dose and obtain the measured point dose and dose distribution, QA plans were delivered in the Cheese and Delta4 phantoms for all treatment plans.

The treatment planning data was transferred to the QA template plan, and the dose was calculated on CT images of phantoms. For the point dose measurement, the dose corresponding to a specific hole in the Cheese phantom was obtained, ensuring that the point was not in a high-dose gradient region. The QA plan was exposed to the Cheese phantom, and the point dose was measured using an ion chamber accurately positioned within the calculated dose volume. For dose distribution measurement, RT dose and RT structure data were extracted and transferred to Delta4 gamma analysis software, and the QA plan was exposed to the phantom to measure dose distribution.

Furthermore, the QA plans were exposed once in the air to obtain the reconstructed point dose and the dose distribution based on the measured LOTs using the DA software. It should be noted that the DA software uses onboard detector information to measure the LOTs sinogram. The relative dose difference (within $\pm$3%) was calculated between the (a) planned and measured point doses, (b) planned and reconstructed point doses, and (c) measured and reconstructed point doses. The relative dose differences between the proposed and conventional methods were compared using the Wilcoxon signed ranks test. Also, the 3D gamma pass rate with passing criteria of 3%/3 mm, 3%/2 mm, 3%/1 mm, 2%/3 mm, 2%/2 mm, 2%/1 mm, 1%/3 mm, 1%/2 mm,1%/1 mm, and an acceptance rate above 95% was employed to compare the planned dose distribution with the measured and reconstructed dose distributions. These comparisons were performed to verify the accuracy of the reconstructed dose derived from the measured LOTs using the DA software, as well as to assess the ability of the DA software to detect discrepancies. In Addition, the gamma analysis was performed for different organs in the reconstructed dose distribution. The discrepancy between the planned and measured LOTs was then assessed using a percentage difference LOTs sinogram comparison to evaluate MLC performance. This comparison involved subtracting the planned sinogram from the reconstructed LOTs sinogram and displaying the result as a percentage of the planned LOTs value. Finally, actual data related to coach speed, coach movement, Monitor Unit (MU), and Rotation Per Minute (RPM) of the gantry were collected from the log file generated at the treatment delivery station. The relative discrepancy between these values and TPS data was then calculated.

3. Results

3.1. Point Dose Delivery Verification

The comparison of the planned, measured, and reconstructed point dose is presented in Figures 2 and 3. The mean relative dose difference with standard deviation (SD) was (a) 1.50% (SD = 0.77%) ranged from 0.37% to 2.74% between the measured and calculated point dose, (b) 1.21% (SD = 0.95%) ranged from 0.00% to 2.64% between the reconstructed and calculated point dose, and (c) 1.19% (SD = 0.64%) ranged from 0.00% to 2.67% between the measured and reconstructed point dose. The mean relative dose difference with standard deviation is presented in Table 1. The pvalue of the relative dose differences was 0.510 between the DA-based and conventional QA methods.

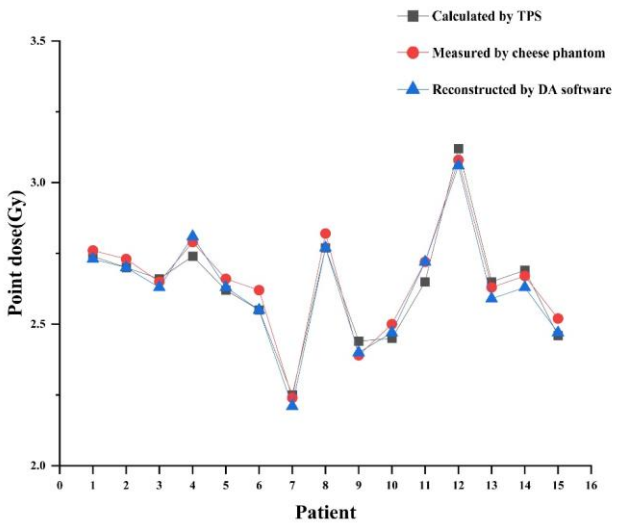


Figure 2. Comparison of the calculated, measured, and reconstructed point dose for all patients

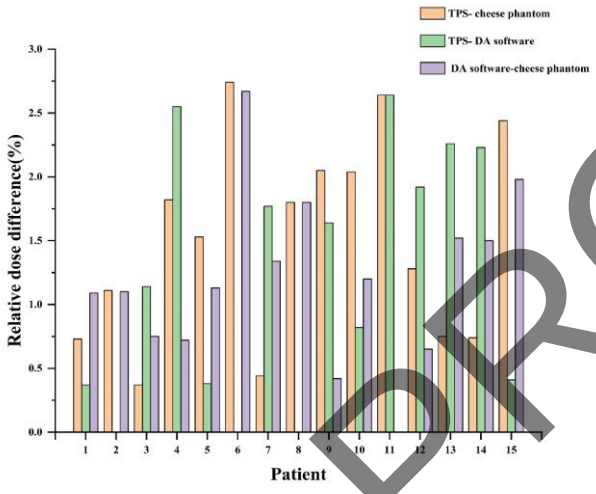


Figure 3. Comparison of the relative point dose differences between calculated by TPS and measured by Cheese phantom, calculated by TPS and reconstructed by DA software, reconstructed by DA software and measured by Cheese phantom for all patients

3.2. Dose Distribution Delivery Verification

The mean gamma pass rate for acceptance criteria of 3%/3 mm was 100% (SD = 0.00%) between the measured and planned dose distribution and 99.53% (SD = 1.31%) between the reconstructed and planned dose distribution. The percentage of gamma passing with 3%/2 mm, 2%/3 mm, and 2%/2 mm tolerances for the DA-based QA method were consistent with those of Delta4 and were higher than 95%. However, the results did not meet the acceptance criteria, falling below 95% for both the 1%/1 mm and 2%/1 mm criteria in the DA-based and Delta4-based QA methods. In contrast, the gamma analysis results with 3%/1 mm, 1%/3 mm, and 1%/2 mm tolerances differed between the QA methods. The relevant results are shown in Figure 4.

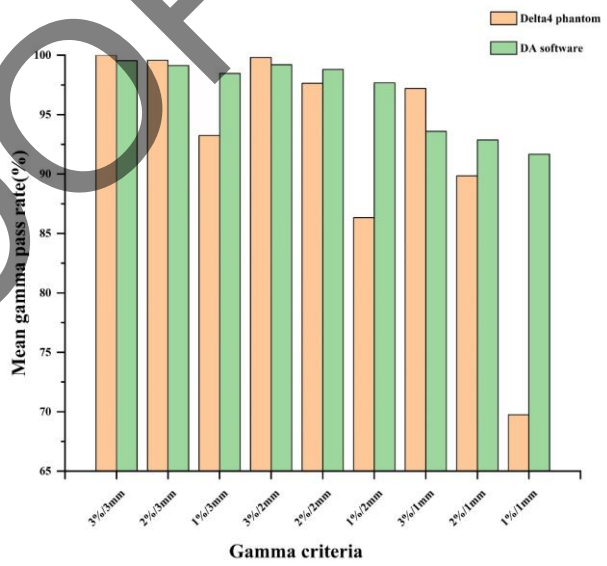


Figure 4. Comparison of the mean gamma analysis for different tolerances between the measured dose distribution by Delta4 phantom and reconstructed dose distribution by DA software for all patients

Table 1. Comparison of relative dose difference between the calculated, measured, and reconstructed point dose for all patients

	Relative dose difference (%)		
	TPS-Cheese phantom	**TPS-DA software**	**DA software-Cheese phantom**
Mean relative dose difference	**1.50%**	**1.21%**	**1.19%**
Standard deviation	**0.77%**	**0.95%**	**0.64%**

In the reconstructed dose distribution, the gamma passing rate with different tolerances was evaluated for the Planning Target Volume (PTV), bladder, rectum, right femur, and left femur. In general, stricter tolerances resulted in a decreased gamma passing rate. As shown in Figure 5, the variation in gamma values was lower in the bladder and higher in the rectum compared to other organs. The gamma passing rates of the left and right femurs were approximately equal.

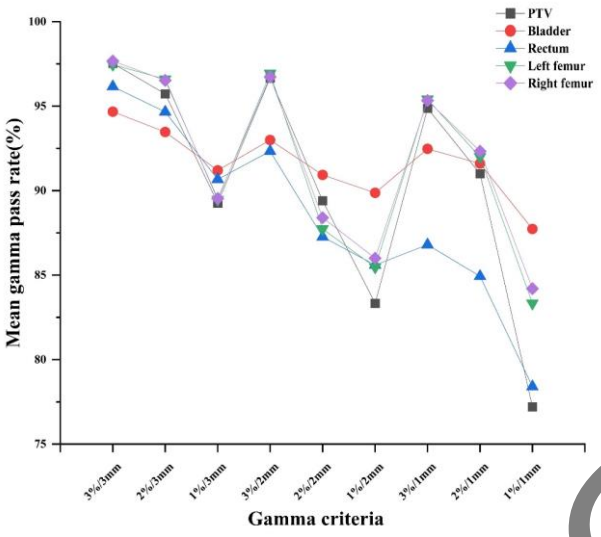


Figure 5. Comparison of mean gamma analysis for different tolerances between the reconstructed dose distribution by DA software and calculated dose distribution by TPS for PTV, Bladder, Rectum, Left femur, and Right femur for all patients

3.3. The Measured Sinogram Verification

The mean percentage difference in LOTs comparison between the planned and measured LOTs was 0.07% (standard deviation = 0.10%), and ranged from -0.029% to 0.087%. Most differences were observed at the edges of the sinogram, hence at the beginning and end of each projection. These differences mostly occurred in very low LOTs, ranging from 0.04% to 0.07%, and in some high LOTs between 0.73% and 0.99%. A sample of the percentage difference LOTs sinogram comparison for one of the patients is shown in Figure 6.

3.4. Log File Data Verification

The relative differences were reported as follows: (a) 1.11%–1.94% for couch movement, (b) 0.00%–2.30% for couch speed, (c) 0.54%–1.23% for MU, and

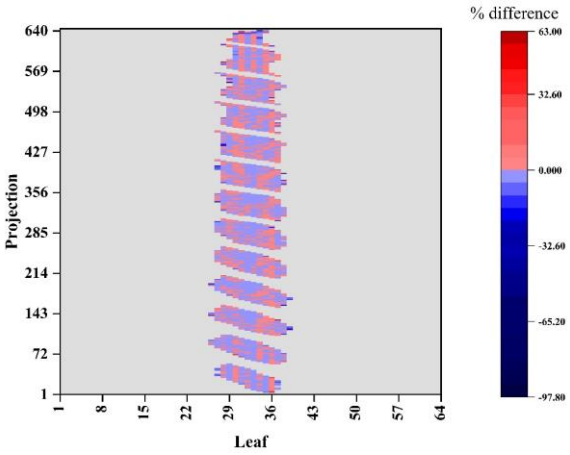


Figure 6. The percentage difference LOTs sinogram comparison for one of the patients. It displays the percentage difference between the planned and measured LOTs sinogram. Red indicates a positive difference, where the measured sinogram data has a higher value than the planned data. Blue indicates a negative difference, where the measured sinogram data has a lower value than the planned data. The difference of zero is gray in the sinogram view

(d) 0.10%–0.27% for gantry RPM. The mean (standard deviation) relative differences were 1.54% (0.24%) for couch movement, 0.39% (0.70%) for couch speed, 1.12% (0.22%) for MU, and 0.18% (0.05%) for gantry RPM. For better visualization, the data is presented as a graph in Figure 7.

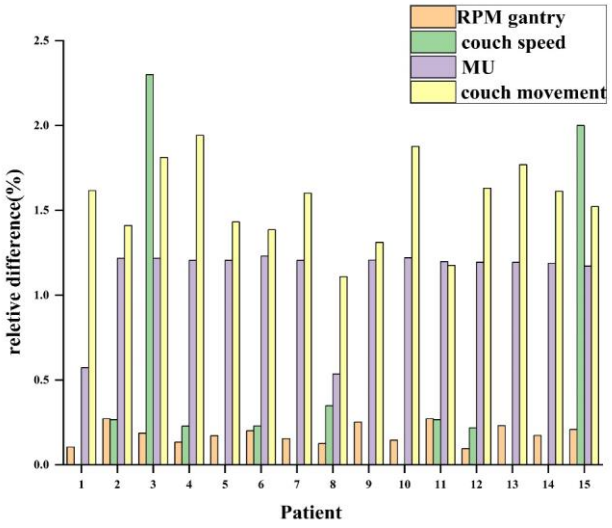


Figure 7. Histogram of relative differences (%) values for gantry RPM, couch speed, MU, and couch movement between TPS and Log File data for all patients

4. Discussion

The ability of the DA software to reconstruct the dose distribution and point dose was validated by comparing it with Delta4 and Cheese phantom measurements. The DA software can provide precise results faster than the conventional methods because it does not require measurement devices, which consist of errors such as setup errors and inherent errors from the phantoms, films, or chambers. To evaluate the machine performance, measured LOTs and log file data were compared with the TPS data. In this study, the reconstructed point dose corresponded well with the measured value within 1.19%. This has been previously validated by other authors [17, 18, 23, 24]. On the other hand, the pvalue of 0.510 showed no statistically significant difference between the measurement and reconstruction dose difference. Chung *et al.* also reported the same conclusion [23]. The gamma pass rate results for acceptance criteria 3%/3 mm and 2%/2 mm were consistent with the results of Thiyagarajan *et al.* [24]. Furthermore, for acceptance criteria 3%/2 mm, 2%/3 mm, 2%/1 mm, and 1%/1 mm, the consistent results between the Delta4 and DA software gamma analysis further indicate the accuracy of the DA software. However, for 3 of 15 patients, the gamma passing rates of 1%/3 mm, and 1%/2 mm acceptance criteria were passed in the DA-based QA method but failed in the conventional method. These results were opposite for the acceptance criteria of 3%/1 mm; it was satisfied in the Delta4-based QA method but failed in the DA-based QA method. So further investigations should be done in these acceptance criteria. For all patients, the gamma value for the acceptance criteria of 3%/3mm was 100% for Delta4 gamma analysis. It showed the precise performance of the tomotherapy machine in the correct implementation of physical parameters, unlike other accelerator devices. Regarding the reconstructed LOTs sinogram, most differences occurred in the low LOTs, with some discrepancies noted in high LOTs as well. These results are consistent with the results reported by Kim and Chang [25, 26]. A linear relation has been reported between the mean relative LOT difference and the dose deviation in the PTV by Deshpande *et al.* [20]. The LOTs below 100 ms are recognized as a plan parameter impacting pre-treatment QA outcomes. The presence of a long bar at the end of the LOTs histogram, indicating numerous leaves with high LOTs, may potentially result in MLC performance errors, even when the average and maximum LOTs are within the acceptable range (average > 100 milliseconds, maximum > 231 milliseconds). Moreover, most differences occurred at the edges of the sinogram, representing the peripheral leaves at the beginning and end of each projection. As Kim *et al.* mentioned in previous research, these leaves exhibit two physical properties. They are located in the penumbra area and constitute the primary source of beam scattering [26].

The accuracy of the delivered dose depends on the accuracy of the machine in implementing parameters planned for the TPS. To evaluate the machine performance accuracy, the recorded data by the log file were assessed with those of the TPS, revealing consistency between the two datasets. In the evaluation of several treatment fractions, Handsfield *et al.* reported that the gantry angles and couch positions recorded by the data acquisition system (DAS) corresponded accurately with the TPS values [17]. Kim *et al.* utilized the Cheese phantom and the film dosimetry as the measurement device for the conventional QA method, which is not able to measure the 3D dose distribution. Therefore, to obtain more robust measurement results, we envision that one can conduct additional experiments using array-based devices in the future. Mobius3D utilizes a simplified version of the dose calculation algorithm (simplified collapsed cone convolution algorithm). Because the DA software reconstructs the dose based on TPS data, further investigations are needed to verify dose calculation accuracy using secondary dose software that matches the primary TPS in terms of performance. Due to the need for further studies on stricter criteria and the inability to independently calculate dose from the primary TPS, this software has not yet been clinically implemented. Previous research has used the collapsed cone convolution algorithm of Mobius3D, which is simpler than the precision TPS [15, 26].

5. Conclusion

This study assessed a PSQA approach based on the measured LOTs by the DA software and the log file data. Phantom-less methods through software with the capability of dose reconstruction independently from

the primary TPS is a validated approach for PSQA. The DA software is one such software. It has proven to be an accurate software for evaluating delivered doses, although further research is needed to assess its performance gamma analysis with acceptance criteria of 3%/1 mm, 1%/3 mm, and 1%/2 mm. Data recorded by the log file and onboard detector are important and reliable indicators for evaluating the machine's performance.

Acknowledgment

We would like to thank the medical physicists in Imam Hossein Hospital's radiotherapy department who willingly helped to collect the data.

References

1- L. Bogner, J. Scherer, M. Treutwein, M. Hartmann, F. Gum, and A. Amediek, "Verification of IMRT: techniques and problems." (in eng), *Strahlenther Onkol*, Vol. 180 (No. 6), pp. 340-50, Jun (2004).

2- G. A. Ezzell *et al.*, "Guidance document on delivery, treatment planning, and clinical implementation of IMRT: report of the IMRT Subcommittee of the AAPM Radiation Therapy Committee." (in eng), *Med Phys*, Vol. 30 (No. 8), pp. 2089-115, Aug (2003).

3- A. C. Hartford *et al.*, "American College of Radiology (ACR) and American Society for Radiation Oncology (ASTRO) Practice Guideline for Intensity-modulated Radiation Therapy (IMRT)." (in eng), *Am J Clin Oncol*, Vol. 35 (No. 6), pp. 612-7, Dec (2012).

4- J. Balog and E. Soisson, "Helical tomotherapy quality assurance." (in eng), *Int J Radiat Oncol Biol Phys*, Vol. 71 (No. 1 Suppl), pp. S113-7, (2008).

5- K. M. Langen *et al.*, "QA for helical tomotherapy: report of the AAPM Task Group 148." (in eng), *Med Phys*, Vol. 37 (No. 9), pp. 4817-53, Sep (2010).

6- D. Létourneau, M. Gulam, D. Yan, M. Oldham, and J. W. Wong, "Evaluation of a 2D diode array for IMRT quality assurance." (in eng), *Radiother Oncol*, Vol. 70 (No. 2), pp. 199-206, Feb (2004).

7- V. Feygelman, D. Opp, K. Javedan, A. J. Saini, and G. Zhang, "Evaluation of a 3D diode array dosimeter for helical tomotherapy delivery QA." (in eng), *Med Dosim*, Vol. 35 (No. 4), pp. 324-9, Winter (2010).

8- Shinhaeng Cho *et al.*, "Patient QA System Using Delta⁴ Phantom for Tomotherapy: A Comparative Study with EBT3 Film." *Journal of Korean Physical Society*, Vol. 74pp. 816-21, April 01, 2019 (2019).

9- Y. H. Yoon *et al.*, "Development of Automated Delivery Quality Assurance Analysis Software for Helical Tomotherapy." *Technology in Cancer Research & Treatment*, Vol. 22p. 15330338231175781, 2023/01/01 (2023).

10- D. A. Low, W. B. Harms, S. Mutic, and J. A. Purdy, "A technique for the quantitative evaluation of dose distributions." (in eng), *Med Phys*, Vol. 25 (No. 5), pp. 656-61, May (1998).

11- L. Xing and J. G. Li, "Computer verification of fluence map for intensity modulated radiation therapy." (in eng), *Med Phys*, Vol. 27 (No. 9), pp. 2084-92, Sep (2000).

12- D. W. Litzenberg, J. M. Moran, and B. A. Fraass, "Verification of dynamic and segmental IMRT delivery by dynamic log file analysis." (in eng), *J Appl Clin Med Phys*, Vol. 3 (No. 2), pp. 63-72, Spring (2002).

13- Wojciech Osewski *et al.*, "Clinical examples of 3D dose distribution reconstruction, based on the actual MLC leaves movement, for dynamic treatment techniques." *Reports of Practical Oncology & Radiotherapy*, Vol. 1911/01 (2014).

14- M Dinesh Kumar, N Thirumavalavan, D Venugopal Krishna, and M Babaiah, "QA of intensity-modulated beams using dynamic MLC log files." *Journal of Medical Physics*, Original Article Vol. 31 (No. 1), pp. 36-41, January 1, 2006 (2006).

15- T. Kodama, Y. Saito, S. Hatanaka, M. Hariu, M. Shimbo, and T. Takahashi, "Commissioning of the Mobius3D independent dose verification system for TomoTherapy." (in eng), *J Appl Clin Med Phys*, Vol. 20 (No. 5), pp. 12-20, May (2019).

16- M. C. Han *et al.*, "TomoEQA: Dose verification for patient-specific quality assurance in helical tomotherapy using an exit detector." (in eng), *Phys Med*, Vol. 82pp. 1-6, Feb (2021).

17- L. L. Handsfield, R. Jones, D. D. Wilson, J. V. Siebers, P. W. Read, and Q. Chen, "Phantomless patient-specific TomoTherapy QA via delivery performance monitoring and a secondary Monte Carlo dose calculation." (in eng), *Med Phys*, Vol. 41 (No. 10), p. 101703, Oct (2014).

18- Q. Chen, D. Westerly, Z. Fang, K. Sheng, and Y. Chen, "TomoTherapy MLC verification using exit detector data." *Med Phys*, Vol. 39 (No. 1), pp. 143-51, Jan (2012).

19- S. Deshpande, M. Geurts, P. Vial, P. Metcalfe, M. Lee, and L. Holloway, "Clinical significance of treatment delivery errors for helical TomoTherapy nasopharyngeal plans - A dosimetric simulation study." (in eng), *Phys Med*, Vol. 33pp. 159-69, Jan (2017).

20- S. Deshpande, A. Xing, P. Metcalfe, L. Holloway, P. Vial, and M. Geurts, "Clinical implementation of an exit detector-based dose reconstruction tool for helical tomotherapy delivery quality assurance." (in eng), *Med Phys*, Vol. 44 (No. 10), pp. 5457-66, Oct (2017).

21- Kazuo Tarutani, Masao Tanooka, Keisuke Sano, Okada Wataru, Masayuki Fujiwara, and Koichiro Yamakado, "Evaluation of Delivery Analysis to Detect Intrafractional Motion during Tomotherapy." *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology,* Vol. 08 (No. 04), pp. 225-35, (2019).

22- K. Tarutani, Masao Tanooka, Keisuke Sano, Wataru Okada, Masayuki Fujiwara, and Koichiro Yamakado, "Evaluation of Delivery Analysis to Detect Intrafractional Motion during Tomotherapy." *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology,* Vol. 08pp. 225-35, 01/01 (2019).

23- E. Chung, D. Kwon, T. Park, H. Kang, and Y. Chung, "Clinical implementation of Dosimetry Check™ for TomoTherapy(®) delivery quality assurance." (in eng), *J Appl Clin Med Phys,* Vol. 19 (No. 6), pp. 193-99, Nov (2018).

24- Rajesh Thiyagarajan *et al.*, "Leaf open time sinogram (LOTS): a novel approach for patient specific quality assurance of total marrow irradiation." *Radiation Oncology,* Vol. 15 (No. 1), p. 236, 2020/10/14 (2020).

25- K. H. Chang *et al.*, "Statistical Analysis of Treatment Planning Parameters for Prediction of Delivery Quality Assurance Failure for Helical Tomotherapy." (in eng), *Technol Cancer Res Treat,* Vol. 19p. 1533033820979692, Jan-Dec (2020).

26- C. Kim, M. C. Han, Y. K. Lee, H. B. Shin, H. Kim, and J. S. Kim, "Comprehensive clinical evaluation of TomoEQA for patient-specific pre-treatment quality assurance in helical tomotherapy." (in eng), *Radiat Oncol,* Vol. 17 (No. 1), p. 177, Nov 7 (2022).