The sensitivity of patient specific IMRT QC to systematic MLC leaf bank offset errors

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Purpose: Patient specific IMRT QC is performed routinely in many clinics as a safeguard against errors and inaccuracies which may be introduced during the complex planning, data transfer, and delivery phases of this type of treatment. The purpose of this work is to evaluate the feasibility of detecting systematic errors in MLC leaf bank position with patient specific checks.
Methods: 9 head and neck (H&N) and 14 prostate IMRT beams were delivered using MLC files containing systematic offsets (± 1 mm in two banks, ± 0.5 mm in two banks, and 1 mm in one bank of leaves). The beams were measured using both MAPCHECK™ (Sun Nuclear Corp., Melbourne, FL) and the aS1000 electronic portal imaging device (Varian Medical Systems, Palo Alto, CA). Comparisons with calculated fields, without offsets, were made using commonly adopted criteria including absolute dose (AD) difference, relative dose difference, distance to agreement (DTA), and the gamma index.
Results: The criteria most sensitive to systematic leaf bank offsets were the 3% AD, 3 mm DTA for MAPCHECK™ and the gamma index with 2% AD and 2 mm DTA for the EPID. The criterion based on the relative dose measurements was the least sensitive to MLC offsets. More highly modulated fields, i.e., H&N, showed greater changes in the percentage of passing points due to systematic MLC inaccuracy than prostate fields.
Conclusions: None of the techniques or criteria tested is sufficiently sensitive, with the population of IMRT fields, to detect a systematic MLC offset at a clinically significant level on an individual field. Patient specific QC cannot, therefore, substitute for routine QC of the MLC itself. © *2010 American Association of Physicists in Medicine*. [DOI: 10.1118/1.3453576]

Key words: IMRT QC, multileaf collimator, systematic errors

I. INTRODUCTION

Intensity modulated radiation therapy (IMRT) requires not only labor intensive planning and delivery system quality assurance but also patient specific quality control (QC) in order to be confident in the accuracy of delivery. Patient specific QC is performed routinely in the clinic through comparison between predicted and actually measured planar dose maps for each beam of each patient. Comprehensive QC tests of the delivery system, and, in particular, the multileaf collimator (MLC), are less frequent.[1,2] Efficiency in the operation of an IMRT QC program would be enhanced if patient specific QC were capable of identifying suboptimal MLC performance at a level at which it becomes clinically significant.

The dosimetric effects of MLC related inaccuracies have been studied in literature.[3–5] In a previous theoretical study,[4] we have found that every 1 mm error in the position of all MLC leaves affects the equivalent uniform dose (EUD) by an average of 2.7% for prostate clinical target volumes (CTVs) and 5.6% for the head and neck (H&N) CTVs with the greater sensitivity for head and neck fields reflecting the greater modulation of these fields. Our results prompted us to suggest a tolerance in systematic leaf position accuracy of 0.3 mm if maximum EUD deviations of 2% in the CTV and 2 Gy for the organs at risk (OARs) are acceptable as a consequence of MLC effects only. The purpose of this work is to evaluate the feasibility of detecting clinically significant systematic MLC leaf bank offsets with routine patient specific IMRT checks.

Patient specific IMRT QC is carried out using a variety of systems including film, ionization chamber arrays, diode arrays, or electronic portal imaging devices (EPIDs). In par-

ticular, diode arrays and EPIDs have been proven to be simple, accurate, and efficient dose verification systems[6,7] and these systems are the focus of this study. Patient specific QC is performed at the Tom Baker Cancer Centre using a MAPCHECK™ device from Sun Nuclear Corp. (Melbourne, FL) and/or the aS1000 EPID from Varian Medical Systems (Palo Alto, CA). MAPCHECK™ contains 445 *n*-type diode detectors arranged in a 22×22 cm^2 grid of two detector densities. Detectors are placed 7 mm apart in the central 10×10 cm^2 area and 14 mm apart in the rest of the sensitive area. The data can be displayed by the MAPCHECK™ software as either relative or absolute dose for comparison to the calculated planar dose map. The aS1000 EPID is an amorphous silicon flat panel consisting of 1024×768 detectors in a 40×30 cm^2 active matrix (the size of each detection element is 0.39×0.39 mm^2 at the imager surface). The device is supported and positioned by a motorized assembly or *ExactArm* with a precision of a millimeter. Varian's Portal Vision displays either relative dose images in percent or absolute dose images in calibration units.

For the purpose of this study, we have taken the equipment exactly as commercially available and employed it as it is routinely used in the clinic. We have not attempted to modify the criteria used by the software, for which there are subtle differences between the systems. It was our purpose to assess the sensitivity of patient specific QC to suboptimal MLC performance under routine clinical conditions.

II. MATERIALS AND METHODS

We have randomly selected 23 6 MV intensity modulated fields (9 for head and neck and 14 for prostate irradiations) of the previously approved ECLIPSE™ treatment plans for this study. The MLC files containing the positions of the leaves during delivery of the beams were exported from ECLIPSE™, altered in order to incorporate systematic errors, and reimported into ECLIPSE™ for transfer to the treatment machine. The modified MLC files contained (a) +1 mm, (b) −1 mm, (c) +0.5 mm, and (d) −0.5 mm offsets in all open leaves of both banks (representing expansion or contraction of the MLC openings respectively) and (e) +1 mm offsets in all open leaves of one bank without modification of the opposite bank. The convention in ECLIPSE™ is that negative shifts regardless of bank side represent contractions of the MLC openings. A total of 115 perturbed plus 23 unperturbed MLC files was then delivered and measured using both MAPCHECK™ and the aS1000 EPID according to local IMRT QC practice. The measured planar dose maps were compared to the calculated dose maps of the reference (unperturbed) fields using five different criteria, four of which are the most common criteria identified in a survey by Nelms and Simon.[8] The criteria were (a) 3% absolute dose, 3 mm distance to agreement (DTA) which we denote 3A3D, (b) 3% relative dose, 3 mm DTA (3R3D), (c) 5% absolute dose, 3 mm DTA (5A3D), (d) 3% absolute dose, 3 mm DTA gamma (33γ), and (e) 2% absolute dose, 2 mm DTA gamma (22γ). MAPCHECK™ measurements were evaluated using the first four criteria together with the following setup parameters: A threshold (dose above which the points are considered in the analysis) of 10% of the maximum dose within the field and a dose difference threshold (the allowable cGy difference between absolute measured and planned points) of 0 cGy. In MAPCHECK™, the difference between the measured absolute dose and the corresponding planned absolute dose must exceed both the dose difference threshold and the percent criterion to fail the test. EPID measurements were evaluated using the last two criteria, viz., 33γ and 22γ.

The degree of agreement between the delivered planar dose distribution, measured with either the MAPCHECK™ or aS1000, and the predicted planar dose map is specified in terms of the percentage of passing points (ppp), which is the percentage of points that fall within the stated criterion.

Modulation of the beams was achieved using a Varian Millennium 120-leaf MLC (leaf width at the isocenter is 0.5 cm for the inner 80 leaves and 1 cm for the outer 40 leaves) in dynamic mode. The selected head and neck fields used 119–165 control points, while prostate fields used 85–129 control points. Routine quality control tests including machine output (which stayed within 1% for all our measurements), visual light field MLC verification (preceded by reinitialization of the MLC), and an EPID test (using the Las Vegas phantom[9]) were performed each day before an experimental session.

The MAPCHECK™ detector array was set at a 100 cm source to detector distance with 7 cm water equivalent buildup and was calibrated using the response to a 10×10 cm^2 field. The EPID was set at a 100 cm source to imager distance with no buildup. Predicted dose maps of the reference fields, i.e., without offsets, were calculated by the ECLIPSE™ treatment planning system for a water phantom (MAPCHECK™) or portal dosimeter (aS1000) using the conditions of our measurements and a 2.5 mm grid size.

Variability inherent in the measurement systems was quantified with 15 consecutive identical irradiations by one field using both MAPCHECK™ and the EPID. A further 11 measurements were made, each time moving the detector and repositioning, to evaluate the effects of setup uncertainty on our verification results. The variability in the readings of each detector and passing rates were recorded and are presented in Sec. III.

III. RESULTS

Figure 1 shows the ppp in the MAPCHECK™ study for the different available verification criteria as the systematic offset in MLC leaf bank position increases. The average ppp and range of data (shown by the error bars) are presented for (a) the 9 H&N fields and (b) the 14 prostate fields. The lines connecting the data are guides to the eye only. It is clear from Fig. 1 that relative dose measurements are very insensitive to MLC offset errors. The other criteria studied, incorporating absolute dose measurement, are somewhat more sensitive to systematic leaf offsets but the sensitivity is still limited when viewed against the spread of passing points (indicated by the error bars in Fig. 1) in this randomly selected population of fields. This is particularly true for the

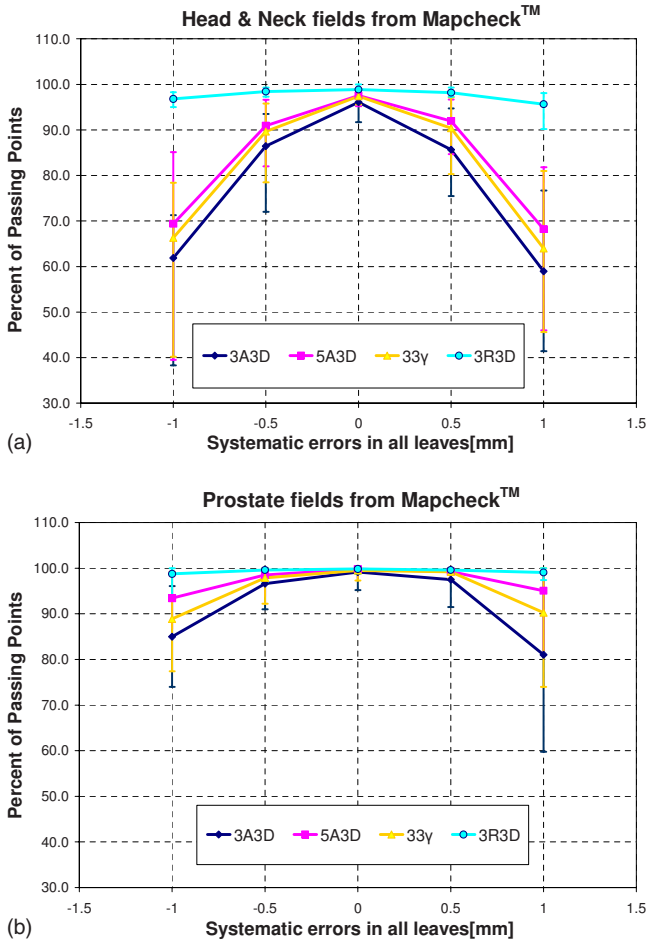

FIG. 1. Percentage of points passing the different criteria in MAPCHECK™ when systematic errors in the MLC leaf positions are introduced.

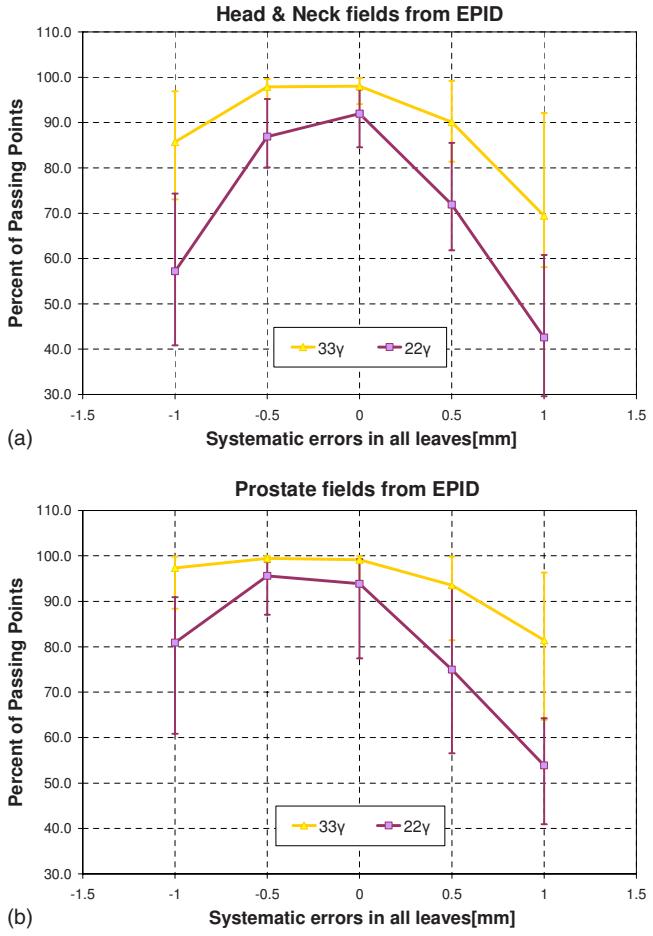

FIG. 2. Percentage of points passing the different criteria in EPID/Portal Vision (Varian Medical System) when systematic errors in the MLC leaf positions are introduced.

less modulated prostate fields [Fig. 1(b)]. The ppp resulting from a 1 mm MLC error in one bank only are not shown in the graph since they are quantitatively similar to the results from 0.5 mm in two banks (Fig. 1). Table I summarizes the statistical comparison between the various trials using MAPCHECK™. For the head and neck fields, the p values that characterize the difference in means between the reference (zero offset) and 0.5 and 1 mm offsets are all less than 0.001 for the most sensitive criterion, 3A3D. For prostate fields, the p value of the data from 0.5 mm offsets is 0.012, while the p value of the data from 1 mm offsets is less than 0.001.

TABLE I. p values from the Kolmogorov–Smirnov test to compare the experimental distributions of ppp with a reference (zero offset) distribution in MAPCHECK™.

p values for MAPCHECK™ results	3A3D	5A3D	33γ	3R3D
H&N				
+1 mm (two banks) systematic	<0.001	<0.001	<0.001	<0.001
+0.5 mm (two banks) systematic	<0.001	<0.001	<0.001	0.066
−0.5 mm (two banks) systematic	<0.001	0.001	0.001	0.019
−1 mm (two banks) systematic	<0.001	<0.001	<0.001	<0.001
+1 mm (one bank) systematic	<0.001	<0.001	<0.001	0.005
Prostate				
+1 mm (two banks) systematic	<0.001	0.001	<0.001	0.267
+0.5 mm (two banks) systematic	0.012	0.267	0.267	1.000
−0.5 mm (two banks) systematic	0.012	0.012	0.111	0.862
−1 mm (two banks) systematic	<0.001	<0.001	<0.001	0.012
+1 mm (one bank) systematic	0.029	0.023	0.417	0.999

Figure 2 shows the percentage of passing points using the EPID with gamma acceptance criteria of 22γ and 33γ as the systematic offset in MLC leaf bank position increases. The average ppp and the range of data (again shown by the error bars) are presented for (a) the 9 H&N fields and (b) the 14 prostate fields. The lines connecting the data are guides to the eye only. As can be seen in Fig. 2, the 33γ criterion, in particular, has a limited sensitivity to systematic errors, especially in prostate fields. The Kolmogorov–Smirnov is a nonparametric test used here to compare the experimental distributions of ppp with a reference (zero offset) distribution. The null hypothesis is that the two distributions have been drawn from the same distribution. Thus, a smaller p value will represent stronger evidence of the difference between distributions. Table II shows the statistical comparison between the experimental groups and the reference. For the head and neck fields, the p values that characterize the difference between the reference (zero offset) and 0.5 and 1 mm

TABLE II. p values from the Kolmogorov–Smirnov test to compare the experimental distributions of ppp with a reference (zero offset) distribution in EPID.

p values for EPID results	33γ	22γ
H&N		
+1 mm (two banks) systematic	<0.001	<0.001
+0.5 mm (two banks) systematic	0.001	<0.001
−0.5 mm (two banks) systematic	0.433	0.066
−1 mm (two banks) systematic	<0.001	<0.001
+1 mm (one bank) systematic	0.001	<0.001
Prostate		
+1 mm (two banks) systematic	<0.001	<0.001
+0.5 mm (two banks) systematic	0.001	<0.001
−0.5 mm (two banks) systematic	0.541	0.862
−1 mm (two banks) systematic	0.012	0.001
+1 mm (one bank) systematic	0.003	<0.001

offsets for the most sensitive criterion, 22γ, reached 0.066 and less than 0.001, respectively. For prostate fields, the p value of the data from 0.5 mm offsets reached 0.862, while the p value of the data from 1 mm offsets was less than 0.001. The difference between the ppp of fields with and without systematic offsets is only evident after the analysis of a group of fields but is not clearly apparent if an individual field is assessed by the IMRT QC criteria.

Irradiations were performed to quantify the inherent variability in the measurement systems and in the experimental setups. 98.5% of the 445 MAPCHECK™ diodes exhibited a standard deviation within 0.1% of the reading over 15 consecutive exposures, without re-set up. The observed variability in the MAPCHECK™ detector response corresponded to a variability in the average ppp of up to 0.6% (using 3A3D, 5A3D, 3R3D, and 33γ criteria). 99% of the 1024×768 pixels of our EPID detector exhibited a standard deviation within 0.1% of the reading and affected the average ppp by up to 0.1% (using 33γ and 22γ criteria). Setup uncertainty in the MAPCHECK™ experiments over 11 exposures affected the average passing rate by up to 1.3%, while setup uncertainty in the EPID measurements resulted in changes of up to 0.8% in the average ppp.

Thus, we conclude that the observed variability in ppp for the clinical fields (indicated by the error bars in Figs. 1 and 2) is not a consequence of variability in detector response, at least over a short time period, or setup uncertainties. From Figs. 1 and 2 and Tables I and II, it is clear that head and neck fields show greater sensitivity to MLC leaf bank offsets than prostate fields with both detectors due to the greater modulation of the head and neck fields.

IV. DISCUSSION

Systematic offsets in leaf bank position result in dose distributions that are higher or lower in absolute dose but with an overall shape that remains similar.[4] This was confirmed by comparing measured vs calculated dose maps in this study as well. The degree of dose deviation was typically uniform across low dose gradient regions but reached larger values in regions of high dose gradient where the measured reference fields (no systematic offset) were already challenged. An increase in the systematic offset by 0.5 mm (in either direction) produced planar dose differences of up to 12% for the H&N fields and up to 6% for the prostate fields, both expressed as a percentage relative to the maximum dose in the calculated field. Systematic deviations in all leaves represent the expansion (contraction) of all apertures contributing to the sliding window. Thus, a uniform increase (decrease) in dose across the field is expected due to the increase (decrease) in the time of exposure to the beam and the higher (lower) output as a consequence of changes in the head and phantom scatter. By considering this, a criterion that scales the measured dose map and the calculated dose map at some point, i.e., MAPCHECK™'s relative dose comparison can be expected to be relatively insensitive to leaf bank offsets. This limited sensitivity is evident in Fig. 1.

The results of MAPCHECK™ evaluations differ from those of the Varian Portal-Vision system for the same gamma criterion, e.g., 33γ, due to the different definitions of dose differences. In MAPCHECK™, a dose difference is expressed as percentage of the local dose whereas in Varian Portal Vision it is expressed as a percentage of a reference dose which is near the maximum dose of the planned map. This near maximum dose is defined by the system after data outliers have been eliminated. As a consequence, percentage dose differences at low doses are reported as being larger by MAPCHECK™'s software and, in the absence of other factors, result in a smaller ppp than that calculated by the Varian system for the same level of agreement between calculated and measured dose maps. The higher resolution of the portal dosimeter is expected to provide more accurate passing rate results compared to MAPCHECK™ when the same evaluation method is used. However, these two systems evaluate dose differences using different normalizations. The method of evaluation of dose differences affects the sensitivity of the system to detect positional errors in the MLC. Clearly, inconsistency in the definition of percentage dose differences requires the adoption of different tolerance levels if equivalent sensitivity to offset or other errors is to be achieved by these two systems.

An additional influence on passing rates is the threshold applied in the MAPCHECK™ system. Our results shown in Fig. 1 were obtained with no threshold. Figure 3 shows an example of the difference in the passing rates when a dose threshold (2 cGy) is applied in MAPCHECK™ compared to no threshold. The "no threshold" comparison is clearly more sensitive to leaf bank offsets. Two other parameters used in patient specific verification, average and maximum gamma values, were also investigated but they provided no additional significant information about the leaf bank offsets.

The results from these experiments with the EPID exhibited an asymmetry in the ppp with respect to the sign of systematic error (Fig. 2). This asymmetry in the passing rate has been reported by other authors[6,10] as well, but no definitive explanation has been given. In our study, the asymmetry cannot be attributed to misalignment as the setup uncertainty

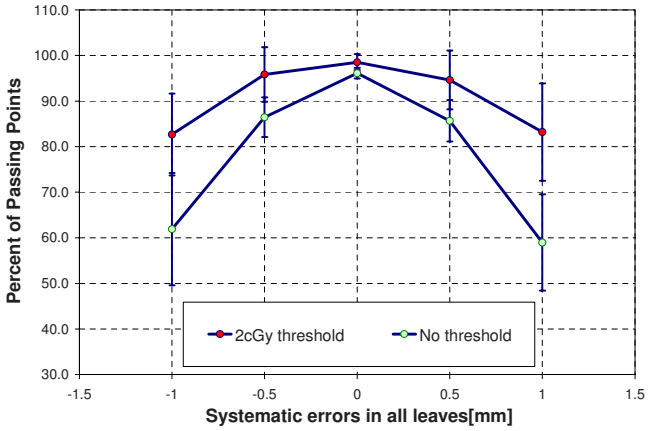

FIG. 3. Change in the percentage of points passing a 3% absolute dose and 3 mm DTA criteria when a dose difference threshold is applied in head and neck fields.

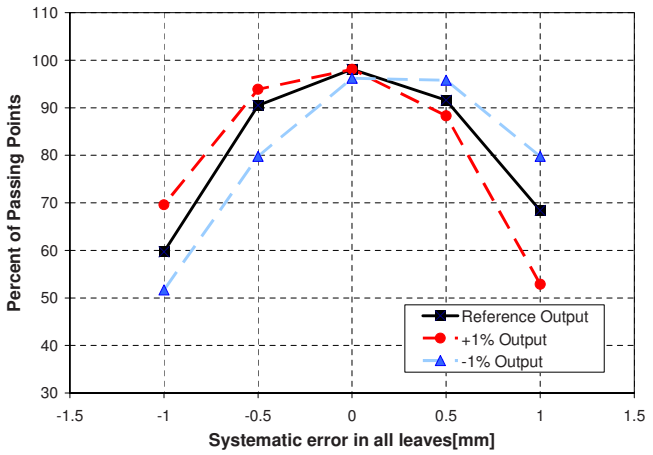

FIG. 4. Change in the percentage of points passing a 3% absolute dose and 3 mm DTA criteria for one head and neck field when the output varies by ±1% (MAPCHECK™).

analysis has suggested only a very small impact on the ppp (change in 0.8% for the average ppp of H&N cases and 1.3% for the prostate cases after 11 setups). In a further attempt to identify the source of instability, three consecutive comparisons between calculation and measurement were made, reinitializing the MLC before each measurement. The ppp for the reference condition (i.e., no leaf bank offset) changed over a range of 0.2%, −1 mm offset also exhibited a range of variation of 0.2%, and +1 mm a range of 2.6%. Thus, effects following reinitialization of the MLC do not seem to be responsible for the asymmetry noted by us and others.[6,10]

Following a suggestion by a reviewer of this manuscript, we have also investigated the role of output variations in the asymmetry shown in Fig. 2. As mentioned above, output tests prior to all measurements indicated a variation within ±1%. Consequently, we have performed a simulation exercise to identify the extent of changes in ppp caused by output variations of the order of ±1%. For convenience, this simulation exercise was performed with the MAPCHECK™ system since no straightforward comparable method was found for manipulating the EPID data. However, we expect both systems to respond in a qualitatively similar manner to a discrepancy between the actual linear accelerator output and that used for comparison between planar dose measurements and calculation. In MAPCHECK™, an absolute dose calibration converts relative to absolute dose by applying a single calibration factor to all detectors. This calibration factor is saved into a dose calibration file "dose.dat" and can be applied to any measured field. For this test, we have added two calibration factors to this file representing exact variations of a reference output by ±1%. We have applied the different calibration factors to one case of an H&N field and evaluated the ppp of 3% AD and 3 mm DTA criteria with respect to the calculated field (Fig. 4). As seen in Fig. 4, the passing rate is affected by the sign of output variation, e.g., the passing rate of negative systematic errors is further reduced by a low output but compensated by a high output. Larger variations in the passing rate occurred for those fields with larger systematic errors. While the ppp of fields with ±1 mm systematic errors changed by up to 27%, the ppp of the field with no errors changed up to 2% when the output was varied by ±1%. Thus, the accelerator output is critically important when performing patient specific IMRT QC with absolute dose tolerances since the ppp may be significantly affected by output variations even within the accepted tolerance range.[11] This effect clearly decreases the level of detectability of any mismatch between the predicted and the measured dose maps irrespective of the evaluation criteria used.

Due to the complexity of the anatomic site (i.e., proximity of the OARs, shape, and extent of the target volume) and beam geometry, H&N plans require more highly modulated fields than do prostate plans. The results of this study show that the sensitivity of common IMRT QC criteria to systematic leaf bank offsets depends on the degree of modulation present in the field. Yan *et al.*[10] also evaluated the sensitivity of IMRT QC using MAPCHECK™ and found that criteria such as 2A2D or 22γ could only detect systematic leaf bank offset errors of the order of 2 mm. Their results are qualitatively similar to those presented here, although they used a step and shoot delivery technique compared to our dynamic delivery and the complexity of their plans may have also been different. As we have seen, plan complexity does affect the ppp with any criterion.

As seen in Figs. 1 and 2, most of the fields with ±0.5 mm offsets and a few of the fields with ±1 mm positional error could pass a criterion of <5% failing points. The failing fields could be subjected to further scrutiny on an individual basis in terms of the locations of higher numbers of failing points and the number of MUs of the specific field and could potentially be accepted without noticing the positional errors of the MLC. Due to the spread of the reference (zero offset) data in Figs. 1 and 2, an individual field analysis of our IMRT data would not be able to distinguish between a failure due to the spread of results in a cohort of plans or due to MLC position errors.

The current analysis of patient specific QC data is performed on an individual basis. Each field is evaluated based on the differences between measured and calculated doses. If

the deviation is within a predetermined tolerance, the field is accepted. Looking at the error bars with our population of IMRT fields (Figs. 1 and 2), it is clear that some IMRT fields could report passing rates that are well within the criteria analyzed in this study and confound the detection of an MLC offset. It is also clear that some IMRT fields could report failing rates but without indicating the cause of failure due to ambiguity between the normal spread in ppp and MLC offset effects. Some authors suggested that in order to detect drifts in the system, it is necessary to analyze specific QC data on a population basis.[12] The results of the Kolmogorov–Smirnov test do suggest that a 1 mm error in the MLC leaf position could be detected from the analysis of a sufficiently large population of fields.

As shown in a previous study by us,[4] systematic leaf position tolerance should be within 0.3 mm if a maximum dose deviation of 2% in the EUD of the target and 2 Gy in the OARs is required using dynamic IMRT delivery. None of the IMRT QC criteria tested is sufficiently sensitive to identify MLC offsets within a clinical tolerance of 0.3 mm on a single field basis. Thus, we support the position[6] that IMRT QC cannot replace routine checks of MLC leaf position.

V. CONCLUSIONS

The combination of EPID detection and analysis system was less sensitive to systematic errors in the position of the MLC leaf banks than the combination of the MAPCHECK™ detector and dose difference analysis with respect to the local dose. Furthermore, the percentage of passing points calculated from the comparison between the predicted and the measured dose maps is very sensitive to small variations in the machine output, which are not corrected for during measurement. The most sensitive criteria to systematic MLC offsets of those tested are the 3% AD, 3 mm DTA for MAPCHECK™ and gamma index with 2% AD and 2 mm DTA for the EPID. However, none of the techniques or criteria tested is sufficiently sensitive, with our population of IMRT fields and delivery/measurement systems, to detect a systematic MLC offset at a clinically significant level on an individual field. Patient specific QC cannot, therefore, substitute for routine QC of the MLC itself.

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