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Dose verification for respiratory-gated volumetric modulated arc therapy (VMAT)

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Abstract

A novel commercial medical linac system (TrueBeam™, Varian Medical Systems, Palo Alto, CA) allows respiratory-gated volumetric modulated arc therapy (VMAT), a new modality for treating moving tumors with high precision and improved accuracy by allowing for regular motion associated with a patient's breathing during VMAT delivery. The purpose of this work is to adapt a previously-developed dose reconstruction technique to evaluate the fidelity of VMAT treatment during gated delivery under clinic-relevant periodic motion related to patient breathing. A Varian TrueBeam system was used in this study. VMAT plans were created for three patients with lung or pancreas tumors. Conventional 6 MV and 15 MV beams with flattening filter and high dose-rate 10 MV beams with no flattening filter were used in these plans. Each patient plan was delivered to a phantom first without gating and then with gating for three simulated respiratory periods (3, 4.5 and 6 seconds). Using the adapted log file-based dose reconstruction procedure supplemented with ion chamber array (Seven29™, PTW, Freiburg, Germany) measurements, the delivered dose was used to evaluate the fidelity of gated VMAT delivery. Comparison of Seven29 measurements with and without gating showed good agreement with gamma-index passing rates above 99% for 1%/1mm dose accuracy/distance-to-agreement criteria. With original plans as reference, gamma-index passing rates were 100% for the reconstituted plans (1%/1 mm criteria) and 93.5–100% for gated Seven29 measurements (3%/3 mm criteria). In the presence of leaf error deliberately introduced into the gated delivery of a pancreas patient plan, both dose reconstruction and Seven29 measurement consistently indicated substantial dosimetric differences from the original plan. In summary, a dose reconstruction procedure was demonstrated for evaluating the accuracy of respiratory-gated VMAT delivery. This technique showed that under clinical operation, the TrueBeam system faithfully realized treatment plans with gated delivery. This methodology affords a useful tool for machine and patient-specific quality assurance of the newly available respiratory-gated VMAT.

Keywords

Gated volumetric modulated arc therapy; QA; dose reconstruction

Introduction

Gated volumetric modulated arc therapy (VMAT) is a new radiotherapy modality that can potentially provide highly conformal treatment despite the presence of significant

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respiration-induced tumor and normal tissue motion during dose delivery. First supported by the TrueBeam™ system (Varian Medical Systems, Palo Alto, CA), this modality involves by far the most complexity in the control of MLC kinetics, dose-rate modulation, and gantry rotation, all of which are frequently interrupted in response to a gating signal from a real-time position management (RPM™) system. For a gated VMAT treatment, the delivery system needs to accommodate these interruptions while ensuring accurate, precise realization of the planned dose parameters. For example, during gated VMAT delivery in the TrueBeam system, in contrast to immediate beam off of MU delivery upon receipt of the gate-close signal, the gantry rotates continuously forward due to inertia, then backward to a position ready for the next cycle of delivery. This phenomenon is illustrated in Figure 1, which is based on a log-file for a gated VMAT delivery. With such complexity, one may well wonder how faithfully a VMAT plan can be realized during delivery with gating under different respiratory conditions.

A recent pre-clinical evaluation found that gated RapidArc delivery was reliable and dosimetrically accurate in a non-clinically released framework (Nicolini *et al.*, 2010). Since the official release of the TrueBeam system, however, dosimetric reliability of gated VMAT delivery in its clinical configuration has not yet been demonstrated. A specific dose verification procedure is still absent for gated VMAT, and the dosimetric impact of different respiratory conditions, such as fast, normal and slow breathing, remains uncertain. Nevertheless, several QA procedures adapted from conventional IMRT have been developed (Bedford and Warrington, 2009; Ling *et al.*, 2008) and new dosimetric devices have been tested for QA of ungated VMAT (Yan *et al.*, 2010; Bedford *et al.*, 2009). Different volumetric dose verification methods have been proposed and validated for ungated VMAT using delivery log-files (Qian *et al.*, 2010; Schreiber *et al.*, 2009; Haga *et al.*, 2009), portal dosimetry (Mans *et al.*, 2010), and gel dosimetry (Ceberg *et al.*, 2010). It would seem useful now to devise a dose verification procedure to evaluate the gated VMAT delivery under various respiratory conditions.

Volumetric assessment of delivered dose in a gated VMAT treatment is quite challenging owing to the freedom in delivery of a number of parameters including leaf position, gantry rotation, dose rate and respiratory-gating signal. Qian *et al.* (2010) recently proposed dose reconstruction techniques using CBCT and delivery log-files for ungated VMAT that take into account delivery errors in the dynamic machine parameters of gantry angle, cumulative MUs and MLC leaf positions. As an extension of a previous study, our aim in this work is to develop and validate a volumetric dose verification technique that is readily applicable to respiratory-gated VMAT in the clinical environment.

The objectives of this work are twofold: 1) adapt the previously developed dose reconstruction procedure to respiratory-gated VMAT; 2) by calculation and measurement, assess the dosimetric fidelity of gated VMAT delivery of the TrueBeam across a clinical range of respiratory periods.

Materials and Methods

2.1 The TrueBeam system

A TrueBeam medical linac, equipped with high-definition multileaf collimator (HDMLC-120), is used in this work (Cho *et al.*, 2011; Mok *et al.*, 2010). In addition to conventional 6 MV and 15 MV beams with flattening filter, a TrueBeam system offers flattening-filter-free (FFF) beams with much higher than previously available dose rate (for 6 MV, up to 1400 MU/min; for 10 MV, up to 2400 MU/min). These beams can be used for either gated or ungated IMRT/VMAT. By integrating the RPM system with RapidArc (Varian's VMAT), the TrueBeam system is capable of respiratory-gated VMAT which has

the potential of improving treatment of lung or abdominal cancers by reducing the size of required treatment margins. Patient respiratory motion is monitored using an integrated 3-D tracking system consisting of a stereo-view infrared video camera installed above the couch and a 4-marker reflector block appropriately positioned on the patient.

2.2 Gated VMAT treatment planning and delivery

Gated VMAT plans are created using the Eclipse treatment planning system (TPS) (version 8.9, Varian Medical Systems, Palo Alto, CA). The planning process is the same as for ungated VMAT planning except that an option for gating must be selected. After a gated VMAT plan is loaded in treatment mode on TrueBeam, a gating protocol must be generated, either by importing RPM data from a simulation session or by acquiring a new 3-D respiratory reference. For this phantom study, all gating protocols were generated by acquiring new reference curves. A programmable 4D Phantom motion platform system (Malinowski *et al.*, 2007) was used to produce several one-dimensional periodic motions of the reflective marker block in the vertical (anterior-posterior) direction of different periods to provide input to the infrared camera of the TrueBeam integrated tracking system.

During each arc of VMAT delivery with or without gating, the expected and actual status of TrueBeam coordinates such as leaf positions and MUs are logged every 10 milliseconds (ms) for up to 10 minutes, and stored in a single binary file called the trajectory log file. The actual delivery parameters of each control point can in this way be readily extracted. This is different from previous studies based on other Varian's systems such as Trilogy, in which separate log-files, namely, the Linac and MLC log-files, must be used to obtain the delivery parameters of each control point (Qian *et al.*, 2010). Compared with those two log files, the single trajectory file provides a more complete record of actual delivery parameters with a higher sampling rate (100 Hz versus 20 Hz) and thus may offer more complete information pertinent to quality assurance of the TrueBeam delivery, particularly valuable for the higher dose rates available in the FFF modes (Georg *et al.*, 2011).

2.3 Log-file-based dose reconstruction and ion chamber array measurement

The dose reconstruction technique is extended from our previous work (Qian *et al.*, 2010). Since log files are part of a linac system, using them for system verification is a type of self-checking. Nevertheless, this is a common practice in the field because log files do record the delivery readouts of the linac system. It is reasonable to assume that log files reflect the history of system parameters during beam delivery.

This trajectory-file-based procedure includes the following steps. After a gated VMAT delivery is completed, trajectory log files are retrieved from the linear accelerator. Actual logged delivery parameters of every control point including gantry angle, cumulative MU percentage and MLC leaf position are determined from the trajectory files using an in-house developed Matlab program (version R2008a, Mathworks, Natick, MA). All resultant control point data are then imported into another Matlab program to synthesize a corresponding DICOM-RT plan file. The reconstituted DICOM-RT file is imported into Eclipse and the delivered dose based on the logged delivery parameters are then calculated on the treatment phase images of the 4D planning CT (pCT).

A 27×27 ion chamber array the Seven29 (PTW, Freiburg, Germany) was used to test our dose reconstruction results and, at the same time, provide an independent verification of delivered dose. Use of this device has been described in several works and the ion chamber array has proven to be a reliable dosimetric tool (Van Esch *et al.*, 2007; Spezi *et al.*, 2005). In this study, the Seven29 was horizontally sandwiched between 10 cm-thick 30 × 30 cm plastic water slab assemblies above and below. The center of the array was positioned at

isocenter for these experiments. To correct for the observed under-response of the Seven29 to radiation from below compared to calculations, we created a 1 cm-thick simulated shell structure in the lower 10-cm solid water of the phantom setup in the TPS software and assigned it a high Hounsfield unit (HU) value of 2000 (see figure 2), as an alternative tactic that is equivalent to using an unsimulated 2 cm-thick physical air cavity as in the PTW Octavius phantom (Van Esch *et al.*, 2007). This method was described in a previous study (Teo *et al.*, 2008) and it is routinely used in our clinic for patient-specific QA.

2.4 Experimental validation and verification

A series of experiments was performed to validate this dose reconstruction technique and verify the fidelity of gated VMAT delivery under clinic-relevant respiratory situations. Treatment plans from three patients intended for treating lung and pancreas cancers, were used. Double-arc 6 MV (600 MU/min), single-arc 10 MV FFF (1200 MU/min) and single-arc 15 MV (600 MU/min) gated VMAT plans were created for two lung patients (#1 and #2) and one pancreas patient (#3), respectively. For the 10 MV FFF plans, the reason why the highest dose rate of 2400 MU/min was not used was because the electronics of the Seven29 in use at our center does not support a dose rate above 1600 MU/min. The reflective marker block was moved using the positioning system programmed with sinusoidal motion of amplitude 3 mm, providing a suitable input signal of simulated periodic motion for the RPM system to use for switching the beam on and off. Motion periods of 3, 4.5 and 6 seconds were used, corresponding to three realistic respiratory situations: fast, normal and slow breathing. Phase gating was used with the open-gate window set from the 25% to the 70% phase of the cycle, 1.4, 2.0 and 2.7 seconds for the three periods. Each plan was delivered on the TrueBeam. After delivery, trajectory log files were retrieved and the dose reconstruction procedure was applied.

Doses were reconstructed on the pCTs of the patient and the sandwich setup of Seven29 and solid water, respectively. Using PTW software (VeriSoft, ver. 4.2), reconstructed dose distribution in the isocentric plane of the Seven29 setup was compared with that of the original plan using the gamma index figure of merit (Low *et al.*, 1998). The same procedure was used for the corresponding Seven29 measurements. In the following, gamma passing rates were obtained with conventional criteria of 3 mm distance-to-agreement (DTA) and 3% relative dose difference (DD) for dose comparison between original/reconstructed plan and ion chamber measurement. These criteria reasonably accommodate the discrepancy between dose calculation and physical measurement. Unless otherwise stated, stricter criteria of 1mm DTA/1% DD were used for measurement-to-measurement comparisons and also for calculation comparisons between original and reconstituted plans. Measurement and calculation points at levels below a threshold of 10% of the maximum calculated dose were excluded from the comparisons. For the reconstituted plan on the patient's pCT, dosimetric endpoints including maximum, minimum and mean doses and DVHs of patient structures were compared with those of the original plan. All measurements were repeated once to check reproducibility.

To demonstrate the sensitivity of this dose reconstruction technique to beam delivery errors, an MLC leaf error was deliberately introduced into the gated delivery of the pancreas patient plan. During the delivery, leaf pair 35, of width 2.5 mm, quickly closed after control point 89, nominally the half-arc position, and remained closed thereafter. After the delivery, the reconstructed and measured doses were compared with the original plan to show the dosimetric effects of this leaf error.

Results

3.1 Delivery time and frequency of interruptions in gated VMAT

Table 1 shows the comparison of total delivery time, beam-on time and number of interruptions corresponding to gated VMAT deliveries under different simulated periodic breathing for all three plans. According to this table, the average number of interruptions per arc for the respiratory periods of 3 s, 4.5 s and 6 s was 98.3, 58.3, and 41.0, respectively.

3.2 Comparison between PTW-Seven29 measurements with and without gating

Figure 3 shows the comparison of Seven29 measurements for double-arc lung patient (#1) plans delivered without gating and with gating under the different respiratory situations. Gamma indices were obtained with the ungated Seven29 measurement as reference. The gamma-index passing rates were 99.8%, 100% and 99.2% for the three simulated respiratory periods, i.e., 3, 4.5 and 6 seconds. The same gamma-index passing rates of 100% were obtained for other two patient cases. (With the planned dose as reference, ungated Seven29 measurements had passing rates of 94.9%, 100% and 98.4% for #1–3 patient cases, respectively.) These results indicate two important findings: i) there were no dosimetric differences among the gated deliveries for the three respiratory periods tested; ii) there were no dosimetric differences between the deliveries with and without gating in these tests.

3.3 Comparison of original plans with reconstituted plans and Seven29 measurements

Calculated dose distribution of a coronal plane of the hybrid plan for lung patient #1 is shown in Figure 4 (central panel), where comparison is made to that of the gated delivery for a simulated respiratory period of 3 seconds, for dose reconstruction (left panel) and for Seven29 measurement (right panel). The coronal plane is 2.5 mm below isocenter, corresponding to the plane that passes through the center of the detectors of the ion chamber array. Gamma indices were obtained with the original plan as reference. The gamma-index passing rates were 100% and 94.4% for reconstructed and measured doses, respectively. Similarly, gamma-index passing rates of 100% were found for reconstructed doses of the gated deliveries with simulated 4.5 s and 6 s periods while the corresponding gamma-index passing rates were 94.3% and 93.5% for Seven29 measurements. Failed (cold and hot) points were observed in the Seven29 measurements were all located in the dose regions below 50%. Histograms show that more than 97% gamma indices were below 0.2 for reconstructed doses and about 90% were below 0.6 for ion chamber measurements.

Similar comparisons for #2 patient case are depicted in figure 5, in which a single-arc 10 MV FFF plan was delivered with a simulated respiratory period of 3 seconds that caused most frequent interruption. This plan was for stereotactic body radiation therapy of lung cancer with a typical target volume which did not require the most complex of VMAT aperture shapes. The gamma-index passing rate was 100% for dose reconstruction and was 99.1% for Seven29 measurement. Identical passing rates were seen for the respiratory period of 4.5 s. For 6 s, the passing rates were 100% for both dose reconstruction and Seven29 measurement. The failed (hot) point in the Seven29 measurements appeared in the high-gradient dose region. The majority of gamma indices were again below 0.2 and 0.6 for dose reconstructions and measurements, respectively. For the pancreas patient plans that were delivered with gating under simulated respiratory periods of 3, 4.5, and 6 seconds, the gamma-index passing rates for reconstructed doses were all 100% and for Seven29 measurements were all 98.3% (figures not shown).

Using the dose reconstruction technique, the delivered dose distribution can be assessed volumetrically. Figure 6 shows that the axial dose distribution and DVH of the #2 lung patient plan were essentially identical with those of the log-file-derived plan for a gated

delivery with the simulated respiratory period of 3 seconds. In this case, the mean, maximum and minimum doses to the target for the original and reconstituted plans were the same, i.e., 119.8%, 140.2% and 74.9%, respectively. The mean doses of the original and reconstituted plans were identical to each of the organs at risk (OAR) including lungs, spinal cord, heart, aorta, esophagus and chest wall while the maximum and minimum dose had negligible differences of not more than 0.1%. The same agreements were observed in gated deliveries of the lung plan with simulated respiratory periods of 4.5 and 6 seconds. This comparison was also done for the pancreas case (shown in figure 7 for the delivery with simulated 6 s respiratory period) and the #1 lung patient case (figures not shown). Similarly, the reconstructed doses were essentially the same as the planned doses in dose distribution, DVHs, mean, maximum and minimum dose to both the targets and OARs.

In the presence of the deliberately introduced leaf error, i.e. the 2.5 mm-wide leaf pair 35 closed after half-arc gated delivery of pancreas patient plan with simulated breathing period of 3s, both dose reconstruction and Seven29 measurement consistently indicated substantial dosimetric difference from the original plan as illustrated in figure 8.

Discussion

Delivery log files have proven to be reliable for machine QA and valuable for dose verification by several groups (Qian *et al.*, 2010; Schreiber *et al.*, 2009; Lee *et al.*, 2008; Stell *et al.*, 2004; Li *et al.*, 2003). Using TrueBeam trajectory files logging the system's delivery parameters every 10 ms, we have developed the volumetric dose reconstruction technique for dosimetric verification of respiratory-gated VMAT. The results obtained through this technique indicate that the TrueBeam system can faithfully realize the planned dose even under simulated respiratory conditions that cause relatively frequent delivery interruptions. These outcomes were independently confirmed by the measurements with the Seven29 ion chamber array.

It is worth mentioning that there are several factors that could cause discrepancies in dose comparison, especially between the planned and measured doses as shown in figures 4 and 5. Any error in dose calculation would contribute to such discrepancies. In addition, the detector measurements integrate over a $(5\text{ mm})^3$ volume, whereas the calculations refer to a single point. Also, the correction for directional dependence of Seven 29 measurements though reliable is not perfect (Van Esch *et al.*, 2007; Teo *et al.*, 2008). Even with correction, there can be slight variations in the response of and inaccuracies of calibration of different ion chambers in the Seven29. The physical setup of the Seven29 and solid water also could never be perfectly identical with that in the pCT. Nevertheless, in the presence of these errors, both dose reconstructions and Seven29 measurements demonstrate that the plans were faithfully realized by the delivery system with gamma-index passing rates ranging from 93.5% to 100% and the majority of failed points locating in dose regions below 40%.

A limitation of the current study is that only regular respiratory motions were simulated in this study and thus the VMAT delivery was gated in an artificially regular way, which is different from the actual clinical situation. Nevertheless, this is sufficient for our present purpose to develop and validate a dose verification technique to test gated VMAT treatment across a range of clinical respiratory rates. Respiratory periods of 3–6 s roughly approximate realistic patterns for fast, normal and slow breathing (Wiersma and Xing, 2007). A respiratory period of 3 seconds, suggesting the most frequent interruptions during gated VMAT delivery, is relatively infrequent in clinical practice. Even under this situation which results in the most frequent interruptions, however, we have seen that the TrueBeam system faithfully realizes VMAT plans.

This static phantom-based study was based on an assumption that the patient remained immobile during the gated delivery, which is not the case in the real clinical situation. The patient might move during beam-on periods as the gating window is not vanishingly small. This would affect the quality of delivered dose to the patient. The proposed technique can nevertheless be used for machine or pre-treatment patient-specific QA.

With the increased complexity of gated VMAT delivery, it is necessary to verify dosimetric accuracy and precision of the Linac system in the presence of frequent interruptions due to respiratory gating. As demonstrated by the experiments, the technique described here affords an easy yet effective method for this purpose. It may also offer a valuable pre-treatment review of the possible dose delivered to the patient during this complicated, highly conformal treatment of moving targets. It thus provides a promising tool for retrospective evaluation of actual dose delivered the patient during gated treatment.

Conclusion

We have developed and validated a procedure to reconstruct the volumetric dose delivered in a respiratory-gated VMAT treatment using trajectory files of TrueBeam system. This easy-to-use method can be readily applied for machine or patient-specific QA in current clinic practice of gated VMAT. Using this method supplemented by physical measurements of an ion chamber array, we found that the TrueBeam system can faithfully realize gated VMAT plans under a variety of simulated periodic respiration situations. The method could potentially find application in future adaptive radiation therapy (ART) (Xing *et al.*, 2009) using respiratory-gated VMAT when gated or 4D CBCT is clinically ready.

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Figure 1.

An example of the kinetics of gantry rotation and cumulatively delivered monitor units (MUs) as a function of time during a fractional treatment of gated VMAT. Data plotted from a TrueBeam™ delivery log-file.

Figure 2.

Phantom setup for dose verification using a PTW Seven29 and plastic water. The left setup is for physical measurement while the right one is for dose calculation. The 1-cm thick simulated shell structure with HU value of 2000 was used for directional correction.

Figure 3. Gamma-index analyses in the #1 lung patient case with the ungated PTW-Seven29 measurement as reference for the Seven29 measurements of gated VMAT deliveries under the three simulated respiratory periods, i.e., 3, 4.5 and 6 s.

Figure 4.

Respective comparison of planned dose distribution with reconstructed dose distribution and Seven29 measurement for #1 lung patient case. The gated plan (double-arc, 6 MV, 600 MU/min) was delivered with 162 interruptions in total under a simulated respiratory period of 3 seconds.

Figure 5.

Comparison of the planned dose distribution for lung patient case #2 with reconstructed dose distribution and Seven29 measurement, respectively. This gated FFF plan (single-arc, 10 MV, 1200 MU/min) was delivered with 107 interruptions under a simulated respiratory period of 3 seconds.

Figure 6.
Volumetric dose comparison between the original and reconstituted plans for the #2 lung patient.

Figure 7.
Volumetric dose comparison between the original and reconstituted plans for the pancreas patient.

Figure 8.

Dosimetric effects of the simulated leaf error in the gated VMAT delivery of #3 pancreas patient plan with simulated respiratory period of 3 s. Gamma-index passing rates were obtained with the original plan as reference and criteria of 3%/3 mm.

Table 1

Summary of total delivery time, beam-on time and interruptions for each gated VMAT delivery.

Patient	Plan detail	Respiratory period (sec)	Total delivery time	Beam-on time	Interruptions
#1: Lung	2 arcs, 6 MV, 600 MU/min, 450 cGy/tx, 775 MUs	ungated	2 min 6 sec		-
		3	8 min 59 sec	3 min 38 sec	162
		4.5	7 min 19 sec	2 min 53 sec	87
		6	6 min 44 sec	2 min 38 sec	59
#2: Lung	1 arc, 10 MV, FFF 1200 MU/min, 1250 cGy/tx, 2409 MUs	ungated	2 min 2 sec		-
		3	6 min 24 sec	2 min 24 sec	107
		4.5	6 min 2 sec	2 min 16 sec	68
		6	5 min 45 sec	2 min 12 sec	49
#3: Pancreas	1 arc, 15 MV, 600 MU/min, 500 cGy/tx, 1364 MUs	ungated	2 min 17 sec		-
		3	6 min 22 sec	2 min 47 sec	124
		4.5	5 min 50 sec	2 min 35 sec	78
		6	5 min 39 sec	2 min 30 sec	56