Quality assurance of dynamic parameters in volumetric modulated arc therapy

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Objectives: The purpose of this study was to demonstrate quality assurance checks for accuracy of gantry speed and position, dose rate and multileaf collimator (MLC) speed and position for a volumetric modulated arc treatment (VMAT) modality (Synergy® S; Elekta, Stockholm, Sweden), and to check that all the necessary variables and parameters were synchronous.
Methods: Three tests (for gantry position–dose delivery synchronisation, gantry speed–dose delivery synchronisation and MLC leaf speed and positions) were performed.
Results: The average error in gantry position was 0.5° and the average difference was 3 MU for a linear and a parabolic relationship between gantry position and delivered dose. In the third part of this test (sawtooth variation), the maximum difference was 9.3 MU, with a gantry position difference of 1.2°. In the sweeping field method test, a linear relationship was observed between recorded doses and distance from the central axis, as expected. In the open field method, errors were encountered at the beginning and at the end of the delivery arc, termed the ''beginning'' and ''end'' errors. For MLC position verification, the maximum error was −2.46 mm and the mean error was 0.0153 ±0.4668 mm, and 3.4% of leaves analysed showed errors of >±1 mm.
Conclusion: This experiment demonstrates that the variables and parameters of the Synergy® S are synchronous and that the system is suitable for delivering VMAT using a dynamic MLC.

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The concept of volumetric modulated arc therapy (VMAT) has been described in many studies [1–5]. VMAT is a system for intensity-modulated radiotherapy treatment (IMRT) delivery that achieves high dose conformity by optimising the dose rate, gantry speed and leaf positions of the dynamic multileaf collimator (MLC) [6]. One study [5] demonstrated quality assurance (QA) checks using dynamic MLC controller log files (Dynalog) for VMAT systems such as RapidArc® (Varian Medical Systems Inc., Palo Alto, CA). It is assumed that the actual delivery process is truly represented in the log files [6]. The major disadvantage of this method is that Dynalog files need to be validated against an independent system. The electronic portal imaging device (EPID) is a dependable system when corrections are made for systematic tilts and shifts [7, 8] and when image sagging due to gantry angle [9] has been taken into account. A significant number of researchers have investigated MLC QA by film or EPID [7–13] to measure the accuracy of the MLC controller independently and ensure that the MLC edge positions agree with the radiation field edges to within 0.3 mm [14]. EPID measurements are highly reproducible, with a standard deviation of <0.1 mm for individual leaf/collimator positions and <0.05 mm for a $10 \times 10\,cm^2$ field [7]. Few studies [15–17] have demonstrated commissioning, QA and patient-specific QA for VMAT using both the RapidArc and the Synergy® S (Elekta, Stockholm, Sweden) systems. The purpose of this study was to demonstrate QA checks for accuracy of gantry speed and position, dose rate, MLC leaf speed and MLC position, and to ensure that all the necessary variables and parameters were synchronous. These simple tests were designed to fulfil the requirements and limits recommended by the American Association of Physicists in Medicine (AAPM) for the clinical implementation of IMRT [18] and a recent recommendation by AAPM task group 142 (TG-142) [19] for the QA of medical accelerators.

Methods and materials

We recently commissioned a Synergy S system with beam modulator (BM), 40 pairs of MLC leaves (4 mm projection at isocentre), RT Desktop 7.0 (Elekta), ERGO++ Treatment Planning System (3D-Line Research and Development S.r.L., Milan, Italy), MOSAIQ® v. 1.6 (Impac Medical Systems, Sunnyvale, CA) and an amorphous silicon flat panel. Control points (CPs) were

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defined for the purpose of VMAT planning and delivery (≤177 CPs for RapidArc and an indefinite number for Synergy S). VMAT simply involves the sequential delivery of these CPs. Each CP defines a gantry angle, collimator angle, MLC shape and monitor unit. For the Synergy S BM, the dose rate, gantry speed and MLC leaf speed between two CPs are constant. The choice of dose rate, gantry speed and MLC leaf speed depends on the amount of dose to be delivered between two CPs. For a fixed dose rate, monitor unit per degree reflects the gantry speed. The available set dose rates for the Synergy S BM are 35, 70, 140, 280 and 560 MU min^{-1}. For an arbitrary dose rate, the next lowest available set dose rate is selected and the rest is adjusted by gantry speed. For example, if 100 MU min^{-1} is required, the set dose rate will be chosen as 70 MU min^{-1} and gantry speed varied accordingly to fulfil the required number of monitor units per degree. Beyond 560 MU min^{-1}, there is no set dose rate and only gantry speed can be used to fulfil the desired number of monitor units per degree. The minimum gantry speed is zero (static condition) and the maximum available gantry speed is one revolution per minute or 6° s^{-1}.

Gantry position–dose delivery synchronisation test

For VMAT delivery, it is essential to ensure that the integral dose, leaf position and gantry position are appropriately synchronised. Failure to achieve proper synchronisation will cause the wrong dose to be achieved [17]. A sliding window technique with a field size of 2 × 16 cm, which sweeps between −10 and +10 cm (slide and shoot) and covers almost the entire field (BM maximum field size is 21 × 16 cm), was used. In this test, the collimator angle, dose rate and gantry speed were constant between two CPs and were liable to change in transition between CPs. The gantry position–dose delivery synchronisation was tested for linear, parabolic and zigzag (sawtooth) variation of monitor units with the gantry angle. The data were recorded in the EPID and transferred to OmniPro-I'm*RT* software (IBA Dosimetry GmbH, Schwarzenbruck, Germany) for further evaluation. The delivered sequences were created using the ERGO++ Treatment Planning System. In the first part of this test (linear variation), a total of 180 MU was delivered using a gantry rotation of 0–100°. The first segment delivered 20 MU in a gantry interval of 0–20°. The second segment delivered 20 MU in a gantry interval of 15° (20–35°), and so on (Table 1). Since the delivered monitor unit level was the same for both segments and the gantry revolution was different, the system adjusted its variables (MLC leaf speed and gantry speed) to achieve the desired dose rate. Dose delivery was interrupted at arbitrary positions and the delivered monitor unit level and corresponding gantry angle were noted (Figure 1). In the second part of this test, the level of monitor units per degree was varied from 0.2 to 7 MU^{-1}, which led to a variation in the gantry speed and resulted in a parabolic relationship between the dose (in monitor units) and gantry angle (Table 1, Figure 2). Dose delivery was interrupted at arbitrary positions and the delivered

Table 1. Linear, parabolic and sawtooth variation of gantry angle and monitor unit (MU) level, and differences in interrupted and predicted monitor unit level and gantry angle

Monitor unit per degree level	Dose rate (MU min^{-1})	Cumulated monitor units (MU)	Gantry position (°)	Deviation in gantry angle (°)	Difference in monitor units (MU)
Linear variation (Segment 1)					
1	280	20	20	0.56	1.1
1.33	280	40	35	0	0
2	560	60	45	0.9	3.4
4	560	80	50	0.35	0.7
2	280	120	70	1.1	2.2
2	280	140	80	0.7	1.4
2	280	180	100	0	0
Parabolic variation (Segment 2)					
0.2	35	2	10	−0.46	−0.11
0.5	140	7	20	0.74	0.37
1	280	17	30	0.86	0.86
2	560	37	40	1.39	2.78
3	560	67	50	0.75	2.25
4	560	107	60	0.34	1.34
5	560	157	70	0.48	2.4
6	560	217	80	0.21	1.28
7	560	287	90	0.24	1.65
Sawtooth variation (Segment 3)					
0.2	35	2	10	−0.4	0.1
8	560	82	20	−1.2	9.3
0.5	70	87	30	−0.8	0.4
7	560	157	40	−0.8	5.6
1	280	167	50	−0.5	0.5
6	560	227	60	−0.7	4.4
2	280	247	70	−1.3	2.8
5	560	297	80	−0.9	4.7
3	560	327	90	−0.7	2.2

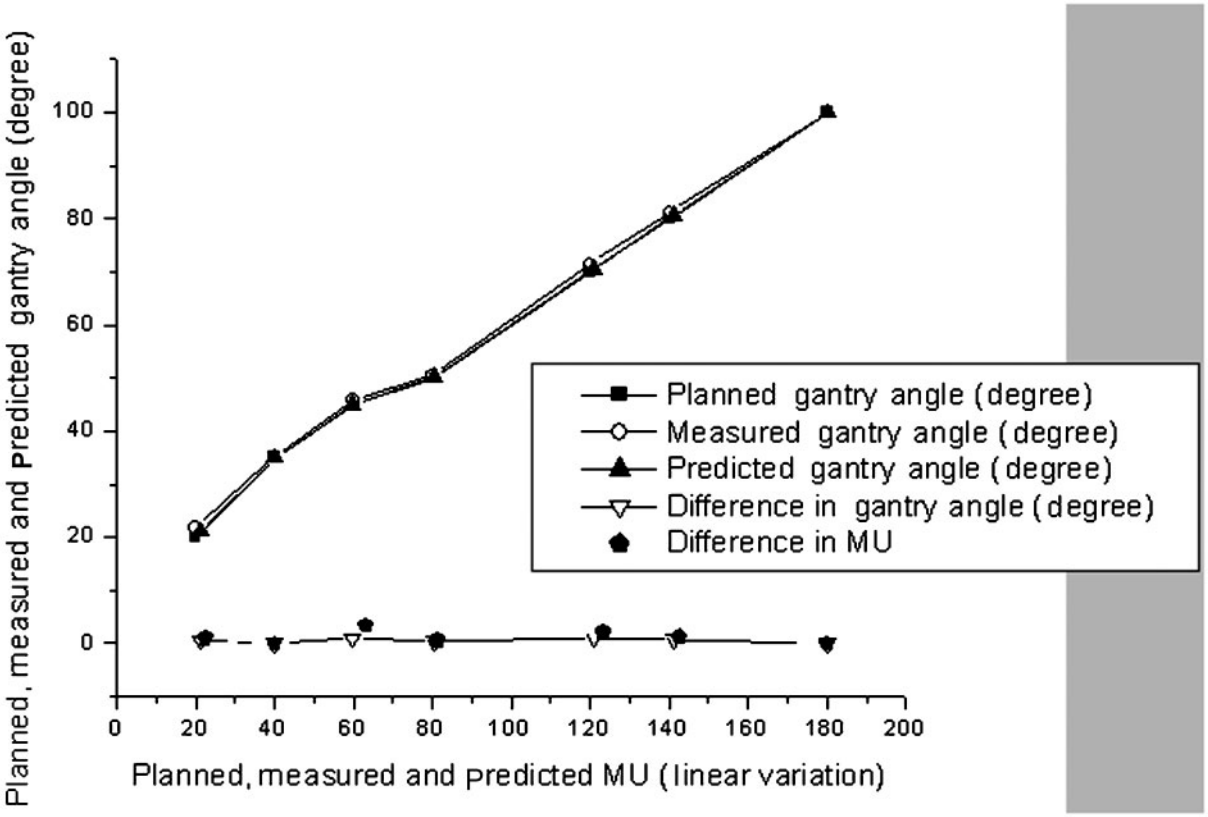

Figure 1. Difference between predicted and measured gantry angle and predicted and measured monitor unit (MU) level for a linear variation of gantry angle with monitor unit level.

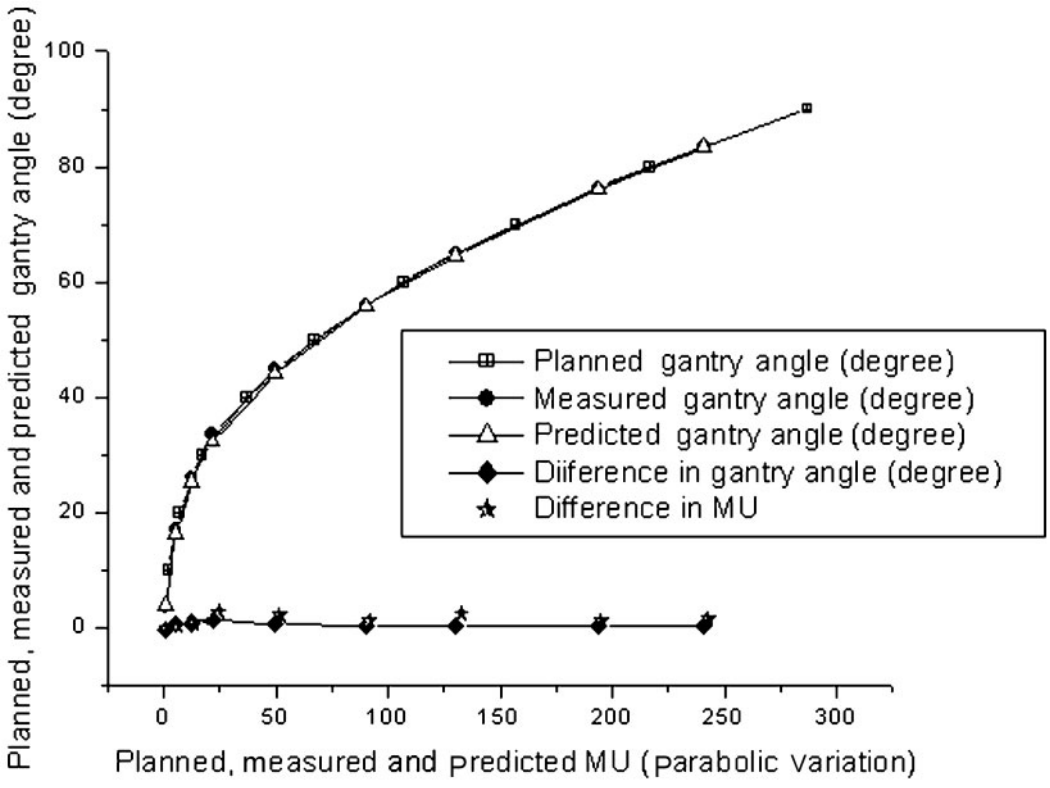

Figure 2. Difference between predicted and measured gantry angle and predicted and measured monitor unit (MU) level for a parabolic variation of gantry angle with monitor unit level.

monitor unit level was checked against the predicted monitor unit level. For a 90° gantry rotation, a dose of 287 MU was delivered (Table 1). The CPs were chosen at 10° intervals. Finally, this test was concluded with zigzag (sawtooth; Table 1) variation of gantry angle and dose rate (Figure 3). Here the level of monitor units per degree was varied as much as possible to get the maximum variation of monitor units in a specified gantry interval of 10°. Interruptions were made either at the middle of the segment (first, third, fifth and eighth interruptions) or at the beginning or the end of the segment.

Gantry speed–dose delivery linearity test (sweeping field method)

This test was performed to check the linearity of the dose rate and gantry speed. The same sweeping field of 2×16 cm was used, which sweeps between −10 and +10 cm, as mentioned previously. The monitor unit level specified for the first field (between −10 and −8 cm in the *x*-axis) was 55 MU; the subsequent fields were given an equal decrement of 5 MU each (45 MU for the second segment, 40 MU for the third segment and so on until 5 MU was given for the last segment). As the variation of the dose was linear in segments, we were expecting the dose rate and gantry speed to be so adjusted that it would lead to a linear variation of the dose. The I'm*RT* MatriXX was irradiated and the dose evaluated for the different segments. At the beginning and the end of the sweep, the signal was low (so that it would not deliver more radiation at the beginning or end); therefore, only the segments measuring between −8 and +8 cm were considered.

Gantry speed–dose delivery synchronisation (open field method)

The purpose of this study was to check the synchronisation of gantry speed with dose delivery. A 21×16 cm^3 field was opened for a 6-MV X-ray and a 0.13-cm^3 ion chamber with a brass build-up cap was placed at the isocentre in air. A dose of 45 MU was planned and delivered to the chamber by a single arc measuring 0–180° with no intensity modulation. The total (integral) meter reading (MR) in nanocoulombs was recorded and the MR per degree level calculated. The machine was started again from the beginning and interrupted at arbitrary positions. The delivered monitor unit level and gantry position were noted. Gantry position was calculated from the noted MR value and the MR per degree value obtained in the first place during the continuous rotation of 0–180°. Cumulative MRs were collected by interrupting the gantry at different arbitrary positions and the difference between the noted gantry angle and the calculated gantry angle was checked. This exercise was performed for 90, 180, 360, 600 and 800 MU with the same gantry revolution of 0–180° and for varying gantry speeds (Table 2).

Multileaf collimator position test

For the Synergy S system, MLC leaf speed is constant between two CPs. Three tests were performed to verify the position of the MLC under different conditions. The first test corresponded to the transition between two regular shapes, the second was for an irregular shape; and the third was for anticlockwise rotation of the

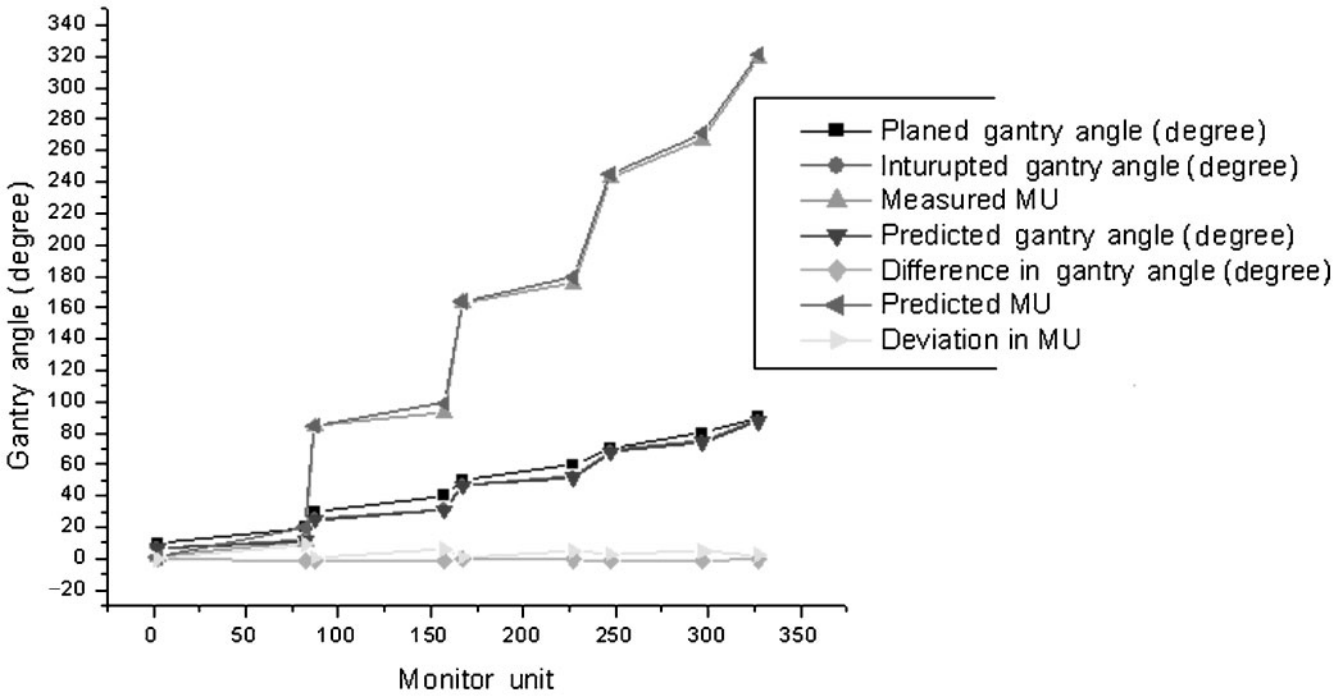

Figure 3. Difference between predicted and measured gantry angle and predicted and measured monitor unit (MU) level for a zigzag (sawtooth) variation of gantry angle with monitor unit level.

Table 2. Linearity of gantry rotation tested for integral and differential settings

Integral testing					Differential testing				
Monitor unit level (MU)	MR (nC)	Gantry stopped (°)	Gantry calculated (°)	Variation (°)	Monitor unit level (MU)	MR (nC)	Gantry stopped (°)	Gantry calculated (°)	Variation (°)
MU=45, GR=0–180°, DR=70 MU min^{-1}, MR=1.675 nC, MR per degree=0.0093055 nC°$^{-1}$									
5.4	0.202	22.9	21.7	1.2[a]	5.4	0.202	22.9	21.7	1.2[a]
11.1	0.4136	45.4	44.4	1	5.7	0.212	22.7	45.8	−0.4
21.5	0.7991	86.9	85.9	1	10.4	0.386	41.4	87.2	−0.3
27.9	1.04	112.8	111.8	1	6.4	0.241	25.9	113.1	−0.3
34.7	1.293	140.0	138.9	1	6.8	0.253	27.2	140.3	−0.3
39.3	1.465	158.4	157.4	1	4.6	0.172	18.5	158.7	−0.3
43	1.601	173.1	172	1	3.7	0.136	14.6	173.4	−0.3
45	1.677	179.9	180.2	−0.3[a]	2	0.076	8.2	181.5	−1.6[a]
MU=90, GR=0–180°, DR=135 MU min^{-1}, MR=3.35 nC, MR per degree=0.018611 nC°$^{-1}$									
14.1	0.5257	29.1	28.2	0.9[a]	14.1	0.526	29.1	28.2	0.9[a]
26.4	0.9825	53.7	52.8	0.9	12.3	0.457	24.5	53.7	0
39.6	1.473	80.2	79.1	1.1	13.2	0.491	26.4	80	0.2
58.3	2.169	117.7	116.5	1.1	18.7	0.696	37.4	117.6	0.1
69.5	2.589	140.0	139.1	0.8	11.2	0.42	22.6	140.2	−0.3
83.5	3.112	168.1	167.2	0.9	14	0.523	28.1	168.1	0
90	3.35	179.9	180	−0.1[a]	6.5	0.238	12.8	180.9	−1.0[a]
MU=180, GR=0–180°, DR=275 min^{-1}, MR=6.714 nC, MR per degree=0.0373 nC°$^{-1}$									
43.9	1.637	44.8	43.9	0.9[a]	43.9	1.637	44.8	43.9	0.9[a]
67.4	2.51	68.3	67.3	1	23.5	0.873	23.4	68.2	0.1
101	3.75	101.4	100.5	0.9	33.3	1.24	33.2	101.5	−0.1
132	4.926	133.2	132.1	1.1	31.4	1.176	31.5	132.9	0.2
157	5.87	158.3	157.4	0.9	25.3	0.944	25.3	158.5	−0.2
178	6.631	178.8	177.8	1	20.3	0.761	20.4	178.7	0.1
180	6.718	180.0	180.1	−0.1[a]	2.3	0.087	2.3	181.1	−1.1[a]
MU=360, GR=0–180°, DR=550 MU min^{-1},MR=13.44 nC, MR per degree=0.0746667 nC°$^{-1}$									
39.7	1.485	20.9	19.9	1[a]	39.7	1.485	20.9	19.9	1.0[a]
53	1.981	27.5	26.5	1	13.3	0.496	6.6	27.5	0
112	4.161	56.7	55.7	0.9	58.5	2.18	29.2	56.7	−0.1
188	7.023	95.1	94.1	1.1	76.7	2.862	38.3	95	0.2
257	9.585	129.3	128.4	0.9	68.5	2.562	34.3	129.5	−0.2
328	12.26	165.1	164.2	0.9	71.2	2.675	35.8	165.1	0
360	13.46	180.0	180.3	−0.3[a]	32.1	1.2	16.1	181.2	−1.2[a]
MU=600, GR=0–180°, DR=550 MU min^{-1}, MR=22.41 nC, MR per degree=0.1245 nC°$^{-1}$									
85.5	3.196	26.4	25.7	0.7[a]	85.5	3.196	26.4	25.7	0.7[a]
160	5.957	48.6	47.8	0.7	74.2	2.761	22.2	48.6	0
232	8.638	70.2	69.4	0.8	71.9	2.681	21.5	70.1	0
298	11.11	89.8	89.2	0.6	66.2	2.472	19.9	90	−0.2
389	14.52	117.3	116.6	0.7	91.3	3.41	27.4	117.2	0.1
459	17.14	138.2	137.7	0.5	69.9	2.62	21	138.3	−0.1
557	20.82	167.8	167.2	0.5	98	3.68	29.6	167.8	0
600	22.43	180.0	180.2	−0.2[a]	43	1.61	12.9	180.7	−0.7[a]
MU=800, GR=0–180°, DR=550 MU min^{-1}, MR=29.9 nC, MR per degree=0.16611 nC°$^{-1}$									
108	4.059	24.8	24.4	0.3[a]	108.4	4.059	24.8	24.4	0.3[a]
201	7.503	45.6	45.2	0.4	92.3	3.444	20.7	45.5	0.1
319	11.93	72.2	71.8	0.3	118.6	4.427	26.7	72.2	−0.1
403	15.05	91.0	90.6	0.4	83.4	3.12	18.8	90.9	0.1
546	20.41	123.3	122.9	0.4	143.3	5.36	32.3	123.3	0
637	23.83	143.8	143.5	0.3	91.2	3.42	20.6	143.9	−0.1
782	29.28	176.5	176.3	0.2	145.2	5.45	32.8	176.6	−0.1
800	29.95	179.9	180.3	−0.4[a]	17.6	0.67	4	180.5	−0.6[a]

DR, dose rate; GR, gantry rotation; MR, meter reading; nC, nanocoulombs.
[a]Indicates ''beginning'' and ''end' errors.

gantry. These tests were performed to verify that MLC movement was linear between two CPs irrespective of dose rate, and to check the positional accuracy of the MLC at any arbitrary point between two CPs. Two CPs separated by a gantry angle of 10° were defined with two different field shapes (MLC configurations). As there were only two CPs, the MLC moved at a constant speed. It is possible to calculate the MLC configuration at any intermediate position or time between initial and final MLC configuration. For the transition between two regular shapes (rectangle to trapezoid), a dose of 100 MU was delivered; radiation was interrupted at 25.2, 50.1 and 75.2 MU. Our intention was to interrupt the machine at 25, 50 and 75 MU; however, it was not possible to interrupt the machine at precisely the desired position. Portal images were taken and transferred to OmniPro-I'm*RT* software for analysis of MLC position. The same test was performed for an irregular arbitrary

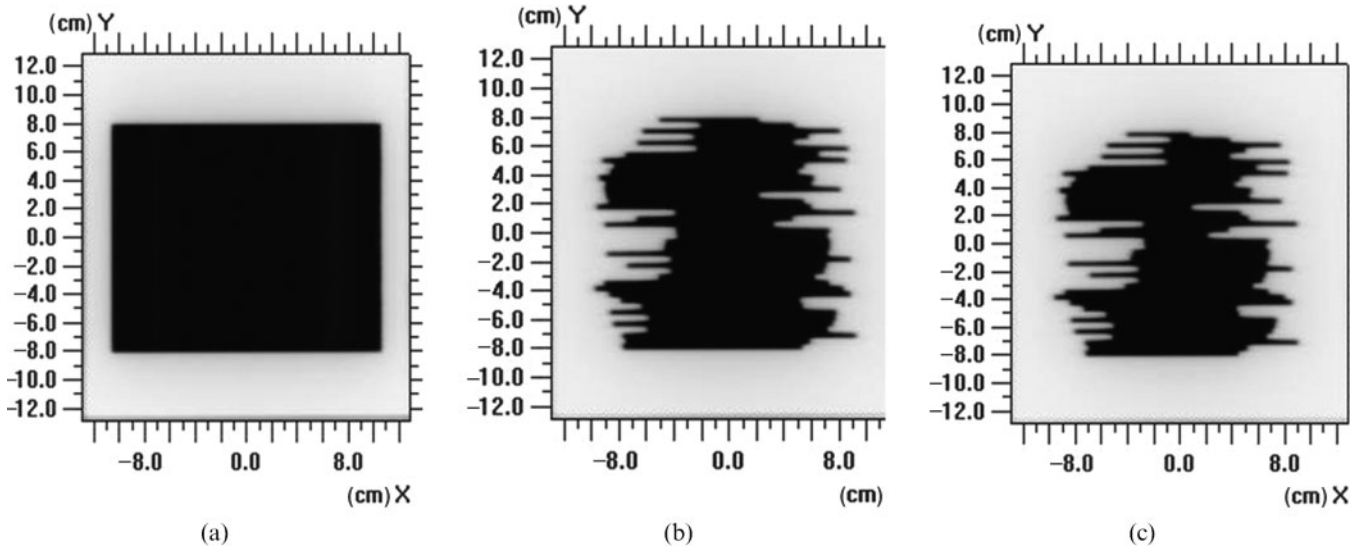

Figure 4. Transition from (a) a regular to (c) an irregular shape meant for 50 MU. (b) A multileaf collimator configuration at the interrupted position (43.2 MU).

MLC shape (Figure 4) and for anticlockwise rotation of the gantry (Figure 5).

Results

Gantry position–dose delivery synchronisation

The results of this test were quite straightforward. In the first two parts of the test, the average error in gantry position was 0.5° and the difference in monitor units was 3. When the dose rate was elevated, there was a higher error in delivered monitor units until the dose rate was saturated. In the first part of the test, planned monitor unit and gantry angle gave an almost linear relationship (Figure 1). If all the variables were performing correctly, the interrupted gantry angle *vs* measured monitor unit level should have maintained the same relationship, as shown by the planned gantry angle and monitor unit level. The second part of the test confirmed the fidelity of the delivered dose (in monitor units) to that of the planned dose (in monitor units) at the gantry position for a parabolic relationship between dose delivery (in monitor units) and gantry angle (Figure 2). In the third part of the test (Figure 3), the results were not so good. When the monitor unit per degree level was varied from 0.2 to 8 MU per degree, the difference between the predicted and measured monitor unit level was 9.3 MU, with a variation of 1.2° in gantry position. However, this is not a true error, but was caused by the interruption of the radiation. The error in monitor unit level and gantry angle was more prominent when the monitor unit per degree level was higher. It should be mentioned here

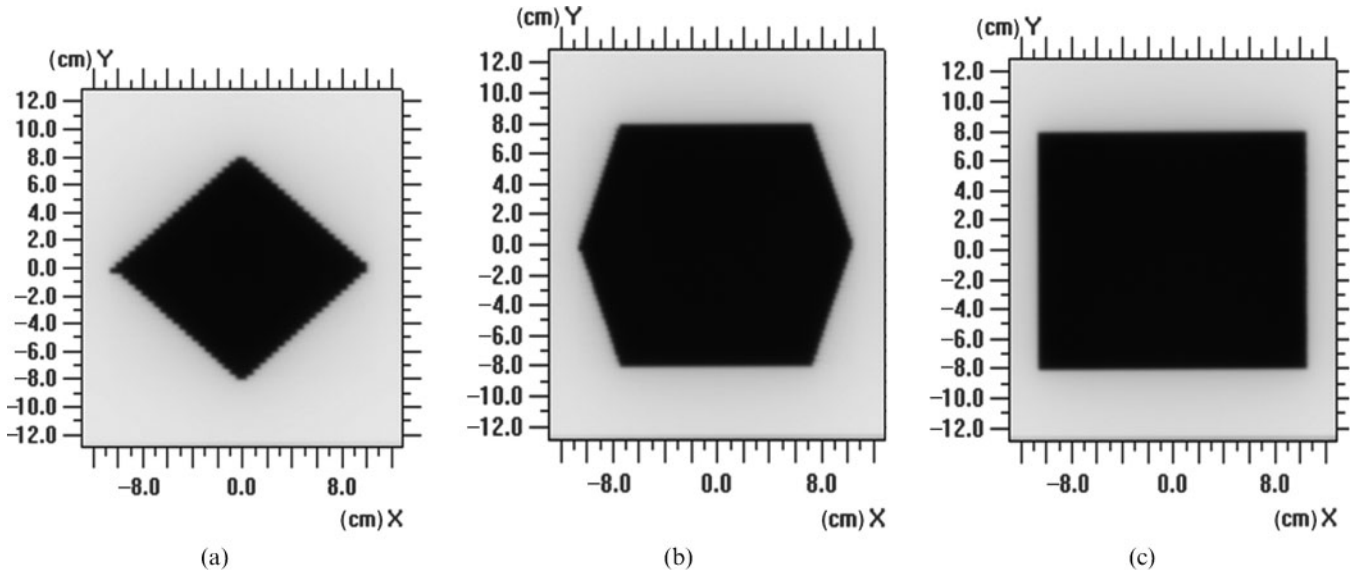

Figure 5. (a) and (c) show a multileaf collimator configuration for initial and destination images for an anticlockwise rotation meant for 50 MU; (b) shows an arbitrary interruption point at 34.5 MU.

that linear interpolation, which may not be exact mathematics, was used to predict the both gantry angle and the monitor unit level.

Gantry speed–dose delivery linearity

Since the planned dose had a linear relationship with the distance from the central axis, a similar linear relationship was expected for the recorded dose. The result for this test was only partially satisfactory. The measured dose showed a linear relationship with distance, as expected; however, the plotted lines for the planned dose and the measured dose were not parallel as has been expected. The measured and planned dose straight-line slopes were -2.839 and $-2.5\,\mathrm{MU\,cm^{-1}}$, respectively. The parallelism of the two straight lines indicated that they were separated by a constant factor. The shift in slope here may have been due to an error in the I'm*RT* MatriXX flat panel and is not particularly significant in this test.

Gantry speed–dose delivery synchronisation

This test was performed for all the dose rates available with the machine except for $35\,\mathrm{MU\,min^{-1}}$. The gantry position error decreased with increasing dose rate. In integral testing, the maximum gantry error was found at $70\,\mathrm{MU\,min^{-1}}$ as $+1.2^{\circ}$. The average error was calculated as 0.67°. 68.18% of the gantry positions in integral testing showed an error of $<1^{\circ}$. The corresponding gantry position analysis in differential testing showed superior results compared with integral testing. 86.4% of the gantry positions showed an error of $<1^{\circ}$. Most errors were $<0.5^{\circ}$ (found at 77.3% of the gantry positions analysed). The maximum error was noted as 1.6°.

Multileaf collimator position

The maximum error in MLC position measured for the irregular field (left leaf bank, 37th leaf; right leaf bank, 38th leaf) was 1.99 mm (speed, $0.99\,\mathrm{cm\,s^{-1}}$) and -2.46 mm (speed, $0.399\,\mathrm{cm\,s^{-1}}$), respectively. However, these two leaves were not travelling at the highest speed. The highest speed encountered was $1.91\,\mathrm{cm\,s^{-1}}$. According to the AAPM TG-142 report [19], leaf position accuracy should be 1 mm. However, an older report by Ezzell et al [18] cited Ramsey et al [20] for leaf position error during conformal dynamic arc and intensity-modulated arc treatment. This stated that the average positional error ranged from 0.3 to 2.1 mm and that the maximum error (4 ± 0.1 mm) occurred during the greatest leaf speed of $3\,\mathrm{cm\,s^{-1}}$. In our study, the maximum error was -2.46 mm, the mean error was 0.0153 ± 0.4668 mm and 3.4% (9 out of 260) of leaves showed $> \pm 1$ mm errors. The errors for these nine MLC leaves could not be correlated by their speed. The number of MLCs with an error of <0.7 mm and <0.5 mm was found to be 231 (88.9%) and 201 (77.1%), respectively. The frequency distribution for MLC positional error showed a gaussian distribution, as expected. However, the gaussian distribution was skewed (-0.09) because the mean and median values were not the same, which means that this particular machine is biased to a positive MLC positional error.

Discussion

Three tests were performed in this study to check the synchronisation and reproducibility of three variables: gantry speed and position; dose and dose rate; and MLC leaf speed and position. The collimator angle was taken as a constant for all three tests. The best method for testing different variables is to study two of them and observe their variation, while keeping the third as a parameter or constant. However, it is not always possible to isolate the two variables by keeping the third constant. For example, in the first test, dose delivery was checked against gantry speed, but a sweeping field of 2×16 cm was used to test this. Therefore, if there was a problem in MLC position or MLC leaf speed, it would have contributed to the dose delivery–gantry positional error. However, in our study, it was possible to measure errors in MLC position because EPID images were taken. In the gantry speed–dose delivery synchronisation test, the MLC was taken as a constant with a static field opening of 21×16 cm to test the synchronisation between dose delivery and gantry position. The results of the integral testing part of this test (Table 2) showed an error of $>1^{\circ}$ for the first segment, which was carried through all the other segments except the last. We were interested to know why this error occurred and was carried forward to subsequent segments. The same experiment was performed in differential mode, where the charge for each individual segment was collected separately. The corresponding gantry angles were calculated and it was found that the first and the last segments had the largest errors, whereas the in-between segments had negligible errors. This was because whenever radiation was interrupted, the gantry moved some degrees ahead of the intended or desired position (this was due to the motional inertia of the gantry head and happened only if the radiation was interrupted before the true stopping position) and, before radiation was restarted, the gantry came back by the amount it moved ahead to the intended or desired position. The differential test confirmed that the interrupted positions, other than in the first and last segments, did not show any significant error, which indicates that, although the gantry showed extra movement of the head, the radiation was terminated at the desired position. The larger errors at the beginning and the end of the sweep were due to faster gantry movement at the beginning and slower gantry movement at the end, referred to as ''beginning'' and ''end'' errors. Where the delivered monitor unit level was large, the gantry speed was low; therefore, the error in the gantry position was also reduced. The uncertainty in the ion chamber calibration was $\pm 2.5\%$, which also contributed to gantry angle positional inaccuracy. The same test was performed by another means to confirm the linearity of gantry rotation and dose delivery obtained by ion chamber measurement. The I'm*RT* MatriXX was attached to the gantry with a gantry mount and a dose of 180 MU was delivered for a $0–180^{\circ}$ rotation (1 MU per degree) with an open field of 21×16 cm. Two profiles were generated with and without interruptions (Figure 6). 1%–1 mm gamma analysis confirmed 99.12% agreement, which indicated excellent conformation between the interrupted and non-interrupted profiles. Gamma analysis (Figure 6) showed two strips of higher error

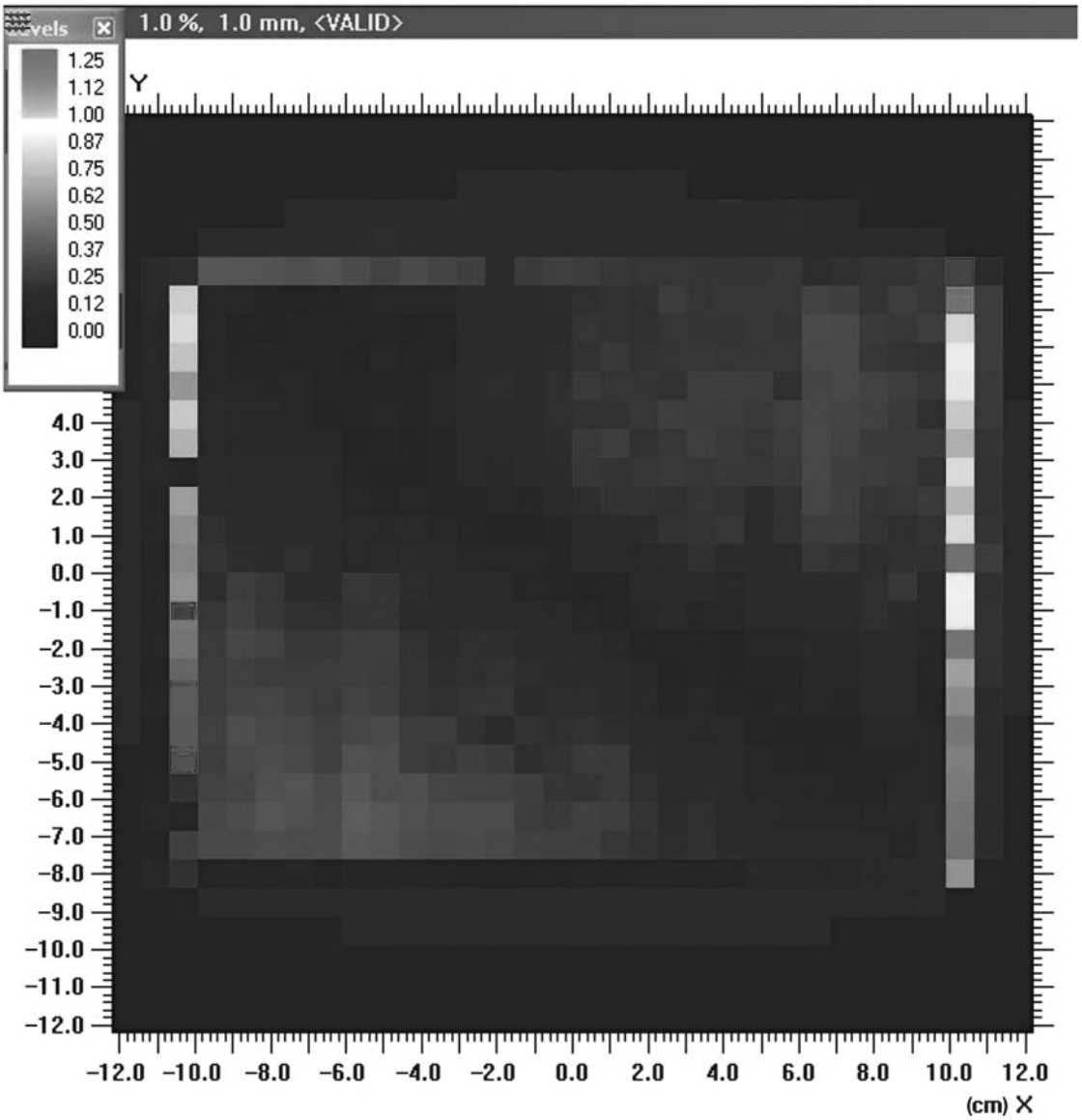

Figure 6. Gamma analysis of the profiles with and without interruptions using I'm*RT* MatriXX (IBA Dosimetry GmbH, Schwarzenbruck, Germany). The gamma analysis showed two strips of higher error at the two ends, confirming the ''beginning'' and ''end'' errors.

between ± 10.0 and ± 10.5 cm (x=21 cm), which confirmed the beginning and the end errors. In the third test, one property of VMAT was exploited to achieve constant dose rate as well as constant gantry speed; that is, the test was performed between two CPs. This introduced a drawback to the test, in that the MLC was moving at a constant speed. The Synergy S BM is based on servo control for the integral monitor unit level at the CPs. This is simply a feedback loop which works in synchronisation with dose delivery. Therefore, any errors in any of the variables, such as dose, dose rate, MLC leaf speed and position, and gantry speed and position, would have been corrected immediately. In the first test, the gantry position, and monitor unit level were checked for linear, parabolic and sawtooth settings. This test found that predicted dose distribution matched well with planned dose distribution. The test for gantry speed–dose delivery synchronisation demonstrated a striking feature. If there was abnormal termination of the dynamic beam, it was handled very efficiently. The MOSAIQ control system resumed the treatment with ≤2% error at the beginning and end of the CPs, and with very negligible (<1%) error in dose distribution in between. This observation is supported by other studies [17]. MLC positional accuracy was very good, with only 3% of leaves found to be out of limit, as specified by TG-142, but all were found to be within the limits recommended in other reports [18]. We have considered TG-142 because, although it does not deal with VMAT directly, it deals with radiosurgery, a procedure in which IMAT is used.

Conclusion

For VMAT, the planned dose distribution was defined using discrete CPs. This was delivered in a continuous manner, with the linear accelerator control system continuously interpolating between the discrete CPs based on

the delivered monitor unit level. Some treatment planning systems correctly model this dynamic behaviour using Monte Carlo dose calculation [*e.g.* the Monaco® Radiation Treatment Planning System (Elekta)]. However, most planning systems, including the ERGO++ used in this study, make an approximation by summing doses calculated at the discrete CP and not in between. The greater the number of CPs, the closer this approximation is to the actual delivery. Despite this, we found that the majority of MLC leaves (96.7%) were within ± 1 mm of tolerable error. Few cases of gantry positional error exceeded the limit of 1°. However, this was found to be a virtual error and did not contribute to error in dose delivery. This experiment demonstrated that the tested variables and parameters of the Synergy S BM were synchronous and suitable for delivering VMAT using a dynamic MLC.

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