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Efficient Verification of X-ray Target Replacement for the C-series High Energy Linear Accelerator

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The manufacturer of a linear accelerator (LINAC) has reported that the target melting phenomenon could be caused by a non-recommended output setting and the excessive use of monitor unit (MU) with intensity-modulated radiation therapy (IMRT). Due to these reasons, we observed an unexpected beam interruption during the treatment of a patient in our institution. The target status was inspected and a replacement of the target was determined. After the target replacement, the beam profile was adjusted to the machine commissioning beam data, and the absolute doses-to-water for 6 MV and 10 MV photon beams were calibrated according to American Association of Physicists in Medicine (AAPM) Task Group (TG)-51 protocol. To verify the beam data after target replacement, the beam flatness, symmetry, output factor, and percent depth dose (PDD) were measured and compared with the commissioning data. The difference between the referenced and measured data for flatness and symmetry exhibited a coincidence within 0.3% for both 6 MV and 10 MV, and the difference of the PDD at 10 cm depth (PDD_{10}) was also within 0.3% for both photon energies. Also, patient-specific quality assurances (QAs) were performed with gamma analysis using a 2-D diode and ion chamber array detector for eight patients. The average gamma passing rates for all patients for the relative dose distribution was 99.1%±1.0%, and those for absolute dose distribution was 97.2%±2.7%, which means the gamma analysis results were all clinically acceptable. In this study, we recommend that the beam characteristics, such as beam profile, depth dose, and output factors, should be examined. Further, patient-specific QAs should be performed to verify the changes in the overall beam delivery system when a target replacement is inevitable; although it is more important to check the beam output in a daily routine.

Keywords: Linear accelerator, Target degradation, Target melting, Beam verification, IMRT verification

Introduction

A linear accelerator (LINAC) is one of the most frequently used radiotherapy machines in which the accelerated electron collides with a tungsten target to generate the photon beam. According to a technical bulletin of the vendor (Varian Medical Systems, Palo Alto, CA, USA), they reported that the target in LINAC was melted or punctured in several institutes due to the excessive usage of monitor unit (MU) with intensity-modulated radiation therapy (IMRT) and with non-recommended output calibration setting (1 cGy/MU at a depth of 10 cm instead of a depth

of maximum dose (d_{max})). To prevent the target burning and degradation, the manufacturer established the target current monitoring system. The main role of this system is to interrupt the beam delivery when it goes over a certain tolerance level.

Therapists in our Institute experienced unusual frequent beam interrupts during patient treatment with target current monitoring system and interlock warning. The inspection followed immediately by beam output check by varying the position of electron-target hit and the maximum beam deviation was shown to be 3.8%. Technologists concluded that the target was punctured with burning, and physicists decided to replace the target. The damaged target was shown in Fig. 1.

In this study, we performed the beam verification to validate the clinically acceptable machine performance after the target replacement. Also, we measured beam flatness, symmetry, output factor, and PDD after fine beam adjustment, also a patient-specific quality assurance (QA) analysis for the end-to-end machine performance verification was performed.[1-3] Safety issue caused by the activated target was carefully concerned.

Materials and Methods

1. Beam tuning

After the target assembly replacement, the beam profiles were finely adjusted to the reference beam data. To measure the beam profile, we used the three-dimensional water phantom (Blue Phantom2, IBA dosimetry, Schwarzenbruck, Germany) plotting tank and two CC13 compact ionization chamber (IBA dosimetry, Schwarzenbruck, Germany) as a reference and field chamber, respectively. The common control unit (CCU, IBA dosimetry, Schwarzenbruck, Germany) and myQA Accept software (ver 8.0., IBA dosimetry, Schwarzenbruck, Germany) was used. Note that we verified the beam profiles for 6 MV and 10 MV photon beams as targets of two photon energies were sealed in a single vacuum tube with assemblies.

Beam profiles measured at initial machine commissioning were used as reference data. The measurement condition was as follows: source-to-surface distance (SSD) of 100 cm, reference depth of 10 cm, and field size of 35×35 cm^2. For each energy, the beam profile was finely adjusted to achieve the maximum difference between measurement and reference beam data less than 1%.

After adjusting the beam profile, output was calibrated for 6 MV and 10 MV by using 0.6 cc Farmer-type chamber (TN 30013, PTW-Freiburg, Freiburg, Germany) according to American Association of Physicists in Medicine (AAPM) Task Group (TG)-51 protocol, which is a global standard for clinical reference dosimetry of linear accelerators.[4,5]

The output was calibrated to deliver 1 cGy/MU with reference conditions; SSD of 100 cm, field size of 10×10 cm^2, and at d_{max}.

Fig. 1. The punched tungsten target.

2. Verification

According to the manufacturers beam commissioning guide, we performed the mandatory PDD measurement where the SSD of 100 cm and field size of 3×3, 6×6, 10×10, 20×20 cm^2 for each energy. We compared the coincidence between measurement and reference data with d_{max} and the PDD at 10 cm (PDD_{10}).

Crossline beam profiles were measured at SSD of 100 cm with field sizes of 3×3, 6×6, 10×10 and 20×20 cm^2 at depth of d_{max}, 5, 10, 20 and 30 cm. They were compared with machine commissioning data of field sizes mentioned above, at 10 cm depth. Both maximum differences in crossline and inline profiles, and flatness and symmetry were compared.

Output factors were measured at SSD of 90 cm and depth of 10 cm, according to equation (1).

$$\text{Output factor}=\frac{\text{output of field size X}\times\text{Y cm}^2}{\text{output of field size 10}\times\text{10 cm}^2} \quad (1)$$

The reference field size was 10×10 cm^2, and the field size varied from 3×3 cm^2 to 40×40 cm^2. Measured output factors were compared with reference data.

The patient-specific QA is the procedure to verify the coincidence between measurement and calculated dose distribution for IMRT plans by using gamma analysis.[6] Eight IMRT plans for breast cancer patients using both 6 MV and 10 MV were involved for verification. Two types of detectors were used; two-dimensional ionization chamber array detector (MatriXX, IBA dosimetry, Schwarzenbruck, Germany) and diode array detector (MapCHECK2, Sun

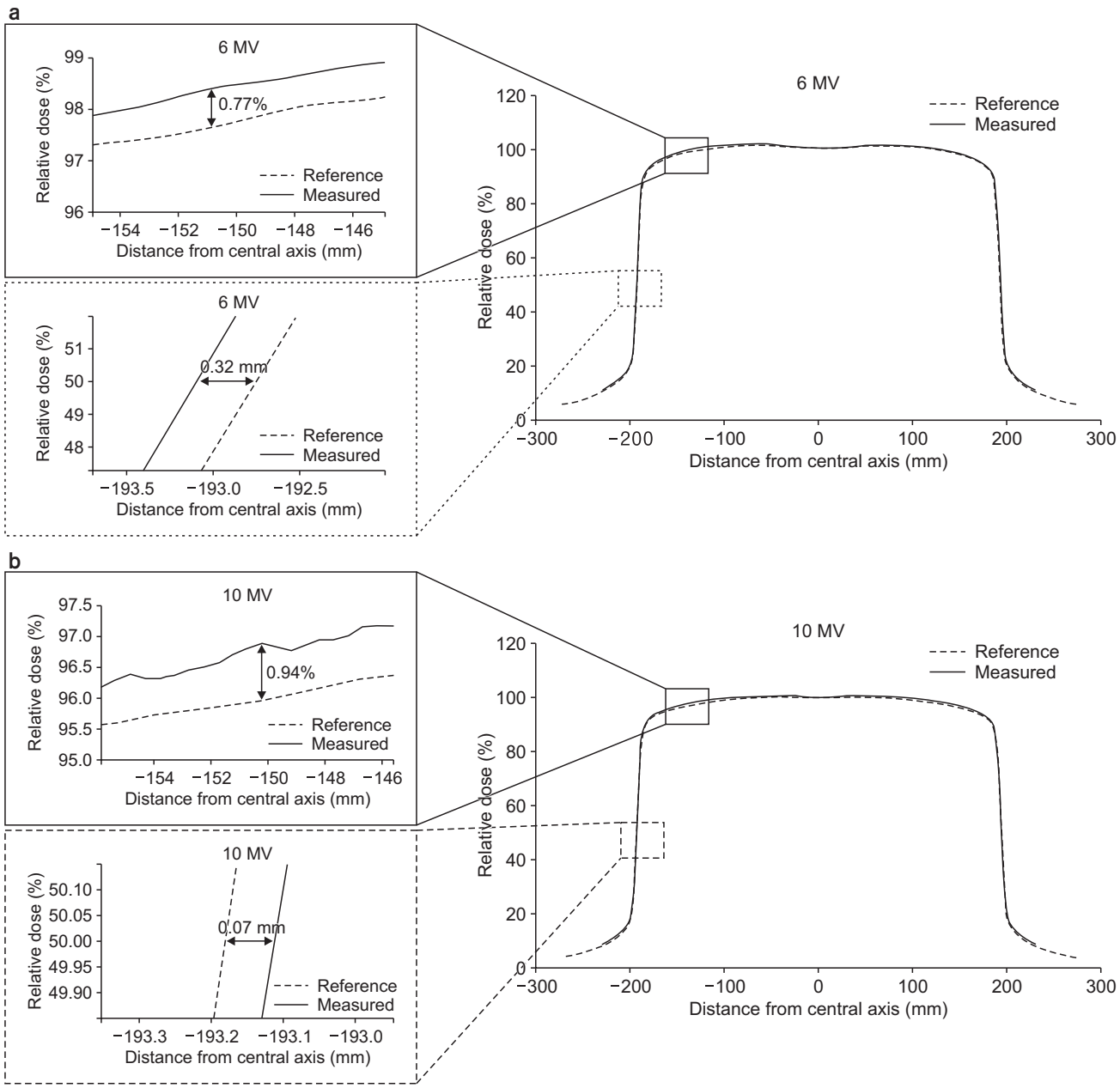

Fig. 2. Profile comparison between reference (dashed line) and measurement (solid line) for (a) 6 MV, (b) 10 MV photon beam. The measurement condition was as follows: source-to-surface distance (SSD) of 100 cm, reference depth of 10 cm, and field size of 35×35 cm^2.

Table 1. Percent depth dose at depth 10 cm (PDD_{10}) comparisons between reference and measurement for 6 MV and 10 MV photon beam.

Field Size (cm^2)	6 MV			10 MV		
	Reference	Measured	Difference	Reference	Measured	Difference
3×3	61.3%	61.3%	0.0%	71.1%	71.2%	0.1%
6×6	64.6%	64.5%	–0.1%	73.0%	73.3%	0.3%
10×10	67.3%	67.3%	0.0%	74.4%	74.6%	0.2%
20×20	70.1%	70.4%	0.3%	75.9%	76.0%	0.1%
40×40	72.7%	72.8%	0.1%	77.3%	77.5%	0.2%

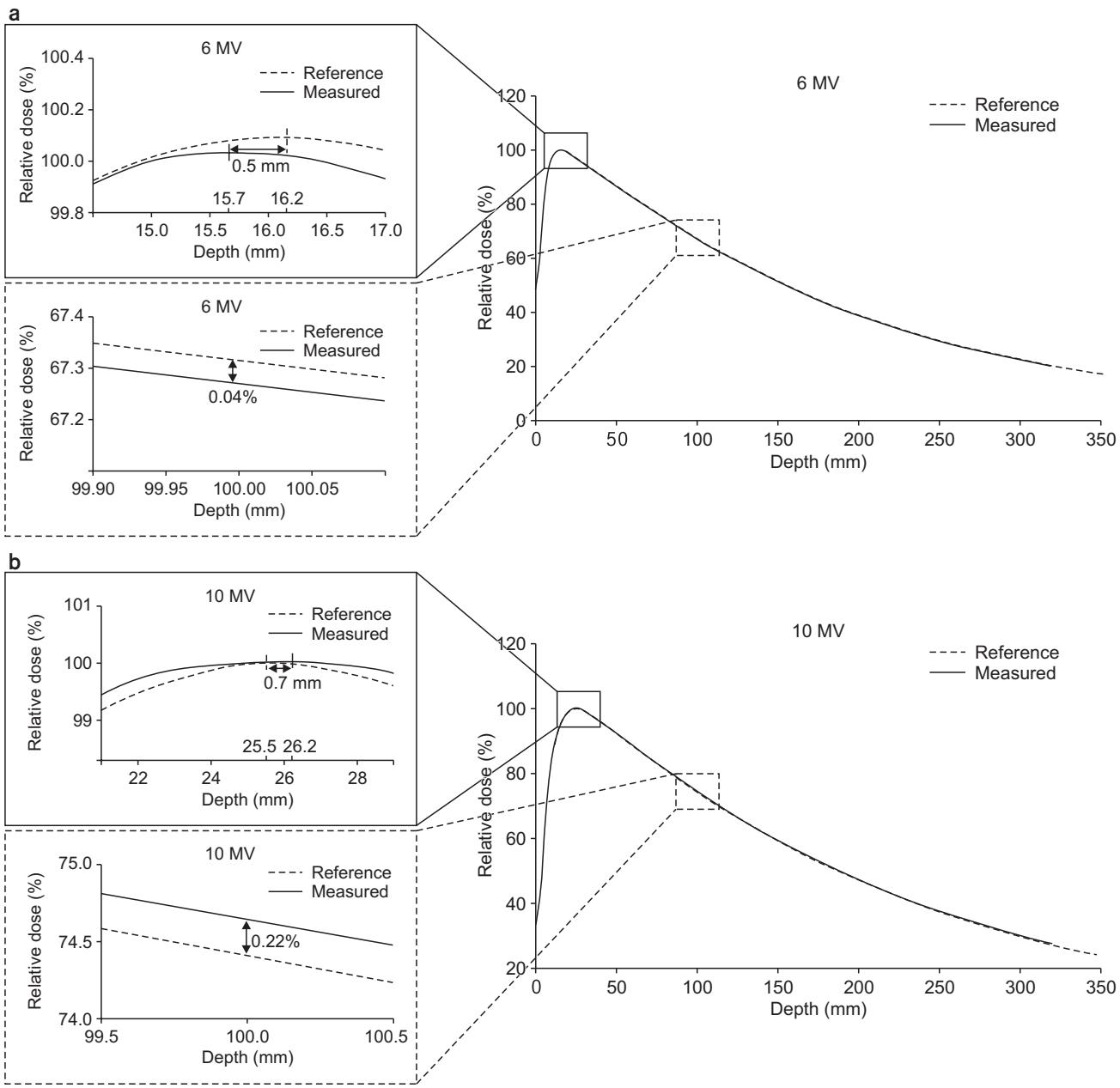

Fig. 3. Percentage depth doses comparisons between reference (dashed line) and measurement (solid line) for (a) 6 MV, (b) 10 MV.

Table 2. Flatness and symmetry comparison between reference and measurement data for different field sizes and depths for 6 MV and 10 MV photon beams.

Field Size (cm^2)	Depth (cm)	6 MV						10 MV					
		Flatness			Symmetry			Flatness			Symmetry		
		Reference	Measured	Difference	Reference	Measured	Difference	Reference	Measured	Difference	Reference	Measured	Difference
3×3	d_{max}	8.4%	7.7%	−0.7%	0.9%	0.5%	−0.4%	10.3%	9.5%	−0.8%	1.1%	0.3%	−0.8%
	5	8.6%	8.0%	−0.6%	0.8%	0.5%	−0.3%	10.4%	10.0%	−0.4%	0.8%	0.5%	−0.3%
	10	8.5%	7.8%	−0.7%	0.9%	0.3%	−0.6%	10.3%	9.8%	−0.5%	0.9%	0.3%	−0.6%
	20	8.0%	7.4%	−0.6%	1.0%	0.8%	−0.2%	9.8%	9.3%	−0.5%	0.9%	0.5%	−0.4%
	30	7.7%	7.0%	−0.7%	0.9%	0.6%	−0.3%	9.4%	8.9%	−0.5%	1.0%	0.7%	−0.3%
6×6	d_{max}	1.8%	1.7%	−0.1%	0.3%	0.5%	0.2%	3.3%	3.1%	−0.2%	0.7%	0.3%	−0.4%
	5	2.5%	2.4%	−0.1%	0.3%	0.6%	0.3%	3.9%	3.7%	−0.2%	0.7%	0.4%	−0.3%
	10	3.0%	3.0%	0.0%	0.3%	0.6%	0.3%	4.1%	4.1%	0.0%	0.7%	0.3%	−0.4%
	20	3.2%	3.2%	0.0%	0.3%	0.5%	0.2%	4.4%	4.3%	−0.1%	0.7%	0.4%	−0.3%
	30	3.3%	3.4%	0.1%	0.3%	0.3%	0.0%	4.3%	4.4%	0.1%	0.5%	0.5%	0.0%
10×10	d_{max}	1.1%	1.0%	−0.1%	0.6%	0.9%	0.3%	1.8%	1.4%	−0.4%	0.8%	0.3%	−0.5%
	5	1.8%	1.7%	−0.1%	0.6%	0.7%	0.1%	2.3%	1.9%	−0.4%	0.7%	0.3%	−0.4%
	10	2.6%	2.6%	0.0%	0.5%	0.8%	0.3%	2.9%	2.7%	−0.2%	0.7%	0.3%	−0.4%
	20	3.4%	3.4%	0.0%	0.5%	0.7%	0.2%	3.6%	3.5%	−0.1%	0.7%	0.3%	−0.4%
	30	3.9%	4.0%	0.1%	0.6%	0.8%	0.2%	4.1%	3.9%	−0.2%	0.7%	0.5%	−0.2%
20×20	d_{max}	1.2%	1.5%	0.3%	0.6%	0.8%	0.2%	0.9%	0.8%	−0.1%	0.7%	0.3%	−0.4%
	5	1.1%	1.2%	0.1%	0.4%	0.9%	0.5%	1.3%	1.0%	−0.3%	0.7%	0.3%	−0.4%
	10	2.3%	2.2%	−0.1%	0.6%	0.9%	0.3%	2.3%	2.1%	−0.2%	0.7%	0.4%	−0.3%
	20	4.4%	4.3%	−0.1%	0.7%	0.7%	0.0%	4.3%	4.0%	−0.3%	0.7%	0.3%	−0.4%
	30	5.6%	5.5%	−0.1%	0.4%	0.8%	0.4%	5.6%	5.5%	−0.1%	0.8%	0.6%	−0.2%

Nuclear Corp., Melbourne, FL, USA). Since the absolute dose calibration was performed with only MapCHECK2, MatriXX was used to verify the relative dose distribution while MapCHECK2 was used for the absolute dose distribution. Gamma analysis between calculated and measured data of both detectors was performed by using SNC Patient software (Sun Nuclear Corporation, Melbourne, FL). Gamma criteria of 3%/3 mm with dose threshold of 10% were used to analyze the coincidence between calculated and measured dose.

Results

1. Beam tuning

As shown in Fig. 2, the maximum deviations of the beam profile were adjusted within 0.77% and 0.94% and field width differences were 0.32 mm and 0.07 mm for 6 MV and 10 MV, respectively.

When the beam output of each energy was adjusted to deliver 1 cGy/MU with reference conditions (SSD of 100 cm, field size of 10×10 cm^2, and at d_{max}), the output deviation between before and after target replacement was 6.78% and 2.66% for 6 MV and 10 MV, respectively.

2. Verification

As shown in Table 1, the differences in PDD_{10} between reference and measurement were less than 0.3% for both 6 MV and 10 MV. As presented in Fig. 3 for PDD comparison with a field size of 10×10 cm^2, the differences at d_{max} between measurement and reference data were less than 0.5 mm and 0.7 mm and the PDD_{10} were 0.04%, 0.22% for 6 MV and 10 MV, respectively.

The profile coincidences were compared with flatness and symmetry, and results were provided in Table 2. For 6 MV, the flatness and symmetry showed good coincidence for 6×6 cm^2, 10×10 cm^2, and 20×20 cm^2 showing less difference than 0.3% and 0.5%, while those for 3×3 cm^2 were slightly higher showing –0.7% and –0.6%, respectively. For 10 MV, the differences were less than –0.4% and –0.5%, while those for 3×3 cm^2 were slightly higher showing –0.8% and –0.8%, respectively.

Table 3 showed the output factors for various field

Table 3. Output factors comparison between reference and measurement data for 6 MV and 10 MV photon beams.

Field Size		6 MV			10 MV		
X (cm)	Y (cm)	Reference	Measured	Difference	Reference	Measured	Difference
3	3	0.830	0.832	0.23%	0.849	0.851	0.21%
3	10	0.889	0.894	0.51%	0.905	0.911	0.59%
3	40	0.924	0.930	0.58%	0.936	0.944	0.76%
5	5	0.895	0.895	–0.03%	0.914	0.915	0.14%
5	15	0.960	0.963	0.26%	0.970	0.973	0.30%
7	7	0.945	0.944	–0.10%	0.955	0.956	0.12%
7	20	1.009	1.011	0.21%	1.009	1.011	0.24%
10	3	0.879	0.879	–0.05%	0.894	0.894	–0.02%
10	10	1.000	1.000	0.00%	1.000	1.000	0.00%
10	30	1.066	1.067	0.15%	1.053	1.055	0.19%
15	5	0.947	0.945	–0.20%	0.954	0.953	–0.05%
15	15	1.063	1.062	–0.13%	1.047	1.046	–0.08%
15	40	1.123	1.125	0.22%	1.097	1.097	–0.04%
20	7	0.995	0.994	–0.14%	0.991	0.991	0.03%
20	20	1.105	1.104	–0.07%	1.077	1.076	–0.08%
30	10	1.050	1.050	–0.01%	1.035	1.035	–0.05%
30	30	1.163	1.163	0.00%	1.121	1.121	0.02%
40	3	0.899	0.898	–0.12%	0.909	0.908	–0.11%
40	15	1.107	1.107	–0.04%	1.077	1.077	0.04%
40	40	1.200	1.204	0.38%	1.153	1.154	0.07%

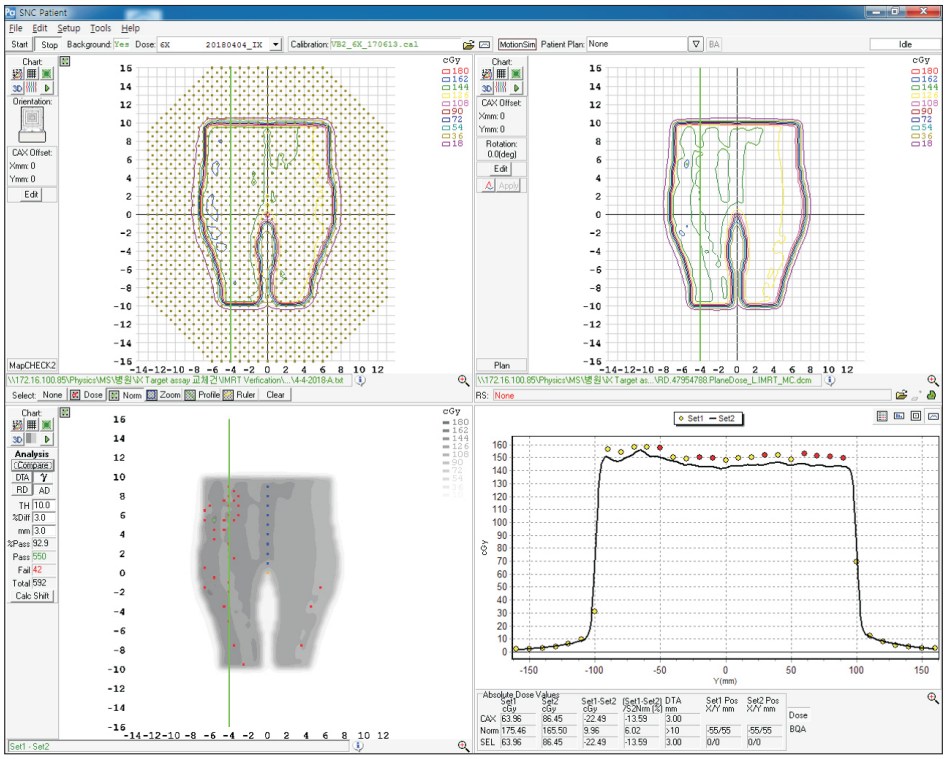

Fig. 4. Sample gamma analysis graphical user interface (GUI) provided by SNC Patient software (Sun Nuclear Corporation, Melbourne, FL) for verification of intensity-modulated radiation therapy (IMRT) plan.

sizes ranging from 3×3 cm^2 to 40×40 cm^2. The means and standard deviations of output factor differences between reference and measurement were 0.08%±0.22% and 0.11%±0.22% for 6 MV and 10 MV, respectively. The maximum differences occurred at field size of 3×40 cm^2 showing 0.58% for 6 MV and 0.76% for 10 MV, respectively.

Fig. 4 showed the sample gamma analysis between calculated and measurement. The gamma passing rates for absolute dose distribution were 97.2%±2.7% and those for relative dose distribution were 99.1%±1.0%. The gamma analysis results for each patient are presented in Table 4.

Table 4. Gamma passing rates for eight patients with two types of detectors.

Patient	Energy	MapCHECK2 (*Abs.)	MatriXX (†Rel.)
Patient 1	6X	92.9%	98.4%
Patient 2	10X	99.5%	99.9%
Patient 3	10X	96.7%	98.5%
Patient 4	6X	92.9%	98.6%
Patient 5	6X	99.0%	100.0%
Patient 6	6X	99.8%	100.0%
Patient 7	10X	99.8%	100.0%
Patient 8	6X	97.2%	97.3%

*The gamma passing rates for absolute dose distribution. †The gamma passing rates for relative dose distribution.

Discussion

After the target assembly replacement, the beam output was tuned and the absolute dose calibration was performed according to AAPM TG-51 protocol. The beam was steered to the reference beam data. All verification parameters such as the profile, PDD and output factor were within tolerance level based on AAPM TG-142 protocol and recommended manufacturer's guidance.[7,8]

The gamma passing rates for 8 patients after the target replacement were 97.2%±2.7% for absolute dose distribution, and 99.1%±1.0% for relative dose distribution, respectively. Li et al.[9] reported the impact of detector types in gamma passing rates with a diode-based array (MapCHECK2) and an ion chamber-based array (MatriXX) detector for the QA of IMRT treatment plans. It has shown that they obtained outstanding gamma passing rates for both detector arrays when compared with the dose distribution of the treatment planning system for three IMRT fields. For gamma passing rate, many radiation oncology clinics have commonly employed 3%/3 mm with a threshold level of 10%, which

was suggested by the American Association of Physicists in Medicine (AAPM) task group (TG) 119.[10-12] In this regards, our patient-specific QA summary turned out to be clinically acceptable even after the target replacement with fine adjustments.

Another consideration is about radiation safety. The possible Linac target activation should be carefully surveyed. The removed target became a radioactive material due to prolonged exposure to the radiation, and we measured the replaced target with a survey meter (TRACERCOTM T402, Johnson Matthey, Pasadena, TX, USA). Before lead shielding, the instantaneous dose rate (IDR) was 1.20 μSv/h near the target and 0.39 μSv/h at 1 m away from the target. After lead shielding, the IDR dropped down to 0.22 μSv/h and decreased to 0.13 μSv/h after the lead-shielded target was stored in a radioactive waste container. Even with confirmation of background IDR level, we determined the periodic IDR measurement to monitor and prevent the possible hazardous situation.

We verified the fundamental beam parameters that agreed within 1% with the reference beam data after the target assembly replacement. The gamma analysis results for eight patients with relative and absolute dose distribution were also acceptable.[13] This study suggests the prevention of the target assemblies; the beam output should be verified with daily routine, and furthermore, calibrated under the recommended conditions, i.e., depth at dose maximum not with 10 cm.[14]

Conclusion

We experienced the photon beam degradation due to the target burning, and thereby the target replacement and the beam verification were performed. We concluded that the patient treatment could be appropriately performed after the target replacement owing to guaranteed mandatory beam characteristics, and acceptable patient-specific QA results. We suggest the compliance with the manufacturer's recommendation for output calibration, i.e. at a depth of maximum dose, not at 10 cm, and the number of IMRT treatments should be controlled for the machine performance. When experiencing the undesired target puncture, beam output, profiles, and energy should be finely adjusted to the reference beam data, and patient-specific QA should be performed for validation. We also recommended that the replaced target should be kept in radiation shielded space, and the activation level should be recorded in a periodic routine.

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Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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