Is RapidArc more susceptible to delivery uncertainties than dynamic IMRT?

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Purpose: Rotational IMRT has been adopted by many clinics for its promise to deliver treatments in a shorter amount of time than other conventional IMRT techniques. In this paper, the authors investigate whether RapidArc is more susceptible to delivery uncertainties than dynamic IMRT using fixed fields.

Methods: Dosimetric effects of delivery uncertainties in dose rate, gantry angle, and MLC leaf positions were evaluated by incorporating these uncertainties into RapidArc and sliding window IMRT (SW IMRT) treatment plans for five head-and-neck and five prostate cases. Dose distributions and dose-volume histograms of original and modified plans were recalculated and compared using Gamma analysis and dose indices of planned treatment volumes (PTV) and organs at risk (OAR). Results of Gamma analyses using passing criteria ranging from 1%–1 mm up to 5%–3 mm were reported.

Results: Systematic shifts in MLC leaf bank positions of SW-IMRT cases resulted in 2–4 times higher average percent differences than RapidArc cases. Uniformly distributed random variations of 2 mm for active MLC leaves had a negligible effect on all dose distributions. Sliding window cases were much more sensitive to systematic shifts in gantry angle. Dose rate variations during RapidArc must be much larger than typical machine tolerances to affect dose distributions significantly; dynamic IMRT is inherently not susceptible to such variations.

Conclusions: RapidArc deliveries were found to be more tolerant to variations in gantry position and MLC leaf position than SW IMRT. This may be attributed to the fact that the average segmental field size or MLC leaf opening is much larger for RapidArc. Clinically acceptable treatments may be delivered successfully using RapidArc despite large fluctuations in dose rate and gantry position.

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I. INTRODUCTION

Despite recent debate on its theoretical justifications,^{1–4} the use of rotational intensity modulated radiation therapy (IMRT) has been readily adopted by many clinics for its promise to deliver IMRT treatments in a shorter amount of time than other conventional IMRT techniques. As different variations of intensity-modulated arc therapy (IMAT) (Refs. 5 and 6) have been implemented clinically, investigators have steadily reported plan and dosimetric comparisons for several tumor sites as compared to other modalities.^{7–26}

In addition to dynamic leaf motion as in dynamic-MLC IMRT, RapidArcTM (Varian Medical Systems, Palo Alto, CA) utilizes gantry rotation as well as variations in gantry speed and dose rate. Many studies have advocated that the inherent complexities of this technique require similar, but additional, commissioning and quality assurance than that of conventional IMRT.^{27–29}

An important task for dynamic MLC QA has been to detect systematic geometric errors, which can lead to large

dosimetric errors in the delivery of IMRT.^{30–32} Many subsequent studies have been performed focusing on primarily fixed field dynamic IMRT to analyze the dosimetric impact of systematic as well as random leaf errors. For example, in a study of MLC and backup diaphragm errors for dynamic IMRT, Parsai *et al.*³³ indicated that when MLCs or backup diaphragms alone were perturbed, random errors of at least $\sigma = 1.5$ mm were required to cause dose discrepancies greater than 5%, while systematic errors on the order of ± 0.5 mm were shown to result in significant dosimetric deviations. In a study that proposed a Monte Carlo based IMRT dose verification method, Luo *et al.*³⁴ found that an average MLC leaf positional error of 0.2 mm can result in a target dose error of about 1.0%. Mu *et al.*³⁵ studied the impact of random and systematic MLC leaf position errors for head and neck IMRT patients. They found that the dosimetric effect was insignificant for random MLC leaf position errors up to 2 mm, but for a 1 mm systematic error, the average changes in $D_{95\%}$ were 4% in simple plans versus 8% in complex plans with notable differences also seen in spinal cord, brainstem, and parotid

glands. Rangel and Dunscombe³⁶ also studied random and systematic MLC positional errors in their study of dynamic IMRT. They found the impact of normally distributed random errors up to 2 mm to be negligible, but noted that if a 2% change in equivalent uniform dose of the target and 2 Gy for the organs at risk (OARs) were adopted as acceptable levels of deviation in dose due to MLC effects alone, then systematic errors in leaf position will need to be limited to 0.3 mm. Ung *et al.*³⁷ noted in their step-and-shoot IMRT study that systematic MLC errors depended on the direction of movement of the MLC relative to the beam central axis.

The impact of MLC errors has also been investigated briefly with respect to Elekta's implementation of IMAT, VMATTM. Ling *et al.*²⁷ discussed MLC errors in their VMAT commissioning and QA study and observed a direct relationship between MLC leaf position errors and leaf speed. In a VMAT study by Oliver *et al.*,³⁸ a linear correlation was observed between MLC errors and generalized equivalent uniform dose (gEUD) for random and systematic errors. Specifically, the gEUD dose sensitivities for PTV70 for eight head-and-neck (HN) cases were -0.2 , -0.9 , -2.8 , and 1.9 Gy mm^{-1} for random, systematic shift, systematic close, and systematic open errors. They suggest that to create plans that are robust against MLC errors, the total MU should be minimized and MLC gaps should be as large as possible without sacrificing plan quality. Tatsumi *et al.*³⁹ used three different treatment planning systems to create VMAT plans for five prostate cases and tested pass rates when systematic MLC leaf positions errors were introduced directly into the linac controller. They found that the impact of leaf position errors on dose distributions depended upon the final optimization result from each planning system due to a correlation between dose error and average leaf gap width.

The dosimetric impact of random and systematic changes in gantry angle during IMRT delivery has been reported by few authors. In their study of angular misalignments on fixed-portal IMRT, Low *et al.*⁴⁰ presented a method that estimates dose errors caused by unintended collimator, gantry and couch setting errors. Xing *et al.*⁴¹ noted that although angular setting misalignments play a smaller role than patient positioning errors, they found that a 5° gantry error in only one of nine coplanar beams resulted in a 1.5% decrease in the minimum target dose or 5.1% in the maximum cord dose. In contrast, it has been shown that the impact of slightly displacing the gantry angle of beam apertures is minimal to IMAT deliveries.^{42,43}

Oliver *et al.*⁴² reported on the dose sensitivity of delivery errors on RapidArc prostate cases that included varying gantry angle, MU, and MLC leaf positional errors. Systematic and random gantry position errors up to 1° were found to be relatively insignificant. Random MU errors up to 5% and random MLC position errors up to 2 mm were found to have an insignificant effect on dose. Systematic MLC gap open/close errors had the greatest impact on gEUD. They described the difference in gEUD(%) per mm of their RapidArc prostate cases versus other IMRT studies to be a function of the percentage of mean gap widths $< 2 \text{ cm}$.

Previous studies report on errors observed on specific delivery systems primarily for fixed-field IMRT. As Oliver *et al.* indicated,⁴² a preferable comparison between two techniques would be to use the same patient cohort for the same deliveries planned with the same planning criteria. In this study, experiments were performed to assess the relative dosimetric impact of delivery errors using a dynamic IMRT technique versus a RapidArc technique. Unlike previous studies, the comparison was carried out with the same clinical cases using the same optimizer and dose calculation engine, which was modeled for deliveries on the same linear accelerator.

II. METHODS

This study evaluated the susceptibility of RapidArc and sliding window (SW) IMRT to several types of delivery uncertainties in the delivery of five HN and five prostate cases. An EclipseTM treatment planning system (v8.6) with the analytical anisotropic algorithm was used to create all cases, which were planned for delivery on a Varian TrilogyTM with a 120 Millennium MLC (Varian Medical Systems, Palo Alto, CA). Using RapidArc, head-and-neck cases were planned using a single arc rotation while all prostate cases were planned using two arcs. Seven-field IMRT plans using the sliding window technique were then created on the same planning system. Beam angles of 0° , 50° , 100° , 150° , 210° , 260° , and 310° were used for prostate plans. HN sites varied, and only one planned treatment volume (PTV) (of typically three) was used to simplify the comparison of the delivery between the two techniques. HN beam angles were equidistant, but some varied for sparing of critical structures by up to 10° . Cases for each site varied in complexity and target volume; planning Target volumes (PTV) and total monitor units (MU) for cases using either technique are listed in Table I. Critical structures included, but were not limited to, brainstem, cochlea, optical chiasm, optical nerves, parotid glands, and spinal cord for head-and-neck patients, and bladder, lymph nodes, rectum, and small bowel for prostate. For HN cases, particular attention was paid to the following dose constraints for violation: brainstem, $0.1 \text{ cc} < 55 \text{ Gy}$; spinal cord, $10 \text{ cc} < 45 \text{ Gy}$. Head-and-neck prescription doses were 50.4 Gy/28 fxs for PTV1, 9 Gy/5 fxs for PTV2, and 10.8 Gy/6 fxs for PTV3. The same optimization objectives and penalties were used for either SW or RapidArc cases, which were checked for compliance. A conformity index (CI) was used as a tightness-of-fit of the PTV to the prescribed isodose volume, which was defined as the volume receiving 95% of the isodose divided by the PTV. A homogeneity index (HI) was also used to quantitatively compare target dose homogeneity between original sliding window and RapidArc plans, which was calculated as $(D_2 - D_{98}) / D_{\text{mean}}$. Average CIs for HN plans were 0.97 ± 0.05 and 0.98 ± 0.01 for SW and RapidArc, respectively; for prostate plans, 0.96 ± 0.05 and 0.94 ± 0.05 for SW and RapidArc, respectively. Average HIs for HN plans were 0.12 ± 0.01 and 0.11 ± 0.02 for SW and RapidArc, respectively; for prostate plans, 0.12 ± 0.02 and 0.10 ± 0.02 for SW and RapidArc, respectively. Note that differences between most individual sliding window and RapidArc plans were

TABLE I. Planning target volumes and total monitor units for cases using either seven-field sliding window (SW) IMRT or RapidArc (RA). Cases 1–5 are head-and-neck and cases 6–10 are prostate.

Case	PTV Vol [cm ³]	Total MU	
		SW	RA
1	58	346	220
2	236	812	233
3	437	661	296
4	431	1360	330
5	609	996	354
6	1330	1329	383
7	1166	2564	397
8	840	1242	432
9	1102	1439	510
10	884	2108	545

small; the difference between the CI and HI of 8 of 10 plans (4 HN, 4 prostate) were within 0.01 and 0.02, respectively.

Plans were exported as DICOM RT files from Eclipse to a separate computer workstation. To emulate delivery uncertainties, modifications were made to cloned DICOM files to create variations in MLC leaf positions, gantry angle, and dose rate using an in-house IDL program (v8.0, ITT Visual Solutions, Boulder, CO). The modified DICOM RT files were then imported back into Eclipse for dose calculation. Scenarios were created that exemplified two types of changes in MLC leaf positions. Systematic errors were created by shifting the entire MLC leaf bank (60 leaves) away from the central axis of the beam (X1 direction) for 0.5, 1.0, 1.5, and 2.0 mm. A separate scenario involved adding uniformly distributed random variations of ± 2 and ± 3 mm to individual leaves that were involved in shaping the beam aperture, i.e., had any change in position during the delivery of the initial arc plan. Random MLC errors therefore included both initial calibration errors as well as successive leaf positioning errors during delivery. Changes to the initial position or gantry angle were performed by rotating a SW or RapidArc plan by 1°, 2°, 3°, 4°, or 5° in the positive (clockwise) direction. To match the original cases and for calculations to proceed without error, any changes to the plan also required a start angle of 179° and a finishing angle of 181°. Because of these two angular constraints, any control point that fell between these two angles was programmed to be placed in next closest open interval and equidistant from adjacent control points. As a result of the angular shift, plans were in practice rotated in the counterclockwise direction.

Variations in nominal dose rate $\Delta MU/\Delta t$ for RapidArc cases resulted from a change in the gantry angle position for a given control point. The MU weight ΔMU and control point spacing $\Delta\theta$ associated with a control point and its preceding control point were used to calculate $\Delta MU/\Delta t$ for a given gantry angle θ , which can be defined as

$$\left(\frac{\Delta MU}{\Delta t}\right) = \Delta MU \left(\frac{\Delta\theta}{\Delta t}\right) \Delta\theta^{-1},$$

where $(\Delta\theta/\Delta t) = 360^\circ/65 \text{ s} = 5.54^\circ \text{ s}^{-1}$ is the reference gantry speed assumed to be constant for nominal dose rates $\leq 600 \text{ MU min}^{-1}$.²⁷ With ΔMU and $(\Delta\theta/\Delta t)$ held constant using this model, fluctuations in dose rate for modified plans were then reflected as a change in gantry angle, θ' . In other words, the change in angular spacing forces a change in the actual MU per degree, which would emulate a change in the actual dose rate versus the planned dose rate for delivery. Dose rates for each segment were modified accordingly by adding a normally distributed random variation of $\sigma = 10\%$, 20%, 30%, 40%, or 50% of the calculated dose rate at each control point. As some changes in dose rate were large, the order of control points was also allowed to change.

For the purposes of this study, the following physical constraints were ignored while performing dose calculations in Eclipse: leaf speed, gantry acceleration, and monitor units per degree (MU°). This allowed the corresponding changes to be made in this study including scenarios where apertures or control points even changed order. Varying MU or gantry angle explicitly is representative of potential errors in the planning stage and is not the focus of this study.

Dose statistics between original and modified plans were compared using dose indices of PTVs and OARs from dose-volume histograms (DVH), 2D Gamma analysis via MapCHECK (Sun Nuclear Corp, Melbourne, FL) for planar dose analyses and 3D Gamma analysis using inhouse Monte Carlo dose verification software. DVH statistics included minimum ($D_{\min}$), maximum ($D_{\max}$), and mean dose (D_{mean}). Gamma analysis criteria (% dose difference and mm distance-to-agreement) ranged from 5%–3 mm down to 1%–1 mm to evaluate both fine and coarse changes in the dose comparison. Absolute dose and a threshold value of 10% (or percent contour above which plan points are included) was used for gamma comparisons. A mean leaf gap (MLG), which was calculated using the distance between opposing MLC leaves that participated in shaping the beam for delivery, was also used for plan and delivery comparisons in the study of systematic MLC leaf position errors.

III. RESULTS

III.A. MLC leaf position errors

Figure 1 shows the results of DVH indices, e.g., average percent differences in $D_{\min}$, $D_{\max}$, and D_{mean} , for PTVs of modified head-and-neck and prostate plans following systematic shifts in MLC leaf bank (X1) positions of 0.5, 1.0, 1.5, or 2.0 mm. Average percent differences of PTV D_{mean} values per mm bank shift using SW and RapidArc were 4.5% mm^{-1} vs. 1.2% mm^{-1} for HN plans and 3.4% mm^{-1} vs. 1.0% mm^{-1} for prostate, respectively. The D_{mean} of most OARs were also about three times as high for SW ($\sim 6.5\% \text{ mm}^{-1}$) than for RapidArc ($\sim 2.2\% \text{ mm}^{-1}$); mean dose changes to the brainstem or spinal cord were $< 0.1\% \text{ mm}^{-1}$. Average maximum dose changes for brainstem and spinal cord in RA cases for a shift of 2.0 mm were 2.6% and 2.3%, respectively, and not violate maximum dose constraints. For SW cases, however, one violated the maximum dose constraint with a bank shift

FIG. 1. Comparison of average PTV minimum, maximum and mean dose values for original vs. modified (a) head-and-neck and (b) prostate cases using either RapidArc (RA) or sliding window (SW) IMRT with systematic shifts in MLC (X1) leaf bank position.

of 1 mm. If the shift in the MLC bank was X2 and not X1, it is possible that other violations may have occurred for either SW or RA.

The average percent differences of PTV D_{mean} values per mm bank shift for all plans were then plotted against MLG (Fig. 2). The figure illustrates that there is a clear difference between the two delivery techniques, and suggests that there is a trend between dose sensitivity to systematic MLC errors and MLG (power law curve fit, $R^2 = 0.94$).

Figure 3 shows results of Gamma analyses performed to compare differences in dose distributions using SW or RapidArc while incorporating systematic shifts in an entire MLC leaf bank position. Distributions were evaluated using criteria of 1%–1 mm, 2%–2 mm, 3%–3 mm, and 5%–3 mm. Using a criterion of 3%–3 mm, pass rates and therefore quality of SW plans quickly fell below what may be required for an acceptable delivery (>95%) for a bank shift <1 mm. Figure 4 illustrates the dosimetric effect of systematic shifts in MLC leaf bank positions when using either SW or RapidArc. In the coronal plane at isocenter, 2%–2 mm criterion

FIG. 2. Comparison of average PTV values per mm due to systematic shifts in MLC (X1) leaf bank position vs. mean leaf gap using either RapidArc (RA) or sliding window (SW) IMRT for head-and-neck (HN) or prostate (P) cases. A power law curve is fitted for comparison.

FIG. 3. Side-by-side comparison of average Gamma pass rates for (a) head-and-neck and (b) prostate plans delivered using either RapidArc (RA) or sliding window (SW) IMRT cases with systematic shifts in MLC leaf bank position.

FIG. 4. Dose distribution comparisons using 2%-2 mm Gamma analysis criterion illustrating pass rates for MLC leaf bank shifts of 0.5, 1.0, 1.5, and 2.0 mm for (a) one HN case and (b) one prostate case. PTV contours are shown. Points that failed are indicated in red.

was used to show the relative changes in pass rates between the use of SW and RapidArc. Points that failed the Gamma test are shown in red, i.e., a higher dose in comparison.

Uniformly distributed random shifts of up to 2 mm in active MLC leaf positions showed no significant change in D_{mean} of PTVs ($<0.1\%$) for all plans using either RapidArc or SW. However, shifts of up to 3 mm resulted up to 0.7% and 0.2% change in D_{mean} of PTV of head-and-neck and prostate plans, respectively. Average gamma pass rates of 99.8% were found for shifts up to 2 mm using 1%-1 mm criterion; shifts up to 3 mm ranged from 96.7% to 99.7% for head-and-neck plans and 98.8% to 100% for prostate plans, respectively. Data points that failed were found roughly equally inside and outside PTVs. Differences in dose homogeneity were seen in some OARs when comparing the impact of random leaf errors. For example, differences in D_{min} and D_{max} values of the bladder and rectum when using SW were $<1.5\%$ as compared to $<0.7\%$ when using RapidArc for prostate plans. However, this is most likely case-dependent given the beam angles used for a SW plan.

III.B. Gantry angle errors

When comparing averaged PTV minimum, maximum and mean dose values alone over the specified range of errors, no clear difference is seen between SW and RA as shown in Fig. 5. Shifts in gantry angle slightly affected OARs (0.1% – 0.2% deg^{-1}) (not shown), and smaller changes were seen in PTVs (0% – 0.05% deg^{-1}). Some OARs were more susceptible to changes in gantry angle due to close proximity to high dose

FIG. 5. Comparison of average PTV minimum, maximum and mean dose values for (a) head-and-neck and (b) prostate cases planned using either sliding window (SW) IMRT or RapidArc (RA) cases with systematic gantry angle variations.

gradients and distance to isocenter i.e. 0.4% deg^{-1} for cochlea and 0.1% deg^{-1} for bladder and small bowel. Steeper dose gradients were present in HN cases and thus roughly doubled percent differences in D_{min} and D_{max} .

Figure 6 shows the results of gamma analyses performed to compare the differences in dose distributions using SW IMRT or RapidArc with systematic shifts in initial starting beam angle of 1° , 2° , 3° , 4° , or 5° . Unlike the DVH data, there is clear evidence that rotational delivery is less susceptible to the same systematic changes in gantry angle. For example, using 3° – 3 mm for a 5° shift, prostate cases using SW passed at a rate of only 81.2% versus 96.4% for RapidArc. In addition, the same SW prostate cases would fail a 95% pass rate with a shift of only $\sim 2^\circ$.

The effect of systematic shifts in gantry angle is illustrated using a HN case in Fig. 7. In the coronal plane at isocenter, a Gamma analysis criterion of 1%-1 mm was used to accentuate the relative changes in pass rates. Points that failed the Gamma test are shown in either red or blue to indicate a higher or lower dose, respectively. The clear difference here is how

FIG. 6. Average Gamma analysis pass rates for (a) head-and-neck and (b) prostate cases planned using either sliding window (SW) IMRT or RapidArc (RA) with systematic gantry angle variations.

FIG. 7. Dose comparisons illustrating Gamma pass rates (1%-1-mm) for systematic gantry angle variations of 1°, 3°, and 5° for a HN case using SW IMRT (top) and RapidArc (bottom). PTV contours are shown. Red and blue indicate Fail Hot or Fail Cold, respectively.

FIG. 8. Comparison of average PTV minimum, maximum and mean dose values between original and modified head-and-neck (HN) and prostate (P) RapidArc cases with added random variations in dose rate.

quickly hot and cold pots appear in the overall SW dose distribution with 1.7% of data points already failing after a 1° shift. The difference in pass rates of SW and RapidArc increases quickly and disproportionately as a function of shift in gantry angle.

III.C. Dose rate

The resulting changes to DVH indices of RapidArc plan PTVs with added random variations in dose rate are presented in Fig. 8. An increase in dose rate variation for PTVs resulted in a statistical spreading of the delivered dose distributions, which explains the gradual decrease in $D_{\max}$ and increase in $D_{\min}$ of PTVs; for most OARs, up to a 0.4% dose difference was observed.

Gamma analysis of the effect of the added randomized dose rate variations is shown in Fig. 9. For example, random variations in dose rate using $\sigma = 10\%$ and 20% had little effect on RapidArc dose distributions ($<0.2\%$) even when with gamma tests using 1%-1 mm criterion as illustrated in the coronal plane at isocenter in Fig. 10. In the figure, a HN case and a prostate case are presented with added random fluctuations of $\sigma = 10\%$, 30% , and 50% of the original dose rate.

IV. DISCUSSION

Despite the added complexities of delivering RapidArc, this study provided evidence that a rotational IMRT technique such as RapidArc is less susceptible to delivery errors than the sliding window IMRT technique.

Systematic MLC positional errors were shown to be of greater dosimetric impact on sliding window IMRT than RapidArc. The difference between the two techniques is in how intensity modulation is achieved: sliding window uses a larger number of overlapping segments and MU, whereas RapidArc by means of rotation uses larger apertures and less MU to achieve the same target dose deposition. Geometric errors in

FIG. 9. Average Gamma analysis pass rates for (a) head-and-neck and (b) prostate cases planned using RapidArc with added random variations in dose rate.

smaller apertures, or those with smaller mean gap widths, will have a larger impact on dosimetric errors. The susceptibility to MLC leaf positional errors is inversely proportional to the mean leaf gap width,^{38,39,42,44} which account for the differences seen in this study. The dosimetric error caused by the systemic MLC leaf positioning errors should be roughly the quotient of the combined leaf position error of both opposing banks and the mean segment width.

Random errors to active MLC leaf positions were found to have little dosimetric effect on PTVs or OARs regardless of which technique is employed, agreeing with previous studies of IMRT and RapidArc.^{35,36,42}

Previous studies have reported on several types of MLC errors to observe their impact on patient dose distributions. In this study, a systematic shift in one leaf bank was sufficient to make a clear comparison between the two techniques,³⁹ but is not the most significant type of MLC error as shown in previous studies, e.g., both leaf banks open.^{37,38,42} Large variability in sensitivity to MLC errors (D_{mean}) between cases

was not seen as compared to a previous study.⁴² However, variability was seen in D_{min} and D_{max} : $\sigma_{\text{RA}} = 0.3\mu$ and $\sigma_{\text{SW}} = 0.2\mu$ for D_{max} of prostate plans and $\sigma_{\text{RA}} = 0.4\mu$ and $\sigma_{\text{SW}} = 0.4\mu$ for D_{max} of head-and-neck plans. Differences between the selected HN and prostate cases were due to differences in dose conformity were achieved, as only one arc was required for HN cases as compared to two arcs for prostate cases. Steep dose gradients accounted for the sharp drop in either D_{min} or D_{max} following the addition of leaf positional errors.

By nature, RapidArc plans were optimized with fixed angles and at each angle with fixed field shapes but delivered with constantly changing field shapes and a constantly moving gantry. Optimized MUs are never intended to be delivered at the planned beam angle for the delivery of IMAT, and so dose deposition is fairly tolerant to small delivery errors in gantry angle,⁶ which may include potential effects due to gantry acceleration and deceleration.⁴⁵ Using a small number of fields in SW IMRT commits a plan to specific beam paths and corresponding intensities, which makes them more susceptible to unwanted dose deposition to critical structures. If acceptance criteria of patient-specific QA for IMRT are set at $>95\%$ for 3%-3 mm Gamma test criterion, systematic errors up to $\sim 2^\circ$ vs. 5° may be considered feasible for the prostate plans in this study using SW vs. RapidArc, respectively. Random changes in gantry angle were not explicitly addressed here as it was changed implicitly due to a change in dose rate. As noted previously, it has been observed that adding random gantry errors to beam apertures is minimal to IMAT deliveries,^{43,46,47} and, similarly, so were the corresponding random variations in dose rate in this study.

Adding random variations to dose rate had little effect to the resulting dose distributions for RapidArc cases. As noted previously, dose rate variation is not an issue with dynamic IMRT as the only dependent variable during delivery is the shape of the aperture. Dose rate was defined as the time required to deliver a fixed number of MU. A change in dose rate thus required a change in gantry angle that was assigned to each segment, which in practice is compensation in gantry speed and leaf speed velocity. This study modeled such compensations in the planning system only, and so this showed that a capable linac should still deliver a clinically acceptable dose distribution.

As stated previously, errors in delivered MU were not addressed explicitly in this study as it is treated as an independent variable; this applies to any dynamic delivery of IMRT. However, altering the shape of the aperture via shifts in MLC leaf positions clearly changed the total delivered MU per segment, which, in our case, escalated the deposited dose. Studies of “overshoot” or “undershoot” phenomena of MLC control systems that lead to MU delivery errors^{48,49} have showed that such effects are relatively small and do not compromise IMRT treatments at higher dose rates (400 or 600 MU^{-1}). Analysis of log files of an MLC control system also showed that no clinically significant consequences were due to segment delivery errors, which were independent of planned segment MUs.⁵⁰ For RapidArc delivery, dose rate is variable and never

FIG. 10. Dose comparisons illustrating Gamma pass rates (1%-1 mm) during a RapidArc delivery with dose rate variations of $\sigma = 10\%$, 30%, and 50% for (a) a HN case and (b) prostate case. PTV contours are shown. Red and blue indicate “Fail-Hot” or “Fail-Cold”, respectively.

turned off from segment to segment; as it is a different technique, such control errors and thus MU error comparisons do not apply.

The results of the dosimetric comparisons presented support the argument that RapidArc, and possibly other IMAT and VMAT implementation, is not any more susceptible to delivery errors despite its added complexities. Therefore, QA procedures for IMRT can similarly be used for IMAT deliveries. A number of methods used for patient-specific QA of IMRT have been adapted for IMAT (see Yu and Tang⁶). This and other studies have demonstrated that detecting geometric errors in MLC positioning is a primary concern for machine QA. Systematic errors during treatment delivery are more significant rather than random errors in terms of clinical outcome;⁵¹ it is the same case at the planning stage, where an accurate model of the MLC system in the treatment planning system is also required. In either case, it is important to know how sensitive a particular dosimetric technique, paired to a particular linac, is to MLC leaf position errors as well as other rotational or translational errors that could compromise quality. Masi *et al.*⁵² reported recently that DELTA4 and MAPCHECK dosimetric systems for VMAT QA varied in sensitivity for some plans, where a 3° gantry angle offset introduced during delivery was rarely detected (with a pass-rate reduction below 4%), which we have shown to be expected unless a more strict tolerance level is used. Rangel *et al.*⁵³ pointed out that patient-specific IMRT QA cannot replace routine MLC QA as none of their IMRT QA criteria tested were sufficiently sensitive to identify MLC offsets within a tolerance of 0.3 mm on a single field basis. MLC log files have been used previously to quantify leaf positional errors for IMRT^{54,55} as well as RapidArc.^{56,57}

We have offered evidence that attention must be paid to assure machine performance for its use in dynamic IMRT much more so than RapidArc. The relative differences in impact of delivery errors using these two techniques are large, but they should not be generalized despite slight differences in other planning and delivery systems; corresponding dose sensitivities should ideally be quantified.³⁸

V. CONCLUSIONS

This study compared the dosimetric impact of different delivery errors in the radiation treatment of prostate and head-and-neck cancers with two common IMRT delivery techniques: fixed-field IMRT and IMAT. RapidArc deliveries were found to be more tolerant to variations in dose rate, gantry position, and MLC leaf position than fixed-field IMRT with dynamic SW delivery. Dose rate variations during RapidArc must be large to affect dose distributions significantly; dynamic IMRT is inherently not susceptible to such variations. Clinically acceptable treatments may be delivered accurately using RapidArc despite large fluctuations in dose rate and gantry position. Comprehensive QA procedures should be designed with the understanding of the different sources of errors and their relative dosimetric impacts to effectively ensure patient safety and accuracy.

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