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Quality Assurance of the Dosimetric Characteristics of the Multileaf Collimator for the VERO 4D-IGRT System

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To qualify the dosimetric characterization of the multileaf collimator (MLC) for the VERO 4D IGRT System, we performed quality assurance (QA), including the field characteristics, leaf position accuracy, leakage, and picket fence test, using a 6-MV photon beam, an electronic portal imaging device (EPID), Gafchromic EBT2 films and a water phantom. The leaf leakage was up to 0.47%, and the tolerance (T) was up to 0.63 for the picket fence test. The dose profile exhibited regions of underdose due to the tongue and groove effect. The mean value of the underdose was 12.3%. Regarding the deviation between the actual and the ideal MLC leaf positions at the end of each segment, the maximum deviation was 0.2 mm in plan 1 and 0.1 mm in plan 2. Regarding the irradiated dose and the gantry movement, the maximum deviations were 3.35% in plan 1 and 0.23% in plan 2. Regarding the deviation between the actual and the plan irradiated dose per unit angle, the maximum deviation was 0.02% in plan 1 and 0.01% in plan 2. Despite the fact that independent jaws not exist in the VERO system due to insufficient space and, therefore, only the MLC represents a specific field shape, QA revealed a dosimetric characterization of high accuracy.

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I. INTRODUCTION

A 4-dimensional image guided radiotherapy (4D-IGRT) system "VERO"was installed in the Kyungpook National University Chilgok Hospital (KNUCH) Fig. 1. Our VERO system enables the dynamic tracking irradiation with a gimbaled X-ray head and a dual on-board kilovolt (kV) imaging system for real-time target localization. The system has a gimbaled X-ray head assembly composed of a compact 6 MV linear accelerator with C-band klystron and a specific multi-leaf collimator (MLC) [1]. A dose rate of up to 500 monitor unit (MU)/min is available and the source axis distance (SAD) is 1000 mm. The issue of VERO is that the gimbaled X-ray head is mounted on the inside of an inflexible O-ring shaped gantry. The gantry can be rotated by ±185° along an O-shaped guide-lane, and providing non-coplanar 3-dimensional conformal beam delivery without any treatment couch movement. Also, the X-ray head can swing along 2 orthogonal gimbals (pan and tilt rotation movements) up to ±2.5°. A gimbal rotation center to isocenter distance is 960 mm. In other words, a distance from beam source to gimbal rotation center is 40 mm. Thus, the beam is shift up to ±41.9 mm in each direction from

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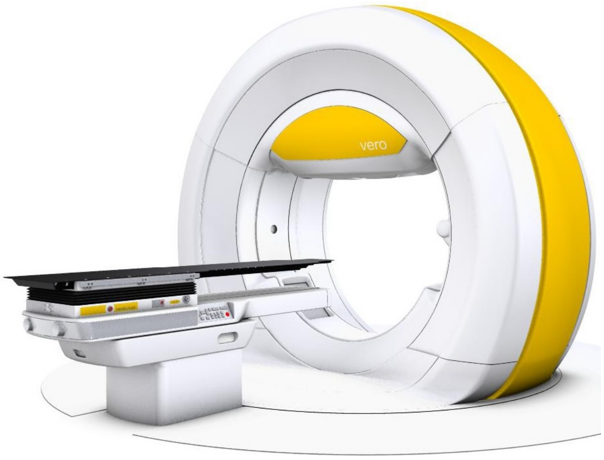

Fig. 1. (Color online)VERO Treatment system in KNUH.

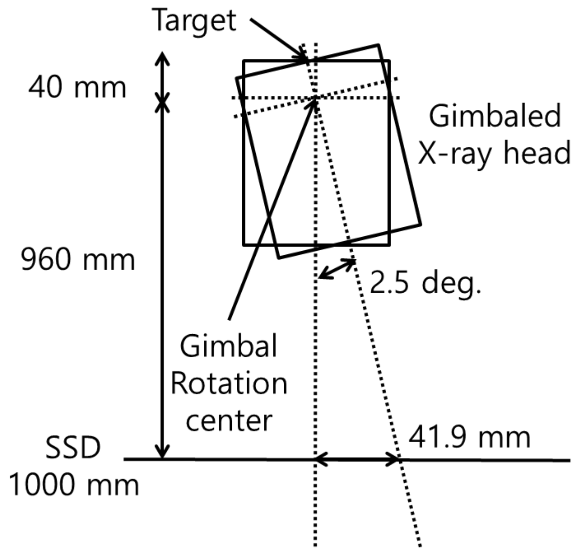

Fig. 2. A simplified geometric model of a tilted X-ray head.

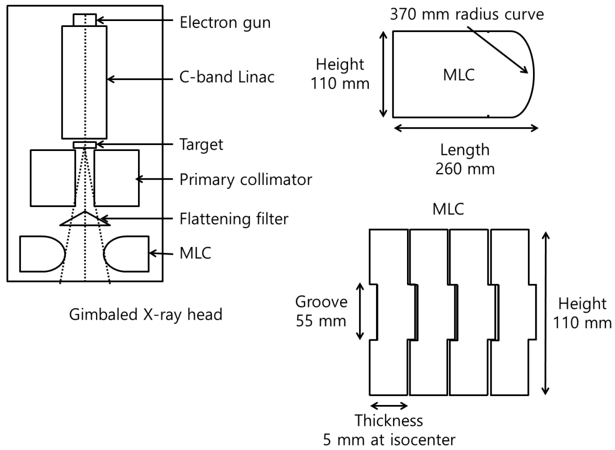

Fig. 3. Geometric scheme of the X-ray head and MLC components (front and side view of MLC leaf).

the isocenter at beam axis point perpendicular to the beam [2]. In this study, we measure the typical dosimetric characterization of the system-specified MLC for VERO such as field characteristics, leaf position accuracy, radiation leakage through the MLC, and dose reduction resulting from the tongue and groove (T&G) effect. And the field characteristic and leaf position accuracy were evaluated under conditions of the pan or tilt rotation for pursuing irradiation. The aim of this paper is to assess the capabilities of VERO system in terms of MLC errors, system sagging versus gravity due to the equivalence of pan and tilt gimbals motion.

II. MATERIALS AND METHODS

1. Descriptions

1) Gimbaled X-ray head description

The design of the gimbaled X-ray head is shown in Fig. 2. The X-ray head is driven to rotate around the pan and tilt axes of the gimbals with a pan and tilt servo, respectively. The pan and tilt axis are located at the center of gravity of the X-ray head. A small and light (350 mm in length and about 10 kg in weight) C-band accelerator guide was developed to produce a 6 MV 500 MU/min photon beam flattened over the 150×150 mm^2 maximum treatment field and SAD is 1000 mm.

2) MLC description

The MLC for VERO is located just below the level of the fixed secondary collimator and made from tungsten alloy. The design of MLC is a single-focus type, has 30 pairs of 5 mm thick leaves at the isocenter level, and produces a maximum field size of 150×150 mm^2. Leakage between adjacent leaves is minimized by an interlocking T&G arrangement, with the 55 mm height of the groove part. The leaf height and length are 110 and 260 mm, respectively. Each leaf end is circular, with a radius of curvature of 370 mm Fig. 3.

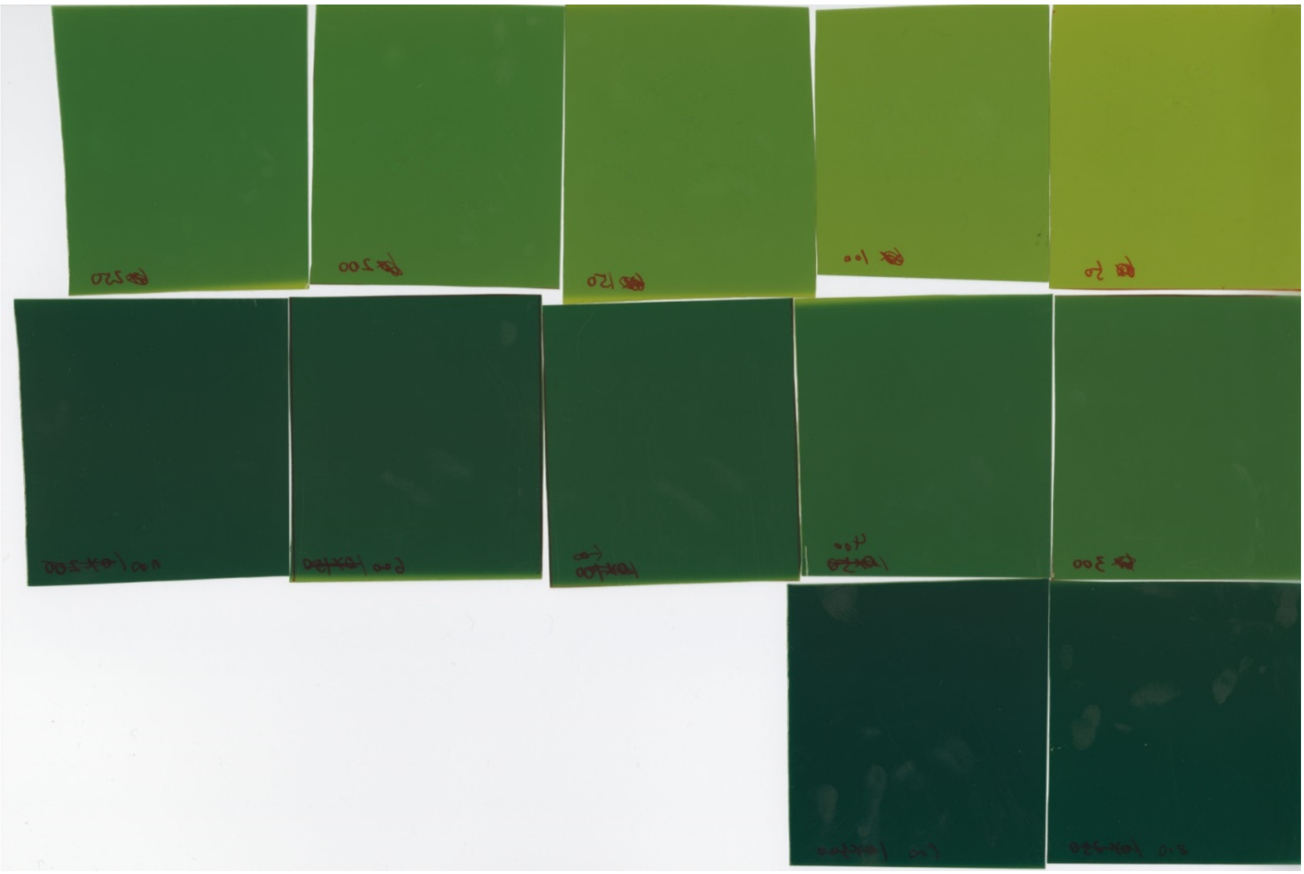

Fig. 4. (Color online) The films calibrated points dose were obtained at different doses (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0, and 8.0 Gy).

2. Test description and specifications

1) Film calibration

The dosimetric characterization of the MLC was evaluated by using a well-commissioned Gafchromic EBT2 films (ISP, USA), and water phantom (Blue phantom, IBA, Germany). All of the following irradiated films were scanned using a flatbed scanner Expression 11000XL (Epson, Japan) with a resolution of 72-dpi in 48-bit color. A calibration data set was acquired by placing a film at a 50 mm depth for SSD of 1000 mm. The film was irradiated perpendicular to the beam axis with a field size of 100 × 100 mm^2 at the isocenter. Both PDDs (percent depth doses) and Profiles were measured using a 0.65 cc ionization chamber (FC-65G, IBA, Germany) annually calibrated by the Dongnam Inst. of Radiological & Medical Sciences (DIRAMS). The 12 dose points were obtained by irradiating the films at different doses (*e.g.* calibration doses; 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0, and 8.0 Gy) Fig. 4. A calibration curve was plotted to convert the film densities into dose on each measurement data.

2) Individual leaf position verification

The gantry is moved to the test position (0°, 90°, 180°, and 270°) and completely retracted the couch to make sure nothing blocks the MV beam between MLC and Electronic Portal Imaging Device (EPID). The MLC shaper is used to adjust the MLC to the desired test field as specified in the test specifications and deliver 5 to 7 MU for each field setup. The acquired image with the EPID is evaluated using Image software. The leaves of each leaf-bank are aligned. The two leaves are searched with the largest displacement to each other and counted the displacement in pixels. The number of pixels is measured from the MLC center pixel to the next leaf edge of each leaf-bank.

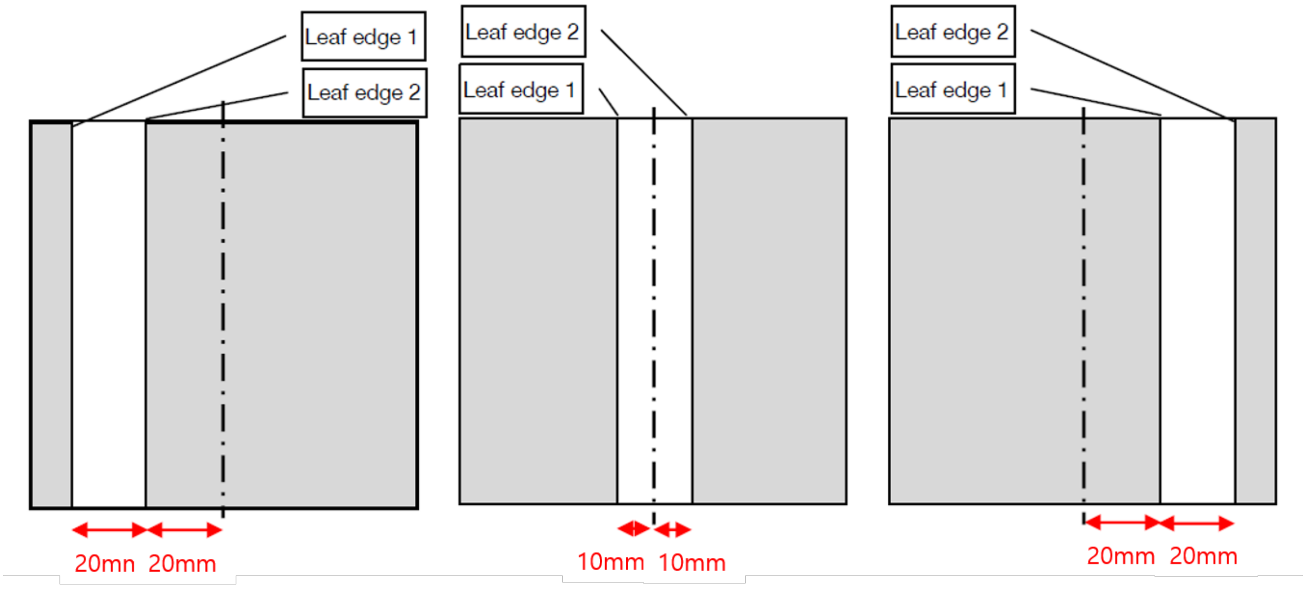

Fig. 5. (Color online) The test fields (1, 2, 3) for leaf position verification.

3) MLC leakage with EPID

The test was performed with a dose of 5 MU and fully closed MLC. Fully open the MLC and beam on. In the EPID image (raw format 1024 by 1024 pixels, 16 bit gray scale) with fully closed MLC search for the X and Y profiles (intensity over pixel count) with the highest interleaf leakage. The pixels (in X and Y direction) for the point with the maximum intensity are measured. In the EPID image with fully open MLC acquire the X and Y profiles at the same position like in the image with fully closed MLC. The maximum intensity of the image is compared with closed MLC with the intensity of the image with open MLC at exact the same position. The percentage amount of the maximum intensity of the image is calculated with closed MLC from the image with open MLC and is verified if the value is within the tolerance of $\pm 2.0\%$.

4) Tongue and groove effect

A field of 150×150 mm^2 was shaped by the MLC, and each 5 pairs of leaves were placed alternately in and out of the field. 150 MU were given to the field with a film placed at a 40 mm depth for SSD of 1000 mm. An additional 150 MU were given to the field shaped by switching alternating leaf positions. 150 MU were given to the open field of 150×150 mm^2 to another unirradiated film. The films obtained in both situations were compared and analyzed using film analyzing program. Then, measured doses for T&G were normalized to the dose at the isocenter for the open field.

5) Picket-fence test for dynamic IMRT & Dynamic/Hybrid Arc

First, the Picket-fence (PF) test was a EBT2 film test used in IMRT Quality Assurance (QA) protocols. The test was executed in static mode under 0° and 90° gantry angles. The PF test delivered a series of 2 mm wide slit-fields in a dynamic way, and provides information about leaf positioning accuracy and leaf speed during a dynamic delivery. The irradiated film at 90° gantry angle additionally provides information regarding gravity effects on the MLC. The different leaf edges were aligned within a tolerance that is calculated in the course of this test. The positions of the slit fields for the 0° gantry angle delivery and the 90° delivery was not deviate by more than 1mm. Second, the test was executed during arc irradiation and dynamic MLC mode. The PF test delivers a series of 2 mm wide slit-fields in a dynamic way, and provides information about leaf positioning accuracy and leaf speed during an arc delivery.

Table 1. Individual leaf position of verification 1.

Gantry angle (Degree)	Test field	Maximum leaf displacement (Pixel)		Reference (Pixel)
		Left leaf-bank	Right leaf-bank	
0	1	3	2	≤ 5
0	2	2	2	≤ 5
0	3	3	2	≤ 5
90	1	1	2	≤ 5
90	2	1	1	≤ 5
90	3	2	2	≤ 5
180	1	2	2	≤ 5
180	2	1	2	≤ 5
180	3	2	2	≤ 5
270	1	1	2	≤ 5
270	2	2	2	≤ 5
270	3	3	2	≤ 5

Table 2. Individual leaf position of verification 2.

Gantry angle (Degree)	Test field	Displacement (Pixel)		Reference (Pixel)	
		Left leaf−bank	Right leaf−bank	Left leaf−bank	Right leaf−bank
0	1	224	110	222 ± 3	111 ± 3
0	2	−57	56	-56 ± 3	56 ± 3
0	3	110	223	111 ± 3	222 ± 3
90	1	221	109	222 ± 3	111 ± 3
90	2	−56	57	-56 ± 3	56 ± 3
90	3	110	224	111 ± 3	222 ± 3
180	1	220	110	222 ± 3	111 ± 3
180	2	−57	57	-56 ± 3	56 ± 3
180	3	110	224	111 ± 3	222 ± 3
270	1	224	111	222 ± 3	111 ± 3
270	2	−57	57	-56 ± 3	56 ± 3
270	3	110	224	111 ± 3	222 ± 3

Table 3. MLC Leakage with EPID.

Pixel coordinates of maximum interleaf leakage (Pixel)		Intensity of interleaf leakage	Intensity of Open Field	Percentage Amount (%)	Deviation (%)
X	Y				
113	534	210	44860	0.41%	2.0%

6) Dynamic MLC Leaf position accuracy, Dose stability dependent on segments, and Irradiated dose and gantry movement accuracy

First, using a dynamic arc QA plan the positioning accuracy of all individual leaf positions, at the end of each segment was verified. The deviation between the ideal MLC leaf positions defined in the QA plan, and the recorded MLC leaf positions, at defined gantry angles are calculated. The maximum positioning deviation of each MLC leaf shall be within a tolerance of ±0.5 mm. Second, using a dynamic arc QA plan, the irradiated dose accuracy for each segment was verified. During the irradiation, the irradiated dose for every segment was logged. For every 15° of gantry rotation the tolerance of dose deviation between actual and planed dose, should be less than ±20%, for gantry rotation angles of 10° the tolerance should be less than ±10%. Third, using a dynamic

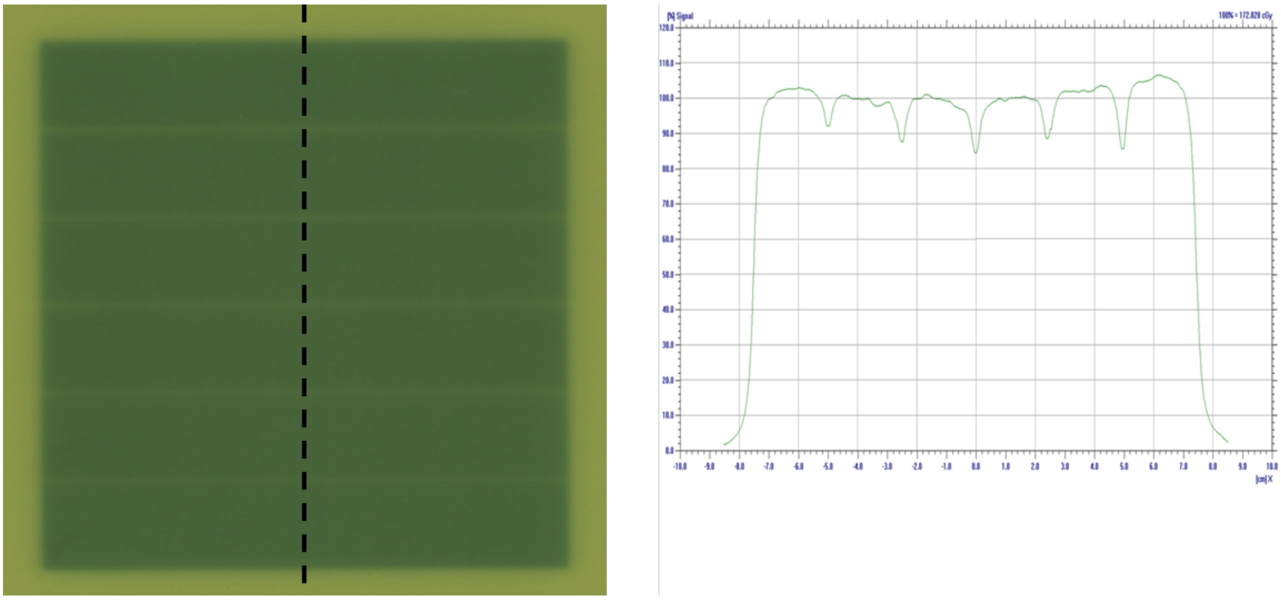

Fig. 6. (Color online) Test of tongue and groove effect on the MLC for VERO (film and cross leaf dose profiles along the dashed line).

arc QA plan, the irradiated dose per unit gantry angle is verified. The irradiated dose and gantry movement were logged and then analyzed. The maximum deviation of irradiated dose depending on gantry angle shall be less than ±1%.

III. RESULTS AND DISCUSSIONS

1. Individual leaf position verification

The test was evaluated the acquired image with the EPID and Image software. It was verified that the leaves of each leaf-bank were aligned. It was measured for the two leaves with the largest displacement to each other and counted the displacement in pixels and was recorded the effective pixel number of the MLC center from the log file. It was measured the number of pixels from the MLC center pixel to the next leaf edge of each leaf-bank and the results are shown in Tables 1 and 2. Maximum leaf displacement of left bank was 3 pixels, and minimum was 1. Maximum leaf displacement of right bank was 2 pixels, and minimum was 1. One pixel is equivalent to 0.18 mm at isocenter. Thus, error deviation was 0.18 to 0.54 mm. The accuracy and reproducibility of individual leaf positions were verified with a sequence of three test fields. This test sequence was performed for gantry angles of 0°, 90°, 180°, and 270° to evaluate gravity effects on the MLC leaf positions [3]. The test fields were to be manually defined in the MLC shaper software and the schematic is shown in Fig. 5. It was defined two slit like openings of 20 mm width at 0 mm and ± 20 mm from the MLC centerline. The individual leaf positioning accuracy of the MLC was 0.5 mm, therefore leaf edge 1 should be at positions ±(19.5∼20.5 mm), - (9.5∼10.5 mm), and leaf edge 2 at positions ±(39.5∼40.5 mm), (9.5∼10.5 mm). Two adjacent leaves were shown a maximum shift relative to each other of 1 mm. In the present study, the picket fence test was performed at gantry angles of 0°, 90°, 180°, and 270°. With the gantry angles of 90° and 270° and the gimbaled x-ray head rotation, the MLC leaf position accuracy was considered to be degraded by the mechanical sag; however, our results of the leaf position verification test showed that the effects of mechanical sag and the gimbaled x-ray head rotation on leaf position were minimal.

2. MLC leakage with EPID

The levels of intra- and interleaf leakage were much smaller than those for other MLCs. For example, the micro-MLC displayed intra- and interleaf leakages of

Table 4. Dynamic Arc QA plan 1.

Dose (MU)	Gantry (Degree)			No. of Segments	Dose/deg. (MU/deg.)	Dose rate (MU/min)	Gantry speed (deg./sec)
	Start	End	Rotation				
921	90	270	CCW	19	5.12	400	1.3

Table 5. Dynamic Arc QA plan 2.

Dose (MU)	Gantry (Degree)			No. of Segments	Dose/deg. (MU/deg.)	Dose rate (MU/min)	Gantry speed (deg./sec)
	Start	End	Rotation				
1610	20	110	CW	10	17.89	322	0.3

1.3% and 2.0%, respectively [4]. For the field size of 100×100 mm^2, measured leakages were 1.7% and 1.6% for the Varian Mark II 80-leaf MLC and Millennium 120-leaf MLC, respectively [5]. The height of the MLCs for VERO is approximately twice those of the Varian. The VERO MLC leakage was measured by comparing EPID images of a beam with fully closed leaves and fully opened leaves. In the closed leaf image, the profile of the highest interleaf leakage is taken. The maximum intensity pixel count was taken from this profile and compared to the average intensity of the open field. Pixel coordinates of maximum interleaf leakage was 113 (X direction) and 534 (Y direction). Intensity of close field interleaf leakage was 210 and intensity of open field is 44850 at same pixel position. Thus, percentage amount of ratio was 0.47%. The International Electronical Committee (IEC) regulations allow a deviation of 2% (Table 3).

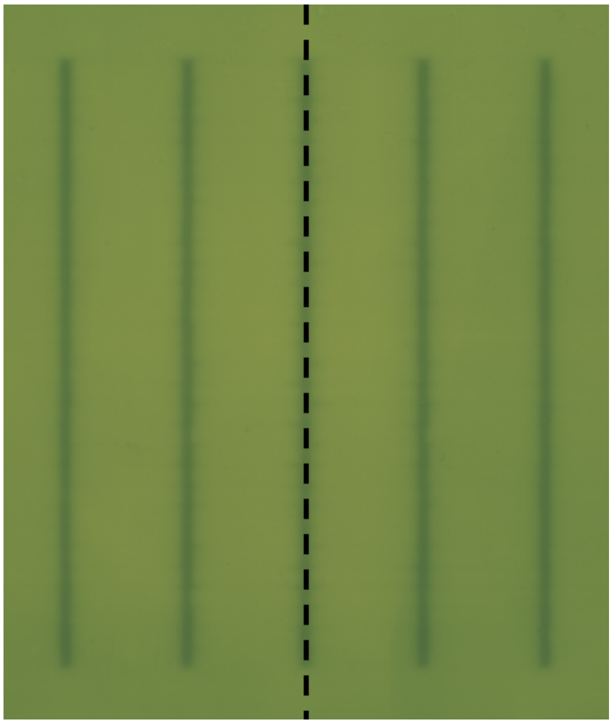

Fig. 7. (Color online) Result of picket fence test for treatment plan.

3. Tongue and groove effect

As shown in Fig. 6, the dose profile exhibits regions of under-dose due to the T&G effect. It was shown the cross-leaf dose profile along the black dashed line indicated. To measure the T&G effect, the dose profile of the irradiated film at T&G circumstance and the irradiated film at open field was compared and the dose profile was analyzed in five T&G areas using a film analyzing program. An under-dose of 12.3% was observed, on average. As pointed out by many investigators, the T&G effect could be result in an under-dose. The magnitude of the dose reduction in these match-line areas ranged from 15% to 33% which is larger than our results [6–8]. Although the MLC for VERO has a similar shape to the Varian HD120-leaf MLC, the height of the groove part of the MLC for VERO is approximately twice those of the Varian HD120-leaf. For the MLC for VERO, the overlapping extrusions from the sides of the leaves were narrower in width and thicker in the beam direction than are those of the T&G of a Varian HD120-leaf MLC. A lower dose reduction was achieved by the structural features, resulting in more conformal IMRT dose distribution.

4. Picket-fence test for dynamic IMRT & Dynamic/Hybrid Arc

The test was calculated the tolerance (T) at film level by using following formula and mark the results below for dynamic IMRT.

$$T = \frac{1000\ \mathrm{mm} - d}{1000\ \mathrm{mm}}$$

The measured distance (d) was 370 mm. Thus, tolerance T value was 0.63 at isocenter level.

5. Dynamic MLC Leaf position accuracy, Dose stability dependent on segments, and Irradiated dose and gantry movement accuracy

First, the MLC and gantry movement were logged. The test was calculated the deviation (D) by using following formula and selected value at maximum diffrent position.

$$D(\mathrm{mm}) = |\mathrm{Actual\ MLC\ leaf\ position(mm)} - \mathrm{ideal\ MLC\ leaf\ position(mm)}|.$$

The maximum D was 0.2 mm in dynamic arc QA plan 1 and 0.1 mm in plan 2.

Second, value was taken the irradiated dose and gantry movement. It was calculated the deviation between actual and plan dose in each segment. Calculation equation was following formula.

$$D(\%) = \frac{|\mathrm{actual\ dose(Gy)} - \mathrm{planned\ dose(Gy)}|}{\mathrm{planned\ dose(Gy)}} \times 100.$$

The maximum deviation was 3.35 % in plan 1 and 0.23 % in plan 2. Third, the irradiated dose and gantry movement were logged. It was calculated the deviation between actual at log file and plan irradiated dose per unit angle. Calculation equation was previous used formula. The maximum deviation was 0.02 % in plan 1 and 0.01 % in plan 2 (Tables 4 and 5).

IV. CONCLUSION

VERO is required high accuracy for Stereotactic Body Radiation Therapy (SBRT) compared with other treatment systems. The independent jaws do not exist in VERO system due to the geometries that is insufficient space. And because it has a function of head tilting for Real Time Tumor Tracking, the accuracy of the gravity is also required. Therefore, only MLC must represent a specific field shape and the dosimetric characterization. Despite the high energy and absent of independent jaws, dosimetric accuracy and characterization showed a highly accurate results in several measurements. Thus, system accuracy is extremely important for the MLC. Will need to find out whether the more complex and detailed treatment applied through an additional verification of the future.

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