On the sensitivity of common gamma-index evaluation methods to MLC misalignments in Rapidarc quality assurance

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Purpose: In this study the effects of small systematic MLC misalignments and gravitational errors on the quality of Rapidarc treatment plan delivery are investigated with respect to verification measurements with two detector arrays and the evaluation of clinical significance of the error-induced deviations.
Methods: Five prostate and six head and neck plans were modified by means of three error types: (1) both MLC banks are opened, respectively, in opposing directions, resulting in larger fields; (2) both MLC banks are closed, resulting in smaller fields; and (3) both MLC banks are shifted for lateral gantry angles, respectively, in the same direction to simulate the effects of gravity on the leaves. Measurements were evaluated with respect to a gamma-index of 3%/3 mm and 2%/2 mm. Dose in the modified plans was recalculated and the resulting dose volume histograms for target and critical structures were compared to those of the unaltered plans.
Results: The smallest introduced leaf position deviations which fail the >90% criterion for a gamma-index of 2%/2 mm are: (1) 1 mm; (2) 0.5 mm for prostate and 1.0 mm for head and neck cases; and (3) 3 mm corresponding to the error types, respectively. These errors would lead to significant changes in mean PTV dose and would not be detected with the more commonly used 3%/3 mm gamma-index criterion.
Conclusions: A stricter gamma-index (2%/2 mm) is necessary in order to detect positional errors of the MLC. Nevertheless, the quality assurance procedure of Rapidarc treatment plans must include a thorough examination of where dose discrepancies occur, and professional judgment is needed when interpreting the gamma-index analysis, since even a >90% passing rate using the 2%/2 mm gamma-index criterion does not guarantee the absence of clinically significance dose deviation.
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Key words: quality assurance, VMAT, Rapidarc, verification, gamma-index

I. INTRODUCTION

The concept of optimizing treatment plans using continuous gantry rotation and constantly changing field shapes, or intensity modulated arc therapy (VMAT), was first introduced in 1995.[1] The optimization problem Yu described exceeded computing capabilities at the time, and as a result VMAT was not introduced into clinical routine until 2001 when hardware with sufficient processing power became widely available. Since then various techniques for arc therapy have been developed.[2–5] All employing various multi-leaf collimator (MLC) parameters. Today there are several commercial solutions available for planning VMAT plans. Rapidarc planning in Eclipse has been developed by Varian (Varian Medical Systems, Inc.), Monaco VMAT (volumetric-modulated arc therapy) by Elekta (Elekta, Sweden), and Smartarc by Pinnacle (Philips Medical Systems, Chicago).

VMAT allows for the delivery of high quality treatment plans for noncomplex cases as regular prostate treatments, comparable with traditional static beam IMRT, in significantly reduced treatment delivery time.[6,7] However, this technology also demands a high level of precision and reliability from the linear accelerator and its control systems, since gantry rotation must be in sync with MLC movement and dose rate adjustment. The 2D detector arrays which are typically used for static beam IMRT plan QA measurements may not be suited to detect clinically significant delivery errors in VMAT plans. In the last years several studies have been performed to develop dosimetric procedures for the special needs in VMAT.[8–15]

We have developed software that will allow the controlled introduction of systematic errors into DICOM RT files in order to investigate how these errors manifest themselves in the Rapidarc VMAT QA measurements.

In this work all verification measurements are performed with the Octavius 2D-Array (PTW-Freiburg) and the Delta4 device (Scandidos). The physical properties of these devices have been discussed in several studies.[16,17] Three different

types of systematic errors, both MLC banks opened, closed, and shifted slightly for lateral gantry angles with the general field shape remaining the same, are applied to a set of eleven prostate or head and neck Rapidarc treatment plans in order to determine the sensitivity of those devices to these specific error types. The effects of those modifications on gamma passing rates of QA results and on resulting dose distributions and dose-volume-histograms of modified plans are investigated. Although we have a fairly good understanding of the correlation between gamma-index-based pretreatment dose QA and clinically relevant DVH-based metrics in IMRT (Ref. 18), there still is the need for further investigation regarding this correlation in VMAT treatment techniques.

This study has the goal to provide clinical users of Rapidarc or other VMAT technologies with guidelines to help users with appropriate QA verification criteria for the referred detector arrays under consideration of the gamma-index and to put detectable introduced systematic MLC errors into the context of their effects on DVH metrics.

II. MATERIALS AND METHODS

II.A. Linear accelerators and treatment planning software

All measurements were performed on Rapidarc-capable Varian Trilogy linear accelerators with Millennium MLCs. For all cases investigated 6 MV photons were used. The Varian Millennium MLC is capable of the dynamic modulation necessary for Rapidarc delivery using a sliding window technique. Leaf width is 5 mm at isocenter and the leaf bank has a total of 120 leaves. Varian specifies the leaf position accuracy in terms of end accuracy to be 1.0 mm and the end repeatability in millimeters at isocenter to be 0.6 mm.

II.B. Detector arrays

Two detector arrays, the 2D-Array Seven29 (PTW-Freiburg, Germany) and the Delta4 (Scandidos), were used in this study. Both detectors have a planar/coplanar geometry in contrast to an axial detector assembly, which was proven to have an impact on passing rates, but suggesting that, since both general geometries are comparable have similar characteristics, opposed to, e.g., ArcCheck.[19] The Eclipse-generated verification plan of each investigated case was measured with both devices and the results in terms of sensitivity are compared using gamma-index passing rates.

The 2D-Array Seven29 consists of a 27 × 27 matrix of small air-filled ionization chambers, each with a volume of $5 \times 5 \times 5$ mm^3. The matrix is assembled in such a way that the distance from the center of one chamber to the next is 10 mm, with a spacing of 5 mm from edge to edge.[17] The 2D-Array is combined with the Octavius phantom for QA of rotational treatments. It has an octagonal cross section to allow for easy measurement setups in multiple planes and reduce angular dependence of the array. It is constructed of polystyrene with a physical density of 1.04 g/cm^3 and a relative electron density of 1.00. The 2D-Array Seven29 fits accurately into a center cavity that is $300 \times 300 \times 22$ mm^3.[12]

The Delta4 device was developed by Scandidos and consists of 1069 *p*-type silicon diodes arranged on a 200×200 mm^2 biplanar matrix. The matrix is embedded in a cylindrical PMMA phantom (physical density 1.19 g/cm^3; relative electron density 1.147) with a diameter of 220 mm and a length of 400 mm. There are two different detector pitches. In the central area (60×60 mm^2) the gap between the diodes is 5 mm; in the outer area the gap increases to 10 mm. The diodes are cylindrical with a cross-sectional area of 0.78 mm^2.[16]

II.C. MLC editor for Rapidarc treatment plan modification

A stand-alone, user-friendly software tool for DICOM file manipulation was created based on a MATLAB-based prototype of MLC editor software provided to us by Professor Beckham and Oliver at the British Columbia Cancer Agency.[20] We took the basic idea behind this MATLAB program and developed it so it could easily be used by service engineers or customers for troubleshooting or to support the commissioning of their Rapidarc QA procedure.

The software program allows the user to import DICOM plan files and modify the position of individual MLC leaves or entire leaf banks systematically or randomly. Various different scripts allow for multiple kinds of modifications and even control-point specific shifts of MLC leaf positions to allow for angular dependent MLC modifications. All technical and mechanical restrictions as given by Varian were displayed as forbidden movements and automatically corrected; for instance, negative leaf gaps resulting from the closure of opposite leaf pairs were automatically set to the smallest permissible leaf gap of 0.5 mm. Generally, modifications were only applied to leaf pairs not blocked by jaws during the treatment delivery.

This software was used to simulate the investigated misalignments of the MLCs which could be applied directly to the exported DICOM plans while maintaining full compatibility with Eclipse and the treatment delivery system.

II.D. Rapidarc treatment plan modifications

Eleven Rapidarc treatment plans were used in this study: five two-arc prostate plans, three two-arc head and neck plans, and three three-arc head and neck plans. The treatment plans were created in the Varian Eclipse (v.8.9) treatment planning system and exported as DICOM files for further modification. Modified and original DICOM plans were then delivered to both the 2D-Array Seven29 and Delta4 detector devices by a Varian Trilogy linear accelerator operating with 6 MV photons.

For this study MLC leaf misalignments were generated by manipulating Rapidarc plan DICOM files before delivery. This was done to analyze the effects of such MLC misalignments on verification measurements. Dynalog files of actual treatment deliveries of Rapidarc plans in our clinic have never indicated errors of the magnitude as investigated in this study, but it was important for us to investigate if and how such

TABLE I. Overview of modifications with respect to introduced errors.

MLC modification	Magnitude of leaf displacement (in millimeters)		
Type 1 (opened MLC leaf banks)	0.25	0.50	1.00
Type 2 (closed MLC leaf banks)	0.10	0.25	0.5
Type 3 (gravitational shift)	1	2	3

errors would manifest themselves in the analysis of our verification measurements and what pass/fail criteria would ensure that the delivery of Rapidarc plans with clinically significant errors would not pass.

The following error types were introduced using the MATLAB-based software described previously and applied to all clinical prostate and head and neck Rapidarc plans: (1) both MLC banks are opened by 0.25 mm, 0.50 mm, and 1.00 mm in opposing directions, resulting in larger fields; (2) both MLC banks were closed by 0.10 mm, 0.25 mm, and 0.50 mm; and (3) both MLC banks were shifted in the same direction for lateral gantry angles to simulate effects of gravitational forces on the leaves by 1 mm, 2 mm, and 3 mm. In our model for the gravitational shift the shift already occurs as soon as the gantry moves to its starting position (-180°). The shift is of fixed magnitude once the gantry reaches -90° and changes its direction when approaching $+90^\circ$. For the last interval till its final position at $+180^\circ$ it will stay the same. The shift for the counterclockwise rotation is applied accordingly. For IMRT random leaf errors up to 2 mm were found to have little dosimetric effects[21,22] and initial tests with random leaf errors suggested the same outcome for Rapidarc treatment plans. The modifications representing conceivable worst case scenarios are summarized in Table I.

The initial idea originates from Oliver *et al.*,[20] in which similar modifications with different software were applied to Rapidarc plans. Whereas the existing study analyzed the significance of the introduced errors on a clinical basis, this study attempts to correlate the potential clinical impact with the gamma-index passing rates of actual verification measurements from two commonly used detector devices. For this, gamma-index passing rates were determined for each error type and magnitude of error with commonly used gamma-index criteria.

Each error type was evaluated both quantitatively and qualitatively. Quantitatively, the relationship between the dropping gamma-index passing rate and increasing magnitude of leaf position deviation for both detectors was examined. Then a closer look at the evaluation options available in each device's software was taken in order to interpret the effects of the applied MLC manipulations. While the first approach gives an understanding of the sensitivity of verification process to small leaf misalignments and the direct effect on the passing rate as a decisive criterion for Rapidarc QA, the closer look as to where the deviations occur and how this looks like in the verification software helps to account for cases in which the $>90\%$ is achieved even with significantly modified plans.

To investigate the clinical significance of the different types of errors introduced, the modified plans were imported into the treatment planning system Eclipse. By projecting the new plans onto the same CT image set as used for the original plan optimization the resulting dose-volume histogram after the dose calculation can be compared directly with the DVH of the original Rapidarc plan. For this study the comparison will focus on the PTV and the rectum as an important organ-at-risk (OAR) for prostate Rapidarc treatment plans. Other studies focusing on the relation between dose deviations in the DVHs of IMRT treatment plans and the correlating evaluation of gamma-index based QA measurements have already suggested that the techniques are insufficiently sensitive to detect small systematic MLC offsets with clinically significant DVH differences for IMRT plans.[20,23–25] For this study we regard an increase of the mean dose to the PTV by more than 2% as clinically significant according to our hospital's code of practice. This value was also proposed by Oliver *et al.*,[20] which gave the initial idea for this study, and has been used to define an action level for MLC position deviation. For IMRT it was shown that a 2% change in the generalized equivalent uniform dose (gEUD) for PTVs due to MLC miscalibration can be detected.[26] This study will investigate which magnitude of dose deviation to the PTV due to leaf errors can be detected for Rapidarc.

II.E. Rapidarc verification measurements

Quality assurance on Rapidarc treatment plans is performed by creating a verification plan in the Eclipse treatment planning system. This was achieved by copying the treatment plan onto volumetric CTs of the distinct phantom/detector devices. The predicted dose to the detector planes was calculated with a dose grid resolution of 2 mm, necessary to probe the strict 2%/2 mm gamma-index criteria. The 2 mm grid resolution was chosen according to an information theory and Fourier based analysis made by Dempsey *et al.*[27] that investigated the errors due to spatial discretization of the dose grid in IMRT which are prevalent in high dose gradient areas. Since it was stated that a 2.5 mm grid resolution is sufficient in order to keep the dose error within $\pm 2\%$, this value was adopted for Rapidarc treatment plans. Due to the delivery technique of permanent gantry and leaf motion the dose distributions tend to be smoother than those of regular static IMRT fields. The verification plans were then delivered by Varian Trilogy linear accelerators with the QA phantoms aligned to the verification plan isocenter. The linear accelerators are calibrated to an output stability of $\pm 1\%$. A follow-up measurement with simple open 10×10 cm field was performed for each plan in order to account for daily irregularities due to setup and machine output. Measured data were collected according to the preset settings chosen in each of the device's evaluation software. Detectors receiving doses less than 10% of the maximum dose measured were excluded from the analysis in order to minimize the effects of noise in low dose regions. For this study a low dose threshold of 10% was chosen as usually done for these kinds of cases in verification process of our hospital and often cited in the literature.[10,28] Nevertheless, the reader

TABLE II. Comparison of type 1, 2, and 3 QA results with gamma-index criteria of 2%/2 mm and 3%/3 mm for a prostate and a head and neck case with two arcs.

Passing rates (in %) for		Octavius coronal		Octavius sagittal		Delta4		
		2 mm/2%	3 mm/3%	2 mm/2%	3 mm/3%	2 mm/2%	3 mm/3%	
Type1	Original	99.5	100	95.6	100	94.8	99.6	
	0.25 mm	99.5	100	100	100	98.8	100	
	0.50 mm	94.6	100	97.8	97.8	97.0	99.8	
	1.00 mm	75.9	95.1	90.8	95.7	75.1	86.7	
Type2	0.10 mm	97.5	100	96.8	100	90.4	98.6	Prostate
	0.25 mm	96.5	100	95.2	99.2	86.2	97	
	0.50 mm	89.4	99.5	83.1	96.8	75.9	90.3	
Type3	1 mm	98.0	100	99.2	100	95.4	99.2	
	2 mm	90.0	100	90.8	100	86.9	97.8	
	3 mm	82.0	96.0	78.0	97	72.3	93.4	
Type1	Original	99.2	100	93.4	98.5	96.7	99.7	
	0.25 mm	99.4	100	96.3	98.9	93.3	99.0	
	0.50 mm	98.2	100	94.6	99.1	91.8	98.8	
	1.00 mm	77.3	97.4	80.5	98.1	70.4	90.5	
Type2	0.10 mm	97.3	100	95.7	98.3	95.5	99.6	Head and neck
	0.25 mm	95.7	100	93.2	97.9	96.2	99.7	
	0.50 mm	91.6	100	88.8	96.4	92.6	99	
Type3	1 mm	94.9	99.6	91.5	97.7	96.6	99.2	
	2 mm	91.3	99.0	77.1	91.3	93.0	98.5	
	3 mm	85.8	95.7	75.0	90.5	87.5	96.6	

should be aware that in some cases also low dose areas may be of great interest. Data from both detector array verification measurements were evaluated using gamma-index criteria of 2%/2 mm and 3%/3 mm for a >90% passing rate. Latter criterion is the standard used in literature[8,9] given as reference by both manufacturers.

Consecutive measurements with the accelerators on different days were performed to investigate the reproducibility of the QA results.

III. RESULTS

III.A. Comparison of gamma-index criteria

To improve the logic of our argumentation, we will first discuss the question if 2%/2 mm or 3%/3 mm should be used. In the second step we show that the passing rate as the only parameter may lead to misinterpretations. In the following the passing rates for one head and neck and one prostate plan are presented in order to illustrate the insensitivity of a 3%/3 mm gamma-index criterion with respect to a systematic opening of both MLC banks and the introduced gravitational shift (see Table II). We think, that in displaying the insensitivity of a common QA measurement with a 3%/3 mm index, as it is widely performed,[8–10,12–15] we would best showcase why we call for a stricter gamma-index and an inspection of dose distributions.

If the widely used 3%/3 mm criterion would be applied, these defective treatment plans would satisfy a QA check if a >90% is required.

III.B. Evaluation of QA measurements of modified Rapidarc treatment plans

As will be presented in the following, a stricter gamma-index (2%/2 mm) proved to satisfy a passing rate of >90% for (almost) all unmodified plans and modified plans drop quickly below 90% with an increase of the magnitude of the leaf shifts applied. With the commonly used gamma-index passing rate of 3%/3 mm, almost no difference between the modified and original verification plans can be observed. Furthermore, gamma-index passing rates for some verification plans with the largest leaf position error of several millimeters were clearly above the 90% passing rate threshold. The graphs presented in Secs. III.C–III.E result from the stricter gamma-index criteria (2%/2 mm), although a direct analysis of the same data with a 3%/3 mm criterion has been given for comparison in Sec. III.A. In the following two graphs (prostate cases and head and neck cases) are shown for each error type. These are given as mean gamma-index passing rates with a standard deviation for all of the investigated cases (five prostate, six head and neck cases). It has to be noted that the passing rates for the unmodified plans measured with the Delta4 were typically lower (~90% passing rate) than for the 2D-Array, which in most cases yielded passing rates close to 100%. However, this will influence the passing rates of the investigated modifications since a lower initial passing rate usually results in an earlier drop for introduced MLC errors, as will be seen in the following. An earlier reach of the 90% passing criterion should therefore not be understood as a quality criterion for the detector arrays. Since the detailed analysis of the performance parameters of the two detectors have not

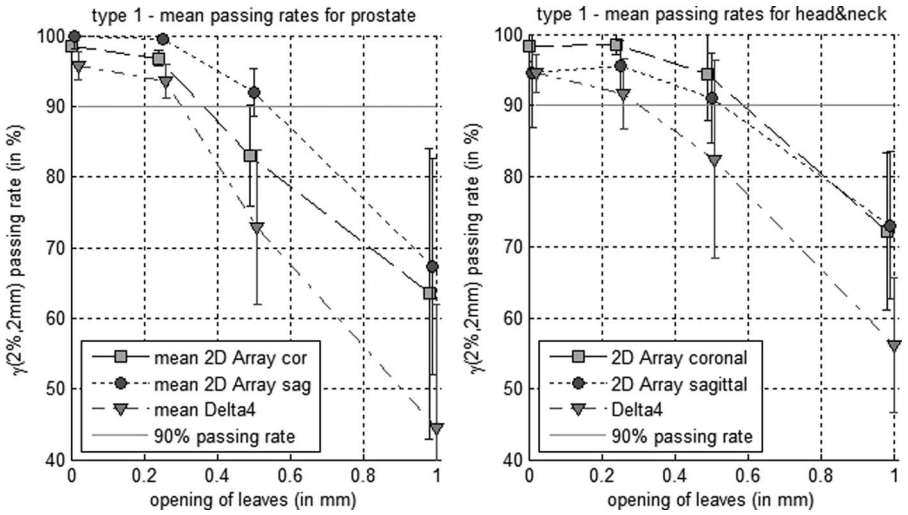

FIG. 1. Average passing rates (left: prostate cases; right: H and N cases) in relation to the introduced type 1 MLC positional error. The first reading point at 0 mm indicates the unmodified plan, followed by 0.25 mm, 0.5 mm, and 1.00 mm (MLC leaf bank opening).

been within the scope of this paper (for this see Refs. 16 and 17) a further analysis of this deviation in the initial passing rate was not performed.

To support our recommendation of treating each Rapidarc treatment plan as an individual case beyond the confinement of a global gamma-index we evaluated the effects on DVH metrics in terms of actual exemplary dose deviations rather than an average. The latter has already been provided by Oliver *et al.*[20] who presented a thorough investigation on the influence of MLC positional errors on the PTV and a broad spectrum of OARs which would exceed the scope of this study.

Type 1 and 2 errors were found to rescale the absolute dose to the PTV, either by increasing it when the leaf deviation resulted in a larger field (type 1) or by decreasing it when the leaf deviation resulted in a smaller field (type 2). The minimum and maximum dose changes as a result as well, but the discrepancies of this are a consequence of the dose shift in the PTV. Hence DVH comparison of type 1 and 2 errors will focus on the change of mean dose to the PTV. The DVH calculations of the modified treatment plans presented in the following were performed for two prostate and two head and neck cases with two and three arcs. Type 3 errors (gravitational shift) lead to cold and hot spots in the QA measurement. In most cases there was an almost equal amount of under- and overdosage, which suggests that the difference in the mean PTV dose in a verification plan modified with type 3 errors and an unmodified verification plan is relatively small. On the other hand, the difference in the maximum and minimum dose to the PTV is significant and would most likely exceed the tolerances accepted by a physician. Therefore, the DVH comparison of type 3 MLC modifications will concentrate on the changes in minimum and maximum dose to the PTV.

A comparison of gamma-index results with two-arc and three arc head and neck cases yielded no conclusive differences related to the number of arcs applied. Hence all head and neck cases were combined in one group for the evaluation step.

QA measurements on different days to confirm the reproducibility of the verification results yielded repeatable passing rates of within $\pm 1\%$ after a follow-up measurement with each device to account for the machine output.

III.C. Type 1 errors

III.C.1. Prostate

The results of type 1 error on gamma-index passing rate are presented in Fig. 1. In all of the investigated prostate plans, the introduction of the smallest type 1 modification (0.25 mm) remains unnoticed and results in $>90\%$ gamma-index passing rates according to both detectors. In some cases there even is an improvement of the passing rate. Three out of the five prostate plans with the 0.50 mm leaf opening fail the 90% criterion for measurements performed with the Delta4 device, whereas the Octavius 2D-Array yields inconclusive results; measurements in the coronal plane reach passing rates below 90% in two cases while the sagittal plane measurement passes, although barely (see Fig. 1). In these cases it is important that any measurement failing the 90% criterion should alert the physicist and hence a failed verification measurement does not necessarily provoke problems since a closer look will reveal any shortcomings of the Rapidarc plan. But still it is obvious that the Delta4, starting with an initial passing rate lower than the 2D-Array, hence yields lower passing rates for the introduced modifications and drops earlier below the $>90\%$ passing rate. The largest modification (1 mm) gives distinct results. All but one prostate case with 1 mm leaf openings fail the $>90\%$ passing rate.

III.C.2. Head and neck

Head and neck cases show similar results. The smallest error (0.25 mm) does not result in a passing rate below 90% for all measurements with the 2D-Array, whereas the Delta4 device detects deviations and a passing rate below 90% for

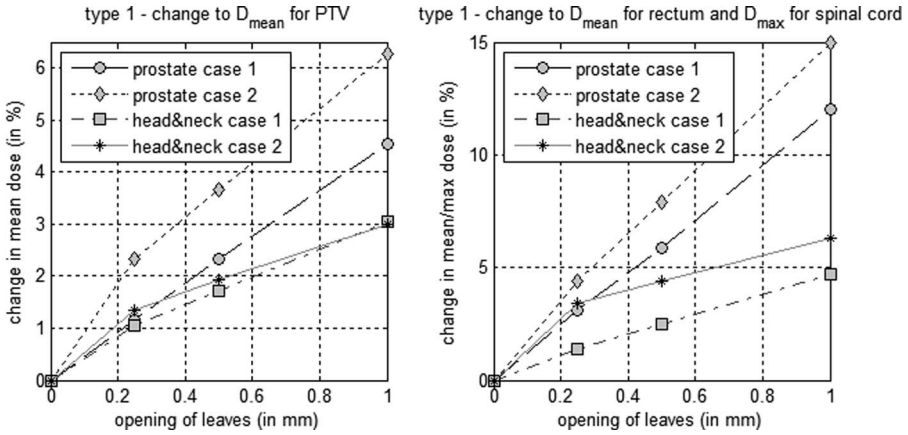

FIG. 2. Comparison of the mean doses to the PTV (left) and to the rectum/spinal cord for four exemplary cases with type 1 errors. (Left) The change in mean doses to the PTV. (Right) Change in mean doses to rectum (prostate cases) and to the spinal cord in case of the head and neck treatment plans.

two out of all six head and neck cases for the same modification in which—again as seen for prostate cases—the initial passing rate was significantly lower (<95%) for the original Rapidarc plan. The second modification (0.50 mm MLC bank opening) is detected in half of the investigated cases but often remains unnoticed. The largest leaf position deviation, 1 mm, yields a failure for all cases with both detectors. Therefore, the threshold sensitivity of the two devices is at a 1.00 mm MLC bank opening (a type 1 error) for both prostate and head and neck cases.

This value is in the range of the value given by Varian as the tolerance specification for leaf positioning (see Millenium MLC equipment specifications 2010). Only MLC misalignments larger than 1 mm will be detected by Varian's control software and interrupt the beam delivery.

III.C.3. Examples for influence on DVHs

At the same time there are significant deviations of >2% in the mean dose of the PTV, even for errors in the range of 0.25–0.50 mm (see Fig. 2).

The largest leaf position deviation that went undetected on the majority of plans with both devices is 0.50 mm. Such an error will increase the mean dose inside the PTV by 1.7% to 3.6% (see Fig. 2). We found that the mean dose increased almost linearly with increasing MLC bank opening. The largest rise was found for a prostate case, which had an initial mean PTV dose of 103.6% (with 100% being the prescribed dose) which was increased to 110.1% for the largest modification of 1.00. This yields a total increase of the mean dose by more than 6%. However, even a 0.25 mm MLC bank opening affected the mean dose of this prostate case significantly, resulting in a >2% higher mean PTV dose. The smallest change in PTV dose was found for a head and neck case (three arcs) in which the mean PTV dose was increased by 3% for a 1 mm shift, which still is >2%.

In addition to the DVH comparison of PTV dose, the rectum as a critical OAR is analyzed with respect to type 1 errors (see Fig. 2) for prostate cases as well as the spinal cord for head and neck cases, respectively. When comparing the mean and maximum doses to the rectum/spinal cord with increasing leaf position deviation, the large impact of relatively small position modifications on dose to an OAR close to the target volume is evident. The mean rectum, respectively, maximum spinal cord dose is almost linearly increased with larger errors. The largest deviation in the dose to the rectum for a 0.25 mm opening, which would typically pass the >90% gamma-index criterion (passing rates for both detectors >97%), is an increase of the mean dose by more than 4%. For the spinal cord the largest deviation is a 1.5% increase in the mean dose while passing rates for both detectors are above 93%, even with the strict 2%/2 mm criterion and the same modification (0.25 mm opening).

III.D. Type 2 errors

III.D.1. Prostate

In all but one of the investigated prostate cases, the smallest modification (0.10 mm MLC bank closing) went undetected by both detectors and the modified plans achieved passing rates higher than 90%, although the passing rate for each case was lower than the one of the unmodified plan (see Fig. 3). Closing the MLC banks on both sides of each segment in the Rapidarc plan produced a directly observed lower dose inside the PTV.

The investigated prostate cases fail the >90% gamma-index passing rate criterion for all modified plans with 0.50 mm closed MLC leaf banks. The 0.25 mm leaf closing does not result in a failure for most modified prostate verification plans.

III.D.2. Head and neck

For head and neck cases, QA results were found to be less predictable with respect to the introduced MLC misalignment. The critical threshold for the sensitivity of both detector arrays with type 2 errors was found to vary depending on the case. While the passing rates for two two-arc head and neck dropped below 90% for a 0.25 mm MLC bank closing, each of the three-arcs plans required an additional increase in leaf

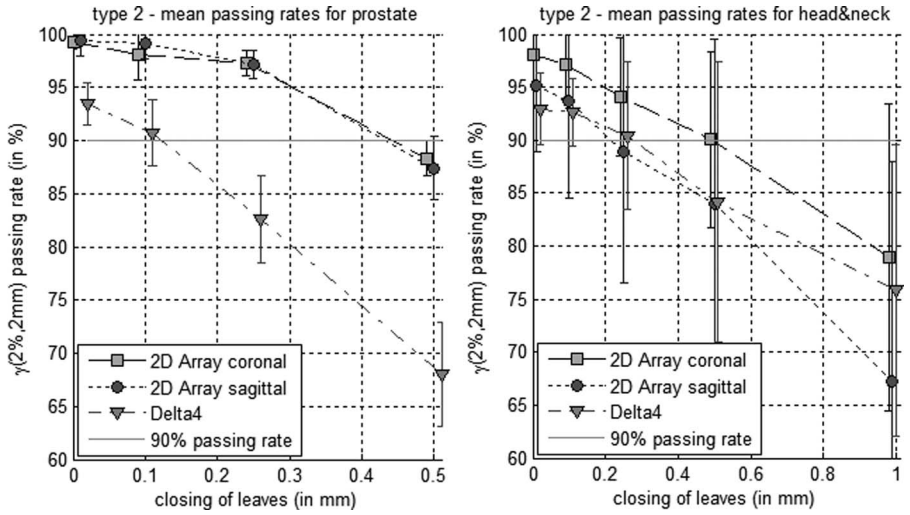

FIG. 3. These graphs show the average passing rates (left: prostate cases; right: H and N cases) in relation to the introduced type 2 MLC positional error. The first reading point at 0 mm indicates the unmodified plan, followed by 0.10 mm, 0.25 mm, 0.50 mm, and a 1.00 mm for the H and N case (MLC leaf bank closing). A 0.5 mm modification already let the passing rates drop below 90% for prostate cases, whereas for the head and neck cases an additional modification was necessary.

position deviation to 1.00 mm, with one particular case requiring a 2.00 mm MLC bank closing to produce a passing rate failure. Hence no universal value for the sensitivity of type 2 errors can be provided for the head and neck plans. However, for most cases the leaf position deviation value lies below 1 mm, which is within the published MLC positioning accuracy (see Millenium MLC equipment specifications 2010).

III.D.3. Examples for influence on DVHs

By closing the MLC leaf banks, the mean PTV dose decreases with increasing leaf position modification. The largest decrease was found in a head and neck case in which the mean dose dropped from 105.4% of the original prescription to 103.0% for the 1 mm modification, yielding a significant difference of more than 2%. The decrease between the largest type 2 modifications for the two prostate plans remains between 1% and 2% (see Fig. 4). The effects on the prostate cases are again higher than on the head and neck cases.

In summary, the smallest error which results in gamma-index passing rates consistently below 90% is in the sub-mm region (in our example 0.50 mm for the 2D-Array and 0.25 mm for the Delta4) for prostate and 1.00 mm for head and neck cases by both devices. This corresponds to a decrease of the mean PTV dose in the range of −0.6% to −1.9% (prostate) and −0.5% to −0.9% (head and neck). The effects of type 2 errors are comparably small in terms of the change in the mean dose to the PTV. This is striking when compared to the previous type 1 modification, where the mean dose change is significantly larger although the basic principle of the introduced modification is the same. This may be due to the fact that leaf pairs cannot be closed beyond the 0.5 mm limit, whereas type 1 errors are not limited by such a constraint.

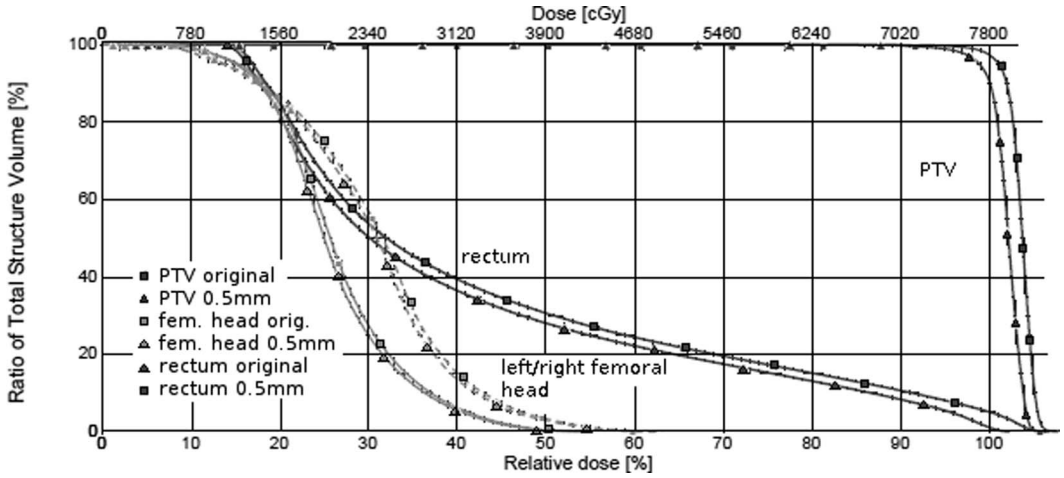

FIG. 4. DVH of example prostate case comparing the original plan ([]) and type 2 modified plan with a 0.50 mm MLC leaf bank closing (Δ). Displayed are the curves for the PTV, the rectum, and the left and right femoral heads.

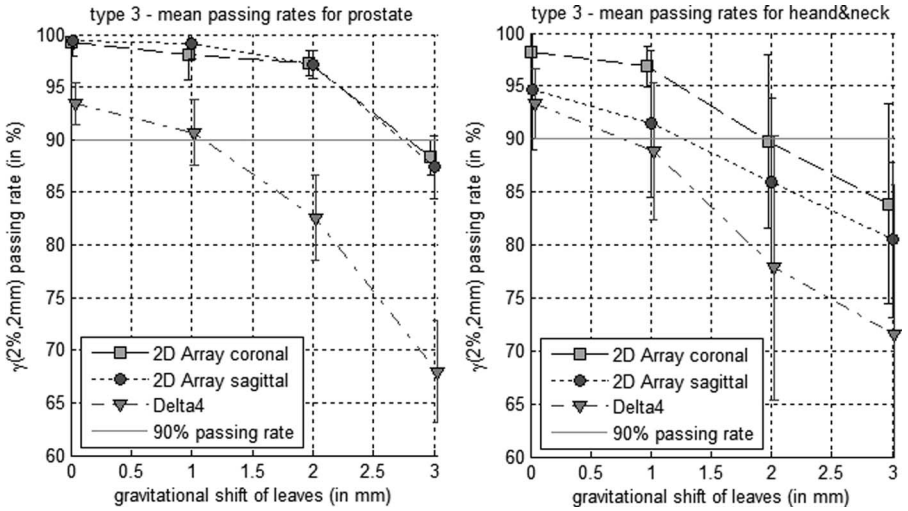

FIG. 5. These graphs show the passing rates (left: prostate cases; right: H and N cases) in relation to the introduced type 3 MLC positional error. The first reading point at 0 mm indicates the unmodified plan, followed by 1 mm, 2 mm, and 3 mm gravitational shift.

Changes in the mean or maximum doses to OARs are not analyzed in this section, since the closing of MLC leaf banks has demonstrably led to a decreased overall dose in the PTV, as well as in the OARs. This was stated in a study by Oliver *et al.*[20] and can be seen in the exemplary DVH in Fig. 4 in which the modification (0.5 mm leaf bank closing) not only affects dose metrics of the PTV but also illustrates that OARs in general show lower doses as well.

III.E. Type 3 errors

III.E.1. Prostate

The modified prostate plans follow the same pattern for both detector devices. The smallest introduced error (1 mm gravitational shift) was found to always meet the >90% criterion and often achieved an even higher passing rate than the original unmodified plan with the Delta4 device which often has, as shown before, a lower (~90%) passing rate than the 2D-Array (see Fig. 5). Hence the second modification (2 mm gravitational shift) results in passing rates of <90% in all five prostate plans measured by Delta4; with the Octavius 2D-Array, only one case achieved a passing rate less than 90% in the sagittal orientation. The threshold for the passing rate of prostate cases with respect to type 3 modifications was found to be 2 mm for the Delta4 device and 3 mm for the 2D-Array with the Octavius phantom due to the difference in initial passing rate.

III.E.2. Head and neck

Analysis of head and neck cases revealed that the smallest introduced error (1 mm gravitational shift) is typically not detected by any of the two detectors. There is a difference between the characteristics of modified three- and two-arc verification plans with respect to gamma-index passing rates, in which the former seems to be less prone to most of the introduced errors. Generally the passing rates drop below 90% for an applied shift of 3 mm, whereas in some cases (mainly three-arc) a 2 mm shift indicates a failure. Furthermore, the fact that the MLC control software is programmed to detect MLC leaf misalignments above 1 mm means that gravitational shifts in the range of 2–3 mm would cause a machine interlock. Nonetheless, due to a miscalibration of the MLC these errors might still emerge and hence provide an understanding of the effects of a possible shift of MLC banks under consideration of gravitational forces.

Type 3 errors in which the investigated QA devices typically do not detect introduced leaf position deviations were of a magnitude of 1 mm for prostate cases and 2 mm for head and neck cases on the Delta4 device, and 2 mm for both prostate and head and neck cases on the 2D-Array. This corresponds to a change in minimum dose of 0.9% and a 1.2% increased maximum dose to the PTV for the 1 mm shift (Delta4 device). The 2 mm shift results in 5.7%–6.0% lower minimum doses and 4.3%–5.1% higher maximum doses in the investigated prostate cases. The head and neck cases yield 2.4%–4.5% lower minimum doses and 0.5%–2.0% higher maximum doses for a 2 mm gravitational shift. It is also evident that head and neck plans are again less prone to the introduced modifications, which is quite well represented in the passing rate curves which in general drop later than for the prostate cases.

III.E.3. Examples for influence on DVHs

The comparison of the DVH for original and modified prostate plans reveals how the dose curve of the manipulated plan with a 2 mm gravitational shift results in higher maximum and lower minimum doses to the PTV (see Fig. 6).

Again the change in the minimum and maximum PTV dose for the head and neck cases is smaller than for the prostate cases (see Fig. 6). The largest decrease in dose was found in two prostate cases with 3 mm gravitational shifts, with differences >13% between the minimum PTV dose of the unmodified and modified plan. The minimum dose of the two head and neck cases dropped by 6% and 10%. The

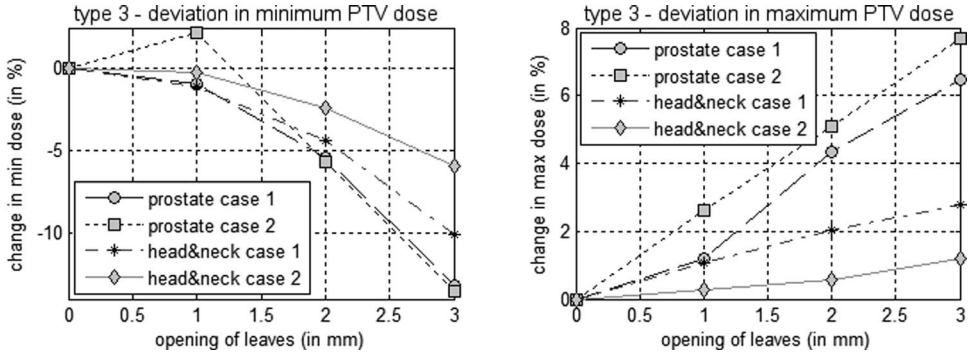

FIG. 6. Comparison of the minimum (left) and maximum (right) PTV doses for the four investigated cases with type 3 errors.

comparison of the maximum PTV dose yields results similar to type 1 and 2 errors in which the prostate cases are more affected by the introduced gravitational shift. The largest increase in maximum PTV dose can be found for a prostate case, where an increase of 9% was observed. The increase of maximum dose is changed almost linearly whereas the decrease of minimum dose is not.

IV. DISCUSSION

IV.A. Evaluation of gamma-index criteria 2%/2 mm and 3%/3 mm

Since the early days of IMRT, a 3%/3 mm criterion was established as the standard for gamma-index based IMRT treatment plan verification and often has been adopted for VMAT as well.[8–10,12–15] At the beginning of this study, the same 3%/3 mm standard was assumed for the QA of Rapidarc treatment plans. However, the initial measurements and QA evaluations showed that larger than expected MLC modifications were necessary in order for the modified plans to fail the standard gamma-index criterion in accordance to other studies which analyzed sensitivity of IMRT QA with gamma-indexes of 3%/3 mm and 2%/2 mm.[29] Thus different settings for the distance-to-agreement (DTA) and dose deviation were tested to see how small the criteria could be pushed to simultaneously achieve >90% passing rates for the unmodified plans and while remaining strict enough to result in error-containing modified plans failing the selected gamma-index criteria. For the cases investigated here, the 2%/2 mm criterion was found to satisfy this purpose best. In fact the most significant reason to use a stricter set of criteria comes from the DVH comparison of the modified plans with the original plan. Rapidarc plans with MLC modifications that could be detected with the standard 3%/3 mm gamma-index criteria revealed huge differences between the DVH curves for the PTV. As shown in the evaluation of the DVHs for the different error types one can see how big the discrepancies are even for the smaller modifications created for a 2 mm/2% analysis. Stricter settings (e.g., 1%/1 mm) showed inconclusive results as the verification of the original plan already yielded a failing passing rate below 90% and were found to be insufficient in order to evaluate the verification results. It was shown that in the range of 1%/1 mm statistical fluctuations and systematical errors of the method become dominant.[17] A >90% passing rate as a criterion was chosen because it yielded a sufficient threshold to include the measurements of the unmodified plans while at the same time distinguishing them from the plans with larger leaf modifications. Other even more error sensitive passing criteria, for example, 1.5%/1.5 mm or 2%/1 mm in combination with a lower passing rate of 80%, were not systematically investigated in our study, but based on our experience would yield similar sensitivity to errors in the delivery of Rapidarc plans. Therefore, they could be chosen as an alternative to the 2%/2 mm at 90% passing criteria we investigated here. However, it should be pointed out that evaluated data was gathered with two detector systems, the Delta4 system and Octavius 2D-Array system, for which the stated gamma-index criteria proved to be most feasible. For other detector systems different pass/fail criteria may be more suitable as geometries of other detector systems differ.

From Table II it is evident that without the stricter criteria even the largest modifications satisfy a >90% passing rate, while the evaluation of plans with the smallest modifications typically show no difference in passing rate results.

IV.B. Detection of systematic MLC misalignments with gamma-index 2%/2 mm

Geometrical properties of the detectors such as the lateral response function or the sampling distance will certainly have an influence on the errors that are detectable. On the first sight, the fact that passing rates are crossing the 90% threshold earlier in the case of the Delta4 device may indicate that for the presented examples the Delta4 device seems more sensitive to small errors. In fact, this may be a result of the fact that the Delta4 device collects data in two planes, whereas the Octavius 2D-Array only collects dose in one plane at a time. This statement is supported by the fact that Delta4 typically showed a lower passing rate even for the original treatment plans. However, a general answer to the question which detector array offers a higher sensitivity to delivery errors was not part of our investigation and in our opinion would require a more detailed analysis due to the complexness of this question. As an example how to perform such an investigation, in a recent study Gago-Arias *et al.*[30] analyzed the influence of chamber response functions on the detectability of delivery errors for several ionization chamber and diode arrays. They showed that standard ionization chamber and diode arrays

performed in a very similar manner as long as the tolerances for the gamma function were not lower than 1.5%/1.5 mm. Due to the wider response function of air-ionization chambers the group found a slightly higher sensitivity to random fluence perturbations for ion chamber arrays while diodes seemed to be more accurate in a point-by-point verification. This complex behavior shows that the question for the best array has always to be answered in the specific context of the dosimetrical situation. However, for the examples showed in this work the Octavius 2D-Array and the Delta4 device are both able to detect small systematic MLC misalignments of the investigated magnitude. On the other hand with both devices errors might not always be detected, sometimes even when they could have a significant effect on the dose distribution. In another study[31] slightly larger detectable error magnitudes were found when investigating systematic MLC errors with a different planar detector array. As our results indicate a >90% passing rate with a strict gamma-index criterion of 2%/2 mm should always be aimed for with both devices. Especially the opening and closing of MLC leaf banks can result in what we consider clinically significant PTV dose changes without alerting the medical physicist to the problem, because the verification plan has a gamma-index passing rate of >90%.

This demonstrates that such an error would neither cause an interlock during the actual treatment nor would it be detected by the majority of the QA measurements performed with the 2D-Array or the Delta4 device, despite a strict >90%, 2%/2 mm gamma-index passing rate criterion. It is therefore necessary to pay close attention to the subtle indications of discrepancies between calculated and measured dose when examining dose distributions in the verification software tool. As pointed out earlier, an analysis of where and how individual ionization chambers and diodes detect deviant doses should also be performed.

In our study introducing leaf errors to the delivery of clinical Rapidarc plans showed a slightly higher impact on prostate cases when compared to head and neck cases. As it has been pointed out by LoSasso *et al.*[32] the magnitude of dose error is directly proportional to the MLC gap error such that treatment plans that are comprised of very narrow gap deliveries will be more sensitive to MLC gap errors. Prostate plans are more similar from patient to patient and are therefore in similar ways influenced by the modifications we introduced to the delivery. The PTV of prostate plans is generally small compared to those of head and neck cases, resulting in Rapidarc plans with very narrow gap deliveries and a higher sensitivity to delivery errors. Head and neck cases on the other hand generally vary more from patient to patient in their degree of complexity and patients selected for this study represent cases of varying complexity from very simple (large gaps between MLCs, very little MLC positional variation) to very complicated (very small gaps between MLCs, lots of MLC movement). This explains the relatively large standard deviation observed in the gamma-index passing rates compared to the more homogeneous results given by the prostate measurements.

The widely used standard criterion of 3%/3 mm (Refs. 8–10 and 12–15) is, as this study has shown (see Table II), insufficient and will not help to detect even large positional errors of the MLC. Most of the largest implemented modifications (1.0 mm leaf bank opening, 0.5 mm leaf bank closing, and 3 mm gravitational shift) would achieve passing rates >90% which would, in a standard QA evaluation, satisfy the verification procedure. Wagner and Vorwerk[13] suggested increasing the criterion to >99% with a 3%/3 mm gamma-index which resembles the passing-rate results of the investigated unmodified treatment plans in this study when a 3%/3 mm criterion was applied. This, however, does not guarantee, as the exemplary cases have shown, that MLC misalignments with significant effects on the PTV and OAR doses will be detected. It has been shown previously that even for large errors the passing-rates are often >99%. With the stricter 2%/2 mm criterion, these modifications can be detected and yield passing rates clearly below 90%. Smaller modifications (e.g., 0.50 mm MLC bank opening) may still remain unnoticed in most cases and are unlikely to be noticed during a machine QA, yet can lead to clinically significant dose deviations in the PTV and adjacent OARs. A study by Oliver *et al.*[20] suggests that the systematic opening/closing of MLC leaf banks are required to be within 0.6 mm to maintain the PTV70 within 2%. Our measurements show that these requirements may not be fulfilled with both detector arrays under consideration of a 2%/2 mm gamma-index in most cases. Even relatively large dose deviations of >2% to the PTV will often remain unnoticed, whereas for IMRT it was found to be within 2%.[25]

The correlation between gamma-index passing rates and dosimetric effects on the DVH is weak, as previous studies have already suggested for IMRT.[20,23–25]

It has to be noted that the magnitudes of introduced modifications for type 3 errors are larger than the threshold given by the control software. Hence the systematic gravitational shift is unlikely to yield significant dose deviations without causing the MLC control system to interlock. Yet these errors were included to provide the user with an idea of what the effect of a gravitational shift might be on the gamma-index based QA method in case of a malfunctioning control software of a miscalibration of MLCs. In our experimental setup any inherent gap MLC misalignments would contribute to the purposely introduced error, hence the overall MLC misalignment is: $\Delta\text{total} = \Delta\text{inherent} + \Delta\text{introduced}$.

This study has shown that even with the stricter gamma-index criterion, an incontestable decision whether a plan is safe to treat cannot solely rely on a simple gamma-index passing rate. The passing rate is certainly a good indicator that allows a preliminary decision, but the next step must include a thorough evaluation of the dose distribution itself by the physicist. Any accumulation of connected cold or hot spots in the region of the target volume, instead of single failing detectors in the areas of high dose gradients, can be indicative of a discrepancy between calculated and delivered dose.

IV.C. Guidelines for Rapidarc QA with gamma-index

The user should aim for a >90% passing rate with the enhanced gamma-index criteria of 2%/2 mm in order to provide a sufficiently strict analysis, with respect to the two types of

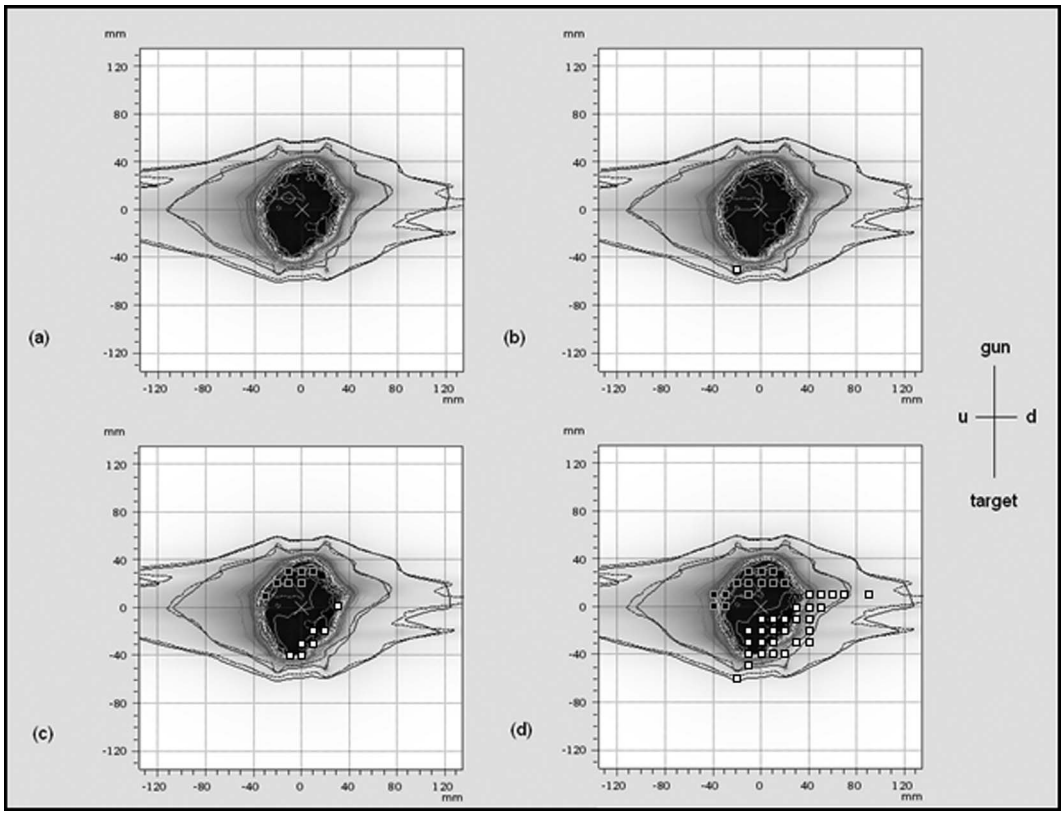

FIG. 7. This figure displays the dose distribution of type 3 errors for a prostate case. The matrices show the comparison of measured with calculated dose for the sagittal measurement: (a) Original plan with passing rate of 100%, (b) 1 mm gravitational shift with 99.5%, (c) 2 mm gravitational shift with 93%, and (d) 3 mm gravitational shift with 80.3%. Black dots indicate cold and white dots hot spots.

detectors being subject in this study. Any treatment plan that fails the >90% passing rate should automatically arouse suspicion as to significant deviations between the calculated and deliverable treatment plan. This should be in accordance to any conventional QA measurements valid for IMRT as well as Rapidarc treatment plans.

Furthermore, any treatment plan that satisfies the >90% criterion, but in which large and connected regions of over- or underdosage appear, must be investigated further. Whereas the Delta4 phantom software contains implemented dose deviation curves which can indicate the type of error (see Sec. III), relationship between the dose distribution curves, and respect to the detectors can be closely examined with PTW's VeriSoft evaluation tool.

This work has indicated that very high doses in large sections of the PTV can be related to type 1 or 2 errors. Type 3 errors may induce cold spots as well as hot spots evenly distributed along an imaginative cross section line through the PTV (see Fig. 7). It is understood that these incidences of hot and cold spot areas are not solely caused by the introduced MLC positional errors. However, any occurrences of this kind, regardless of passing rate, should result in the same response as any failed QA measurement. Most likely these cases are indicating flaws in the leaf positions of the treated plan according to the investigated error types. If there are very few points in the regions of high dose gradients, as is typical for IMRT verification plans, and the gamma-index passing rate is above 90%, the treatment plan most likely satisfies the QA standards. Again it is emphasized that the gamma-index criterion as the single decisive tool for treatment is insufficient, and further evaluation as to the distribution of deviant doses should be mandatory.

V. CONCLUSION

The present study shows that the strict 3%/3 mm gamma-index criterion to analyze VMAT treatment plans is not sufficient for judging plan quality, a 2%/2 mm gamma-index criterion in general is. However, we always recommend a supplemental inspection of the dose distribution and the whereabouts of failing detectors because clinically significant modifications can even remain unnoticed with a strict 2%/2 mm gamma-index criterion.

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[1]C. X. Yu, "Intensity-modulated arc therapy with dynamic multileaf collimation: An alternative to tomotherapy," Phys. Med. Biol. **40**, 1435–1449 (1995).

[2]C. Cameron, "Sweeping-window arc therapy: an implementation of rotational IMRT with automatic beam-weight calculation," Phys. Med. Biol. **50**, 4317–4336 (2005).

[3]S. Ulrich, S. Nill, and U. Oelfke, "Development of an optimization concept for arc-modulated cone beam therapy," Phys. Med. Biol. **52**, 4099–4119 (2007).
[4]T. Bortfeld and S. Webb, "Single-Arc IMRT?," Phys. Med. Biol. **54**, N9–N20 (2009).
[5]K. Otto, "Volumetric modulated arc therapy: IMRT in a single arc," Med. Phys. **35**, 310–317 (2008).
[6]M. Oliver, W. Ansbacher, and W. Beckham, "Comparing planning time, delivery time and plan quality for IMRT, Rapidarc and tomotherapy" J. Appl. Clin. Med. Phys. **10**, 117–131 (2009).
[7]M. Pasler, H. Wirtz, and J. Lutterbach, "Impact of gantry rotation time on plan quality and dosimetric verification – VMAT vs IMRT," Strahlenther. Onkol. **187**, 812–819 (2011).
[8]S. Korreman, J. Medin, and F. Kjaer-Kristoffersen, "Dosimetric verification of RapidArc treatment delivery," Acta. Oncol. **48**, 185–191 (2009).
[9]J. L. Bedford and A. P. Warrington, "Commissioning of volumetric modulated arc therapy (VMAT)," Int. J. Radiat. Oncol., Biol., Phys. **73**, 537–545 (2009).
[10]I. Iftimia, E. T. Cirino, L. Xiong, and H. W. Mower, "Quality assurance methodology for Varian RapidArc treatment plans," J. Appl. Clin. Med. Phys. **11**, 130–143 (2010).
[11]R. Boggula, M. Birkner, F. Lohr, V. Steil, F. Wenz, and H. Wertz, "Evaluation of a 2D detector array for patient-specific VMAT QA with different setups," Phys. Med. Biol. **56**, 7163–7177 (2011).
[12]A. Van Esch, C. Clermont, M. Deviller, M. Iori, and D. P. Huyskens, "On-line quality assurance of rotational radiotherapy treatment delivery by means of a 2D ion chamber array and the Octavius phantom," Med. Phys. **34**, 3825–3837 (2007).
[13]D. Wagner and H. Vorwerk, "Two years experience with quality assurance protocol for patient related Rapid Arc treatment plan verification using a two-dimensional ionization chamber array," Radiat. Oncol. **6**, 1–8 (2011).
[14]H. Fakir, S. Gaede, M. Mulligan, and J. Chen, "Development of a novel ArcCHECK insert for routine quality assurance of VMAT delivery including dose calculation with inhomogeneities," Med. Phys. **39**, 4203–4208 (2012).
[15]S. Syamkumar, S. Padmanabham, P. Sukumar, and V. Nagarajan, "Characterization of responses of 2D Array Seven29 detector and its combined use with octavius phantom for the patient-specific QA in Rapidarc," Med. Dosim. **37**, 53–60 (2012).
[16]V. Feygelman, D. Opp, K. Javedan, A. J. Saini, and G. Zhang, "Evaluation of a 3D diode array dosimeter for helical tomotherapy delivery QA," Med. Dosim. **35**, 324–329 (2010).
[17]B. Poppe, A. Blechschmidt, A. Djouguela, R. Kollhoff, A. Rubach, K. Willborn, and D. Harder, "Two-dimensional ionization chamber arrays for IMRT plan verification," Med. Phys. **33**, 1005–1015 (2006).
[18]H. Zhen, B. E. Nelms, and W. A. Tome, "Moving from gamma passing rates to patient DVH-based QA metrics in pretreatment dose QA," Med. Phys. **38**, 5477–5489 (2011).
[19]V. Feygelman, G. Zhang, C. Stevens, and B. Nelms, "Evaluation of a new VMAT QA device, or the "X" and the "O" array geometries," J. Appl. Clin. Med. Phys. **12**, 146–168 (2011).
[20]M. Oliver, I. Gagne, K. Bush, S. Zavgorodni, W. Ansbacher, and W. Beckham, "Clinical significance of multi-leaf collimator positional errors for volumetric modulated arc therapy," Radiother. Oncol. **97**, 554–560 (2010).
[21]G. Mu, F. Ludlum, and P. Xia, "Impact of MLC leaf position errors on simple and complex IMRT plans for head and neck cancer," Phys. Med. Biol. **53**, 77–88 (2008).
[22]M. Oliver, K. Bush, S. Zavgorodni, W. Ansbacher, and W. Beckham, "Understanding the impact of RapidArc therapy delivery errors for prostate cancer," J. Appl. Clin. Med. Phys. **12**, 32–43 (2011).
[23]J. Kruse, "On the insensitivity of single field planar dosimetry to IMRT inaccuracies," Med. Phys. **37**, 2516–2524 (2010).
[24]B. Nelms, H. Zhen, and W. Tomé, "Per-beam, planar IMRT QA passing rates do not predict clinically relevant patient dose errors," Med. Phys. **38** 1037–1044 (2011).
[25]A. Rangel, G. Palte, and P. Dunscombe, "The sensitivity of patient specific IMRT QC to systematic MLC leaf bank offset errors," Med. Phys. **37**, 3862–3867 (2010).
[26]V. Moiseenko, V. LaPointe, K. James, L. Yin, and M. Liu, "Biological Consequences of MLC calibration errors in IMRT delivery and QA," Med. Phys. **39**, 1917–1924 (2012).
[27]J. Dempsey, H. Romeijn, J. Li, D. Low, and J. Palta, "A Fourier analysis of the dose grid resolution required for accurate IMRT," Med. Phys. **32**, 380–388 (2005).
[28]A. Gloi, R. Buchanan, C. Zuge, and A. Goettler, "RapidArc quality assurance through MapCHECK," J. Appl. Clin. Med. Phys. **12**, 39–47 (2011).
[29]G. Yan, C. Liu, T. A. Simon, L. C. Peng, C. Fox, and J. G. Li, "On the insensitivity of patient-specific IMRT QA to MLC positioning errors," J. Appl. Clin. Med. Phys. **10**, 120–128 (2009).
[30]A. Gago-Arias, L. Brualla-Gonzáles, D. Gonzáles-Castano, F. Gómez, V. Vega, J Sueiro, and J. Pardo-Montero, "Evaluation of chamber response function influence on IMRT verification using 2D commercial detector arrays," Phys. Med. Biol. **57**, 2005–2020 (2012).
[31]G. Betzel, Y. Niu, and C. Yu, "Is RapidArc more susceptible to delivery uncertainties than dynamic IMRT?," Med Phys. **39**, 5882–5890 (2012).
[32]T. LoSasso, C. Chui, and C. Ling, "Physical and dosimetric aspects of a multileaf collimation system used in the dynamic mode for implementing intensity modulated radiotherapy," Med. Phys. **25**, 1919–1926 (1998).