Experimental investigation of a moving averaging algorithm for motion perpendicular to the leaf travel direction in dynamic MLC target tracking

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Purpose: In dynamic multileaf collimator (MLC) motion tracking with complex intensity-modulated radiation therapy (IMRT) fields, target motion perpendicular to the MLC leaf travel direction can cause beam holds, which increase beam delivery time by up to a factor of 4. As a means to balance delivery efficiency and accuracy, a moving average algorithm was incorporated into a dynamic MLC motion tracking system (i.e., moving average tracking) to account for target motion perpendicular to the MLC leaf travel direction. The experimental investigation of the moving average algorithm compared with real-time tracking and no compensation beam delivery is described.

Methods: The properties of the moving average algorithm were measured and compared with those of real-time tracking (dynamic MLC motion tracking accounting for both target motion parallel and perpendicular to the leaf travel direction) and no compensation beam delivery. The algorithm was investigated using a synthetic motion trace with a baseline drift and four patient-measured 3D tumor motion traces representing regular and irregular motions with varying baseline drifts. Each motion trace was reproduced by a moving platform. The delivery efficiency, geometric accuracy, and dosimetric accuracy were evaluated for conformal, step-and-shoot IMRT, and dynamic sliding window IMRT treatment plans using the synthetic and patient motion traces. The dosimetric accuracy was quantified via a γ -test with a 3%/3 mm criterion.

Results: The delivery efficiency ranged from 89 to 100% for moving average tracking, 26%–100% for real-time tracking, and 100% (by definition) for no compensation. The root-mean-square geometric error ranged from 3.2 to 4.0 mm for moving average tracking, 0.7–1.1 mm for real-time tracking, and 3.7–7.2 mm for no compensation. The percentage of dosimetric points failing the γ -test ranged from 4 to 30% for moving average tracking, 0%–23% for real-time tracking, and 10%–47% for no compensation.

Conclusions: The delivery efficiency of moving average tracking was up to four times higher than that of real-time tracking and approached the efficiency of no compensation for all cases. The geometric accuracy and dosimetric accuracy of the moving average algorithm was between real-time tracking and no compensation, approximately half the percentage of dosimetric points failing the γ -test compared with no compensation. © 2011 American Association of Physicists in Medicine. [DOI: 10.1118/1.3590384]

Key words: MLC tracking, moving average, tumor motion

I. INTRODUCTION

There has been a remarkable growth in the number of real-time target position monitoring systems either commercially available or under development. These monitoring systems

span much of the electromagnetic spectrum, with radiofrequency, magnetic resonance imaging (MRI), optical imaging, kilovoltage, γ -ray, and megavoltage radiation used to sense target position. Real-time ultrasound position monitoring systems are also under development. Given this growth,

it is likely that real-time position monitoring will become more widely implemented in future radiotherapy treatments. This real-time position monitoring can be used for different techniques in radiation therapy, such as motion inclusive, gating, and tracking.¹ Of these approaches, tracking is more accurate than motion inclusive and more efficient than gating. Tracking can account for baseline shifts within the limitations of the tracking system used to align the beam and the patient. There are several approaches to realign the beam and the patient, including using a robotic arm,² couch tracking,^{3,4} gimballed linac tracking,⁵ and, the focus of this work, multileaf collimator (MLC) tracking.^{6–15} The recent literature shows that MLC tracking has been and is being experimentally investigated by a number of different groups working with equipment from a variety of vendors in addition to the development of theoretical solutions.

The term “tracking” is used in the literature to describe both target position monitoring and motion compensation. For clarity in this manuscript, tracking only refers to motion compensation.

Experimental data on the MLC leaf dynamics^{16,17} indicates that current MLCs, with velocities of 3.3 cm/s, are capable of tracking respiratory motion parallel to the leaf travel direction. Wijesooriya *et al.*¹⁷ calculated that 97% of patient motion could be compensated for using currently available MLC technology. Therefore, a moving average algorithm is not needed for target motion parallel to the beam direction. However, as shown schematically in Fig. 1 of George *et al.*¹⁸ and quantified by Sawant *et al.*,¹⁰ target motion perpendicular to the leaf travel direction can result in large requested instantaneous leaf shifts. If the leaves are not within a prespecified tolerance (typically 1–5 mm) of their desired positions,

a beam hold will occur, which will affect treatment efficiency. These beam holds have resulted in reported delivery efficiencies as low as 20%.¹⁰ A reasonable method to minimize target motion perpendicular to the leaf travel direction is to create a treatment plan in which MLC leaves travel along the major axis of target motion.^{19,20} However, due to the complexity of tumor motion, there will be motion components perpendicular to the leaf travel direction and the motion direction may change during treatment. This motion perpendicular to the leaf travel direction can be either explicitly tracked or taken into account by estimating the mean position of this motion component and realigning the beam to follow this mean position. Compared with no correction, aligning the mean position of the beam with the target substantially reduces the systematic errors of treatment delivery, whilst the residual motion about the mean position is not explicitly corrected for and can be treated as a random error. According to margin formulas, the systematic errors are the greatest contributor to the overall treatment margin and therefore reducing this error can result in a possible PTV margin reduction.²¹

There have been several investigations of mean position estimation,^{4,18,22,23} of which for radiotherapy delivery, the moving average algorithm is perhaps the simplest. George *et al.* investigated the moving average algorithm using patient motion traces to quantify the magnitude of margin reduction and compared the results with other motion compensated delivery techniques such as gating and tracking.¹⁸ Wilbert *et al.* implemented the moving average algorithm into a couch tracking for real-time compensation of the target mean position.⁴

The purpose of this work was to investigate the efficiency and geometric and dosimetric properties of dynamic MLC (DMLC) tracking using the moving average algorithm where

FIG. 1. Schematic diagram for the experimental dosimetric investigation of the moving average algorithm. Target motion is reproduced with synthetic and patient 3D tumor motion traces on the moving platform. A real-time 3D position measured from the RPM marker block on the moving platform is transferred to the DMLC tracking system where MLC leaf positions are corrected to: (1) follow a moving average of previous target trajectories perpendicular to the leaf direction while real-time tracking is used for the target motion parallel to the leaf direction (moving average tracking, MA), (2) follow the 3D target position in real time (real-time tracking, RT), or (3) not account for motion (no compensation, NC beam delivery). The efficiency and geometric and dosimetric accuracies were measured for MA, RT, and NC using conformal, step-and-shoot IMRT, and sliding window IMRT treatment plans.

target motion perpendicular to the MLC leaf direction is accounted for and real-time tracking is used for motion parallel to the MLC leaf direction. The results were compared with those from (1) real-time DMLC tracking (accounting for both motion parallel and perpendicular to the MLC leaf travel direction in real time) and (2) no compensation beam delivery (no tracking).

II. MATERIALS AND METHODS

The experimental investigation combined efficiency and geometric and dosimetric measurements of the moving average algorithm compared with no compensation for a variety of tumor motion patterns and radiation delivery types. A schematic diagram for the experimental investigation of the moving average algorithm is shown in Fig. 1.

II.A. DMLC tracking

A DMLC tracking system was used to compensate target motion during radiation delivery where the positions of MLC leaves were adjusted to follow the real-time 3D target position. For these experiments, the target position was provided by a real-time position monitoring system (RPM, ver. 1.7, Varian Medical Systems, Palo Alto, CA). Without loss of generality, other 3D position monitoring systems, including those that monitor the tumor or surrogates directly, could have been used. A modified linear adaptive filter prediction algorithm²⁴ was incorporated for the real-time DMLC tracking to compensate for the DMLC tracking system time response (~ 160 ms).²⁵ The moving average algorithm was coded and implemented into the DMLC tracking system as a delivery option (termed “moving average tracking” throughout). The time window for the moving average was set to 15 s based on the results of George *et al.*¹⁸ In that paper, they studied other time windows spanning (5,25) s and concluded that their results were insensitive to the magnitude of this value over the range studied. A shorter averaging time window would respond more quickly to baseline shifts but would be sensitive to intracycle period and shape variations. A longer time window would respond more slowly to baseline shifts but would be less sensitive to intracycle changes. The conformality of the MLC beam and management of a target motion smaller than the MLC leaf width was improved by using five subleaves.^{10,26} The MLC leaf of

finite width was divided into virtual “subleaves,” where points of intersection with a treatment field are determined, then an actual “parent” leaf position was the position averaged over the intersection points on the subleaves.

The definition and justification for the three motion compensation methods investigated in this study is given in Table I. Gating was not considered, as gating suffers from low efficiency, typically 30%–50%,^{27,28} which is the same limitation as that of real-time tracking that the moving average algorithm aims to alleviate.

II.B. Tumor motion traces

To demonstrate the moving average algorithm, a synthetic motion trace was generated with a peak-to-peak displacement of 8 mm, a period of 2.5 s, and a baseline drift of 10 mm. Tumor motion traces with a mean peak-to-peak displacement more than 0.5 cm for lung and retroperitoneal tumor cases were selected from the patient traces treated with stereotactic body radiotherapy using the Cyberknife Synchrony (Accuray, Inc., Sunnyvale, CA) system at Georgetown University Hospital.²⁹ The synthetic case was included to quantify the dosimetric and geometric accuracy of the moving algorithm under known, controlled conditions representing a “best case” comparison with no compensation. From the tumor motion database, traces were manually selected with regular and irregular motions and different baseline shifts. All traces had motion ranges >5 mm and represent average to above average motion ranges observed in the population. (See, e.g., Table I in AAPM TG76).¹ The four traces selected, shown in Fig. 2, were as follows:

1. a gradual increase in the baseline drift with time “regular motion with a gradual baseline drift”
2. an abrupt baseline shift “regular motion with an abrupt baseline shift”
3. varying baseline shifts “irregular motion with varying baseline shifts”
4. small baseline shifts “regular motion with a small baseline drift”

The latter was included for reference as least difference is expected between the moving average and no compensation as the baseline shifts tend to zero. Also note that irregular motion, by definition, will cause baseline shifts. The synthetic and patient tumor motion traces were reproduced by a

TABLE I. Methods and justification for use in this study. Note that throughout this study, the moving average algorithm (MA) refers to the application of the moving average for motion perpendicular to the leaf direction and real-time tracking for motion parallel to the leaf direction.

Motion compensation method	Method to account for motion perpendicular to leaf travel	Method to account for motion parallel to leaf travel	Justification
Moving average (MA)	Moving average	Real-time tracking	Real-time tracking sufficiently compensates for motion parallel to leaf direction (Refs. 16 and 17). Goal to keep error low and efficiency high by applying MA for motion perpendicular to leaf travel.
Real-time tracking (RT)	Real-time tracking	Real-time tracking	DMLC tracking method with the lowest error. Can suffer from efficiency loss for motion perpendicular to the beam direction (Ref. 10)
No compensation (NC)	No compensation	No compensation	Current standard of care.

Fig. 2. Geometric accuracy of moving average tracking in the superior-inferior direction for the four patient cases: (a) regular motion with a gradual baseline drift, (b) regular motion with an abrupt baseline shift, (c) irregular motion with varying baseline shifts, and (d) regular motion with a small baseline drift. The black curves indicate the target center position in the motion trace, green the theoretical beam center of moving average tracking, and red the experimental beam center of moving average tracking.

moving platform.³⁰ The tumor motion traces were converted to motion input files suitable for the moving platform using the MATLAB (MathWorks, Natick, MA) program. A Butterworth filter with a cutoff frequency of 2.5 Hz was applied to the motion traces to circumvent the motion constraint of the moving platform, which hangs if an abrupt motion change is requested.

II.C. Evaluation of the moving average algorithm

Delivery efficiency and geometric and dosimetric accuracies were evaluated for moving average tracking and real-time tracking with different types of beam modulation and target motion. A circular conformal treatment plan (conformal), a step-and-shoot intensity-modulated radiation therapy treatment plan (sIMRT), and a dynamic sliding window IMRT plan (dIMRT) for lung patients were developed. One field of each plan was selected for delivery with different beam modulation.

The delivery efficiency was defined as the percentage of the time to deliver the “no compensation” beam divided by the time taken to deliver the motion compensated beam (moving average or real-time tracking). For example, if the delivery of a 200 monitor unit (MU) conformal field at 300 MU/min takes 40 s for no compensation and 103 s with real-time tracking, the efficiency is 39%. To quantify the geometric accuracy, a real-time beam’s-eye-view video of a circular MLC beam aperture was acquired from a 640/480 charge-coupled device camera (Toshiba Teli, Concord, CA) at a frame rate of 15 Hz. In each frame of the video file, the centroid of the beam aperture (beam center) and the cross-hair of the target (target center) were identified. The geometric accuracy was quantified by a root-mean-square (rms) error of the displacement between the beam center and the target center.¹⁰ Consistent with George *et al.*,¹⁸ for the calculation of an RMS error without motion compensation, the target center was set to the moving average for the first 15 s of measurement.

For dosimetric measurements, a PTW 729 ion chamber array (PTW, Freiburg, Germany) was sandwiched between two 2-cm thick solid water phantoms and placed onto the moving platform. The dose rate and monitor units were set to 300 MU/min. and 200 MU, respectively. Measured dose distributions with a moving target were compared with the dose distribution with a static target, which was considered as a ground-truth dose distribution.³¹ Dosimetric accuracy was quantified through a γ -test²⁹ (Verisoft, PTW) with a 3% dose difference and 3 mm distance-to-agreement criteria.

III. RESULTS

III.A. Delivery efficiency

Delivery efficiencies for the various motion traces and treatment plans are shown in Table II. The delivery efficiency ranged from 89 to 100% for moving average tracking, 26%–100% for real-time tracking, and 100% (by definition) for no compensation beam delivery. The real-time tracking efficiency decreased with the complexity of beam modulation, in order of conformal, sIMRT, and dIMRT plans. The real-time tracking efficiency was as low as 26% for the dIMRT beam delivery to a target moving with regular motion and a gradual baseline drift trace. The moving average tracking efficiency was $\geq 89\%$ in all cases studied.

III.B. Geometric accuracy

Figure 2 shows the geometric accuracy of moving average tracking with the various tumor motion traces. The experimental beam center of moving average tracking (red) follows the theoretical beam center (green) (the calculated moving average of the measured target center). The agreement between the experimental and theoretical moving average curves validates the implementation and gives an overall estimate of the system error (less than 1 mm). The RMS geometric error ranged from 3.2 to 4.0 mm for moving average tracking, 0.7–1.1 mm for real-time tracking, and 3.7–7.2 mm for no compensation beam delivery (Table III).

TABLE II. Delivery efficiency of moving average tracking and real-time tracking measured with different treatment plans and motion traces: the efficiency was defined as the percentage of the time to deliver the “no compensation” beam divided by the time taken to deliver the taken to deliver the motion compensated beam (MA or RT). By definition the no compensation beam delivery efficiency is 100%.

Type of motion trace	Delivery efficiency (%)					
	Conformal		sIMRT		dIMRT	
	MA	RT	MA	RT	MA	RT
Synthetic trace	99	100	97	90	89	65
Regular motion with a gradual baseline drift	99	39	98	33	100	26
Regular motion with an abrupt baseline shift	99	97	98	89	89	68
Irregular motion with varying baseline shifts	99	99	98	95	94	88
Regular motion with a small baseline drift	99	94	98	89	100	70

Note: RT: real-time tracking; MA: moving average tracking; sIMRT: step-and-shoot IMRT plan; dIMRT: sliding window IMRT plan.

TABLE III. Geometric accuracy of moving average tracking, real-time tracking, and no compensation beam delivery: the accuracy was defined as the root-mean-square error between the beam center and the target center.

Type of motion trace	Geometric accuracy (mm)		
	MA	RT	NC
Synthetic trace	3.2	0.73	7.2
Regular motion with a gradual baseline drift	3.7	1.1	4.3
Regular motion with an abrupt baseline shift	4.0	1.0	5.7
Irregular motion with varying baseline shifts	3.6	0.95	4.8
Regular motion with a small baseline drift	3.7	1.0	3.7

Note: MA: moving average tracking; RT: real-time tracking; NC: no compensation beam delivery.

III.C. Dosimetric accuracy

Figure 3 shows dose distributions for the conformal circular field delivery to a moving target with the synthetic motion trace, with and without motion compensation. The isodose lines without motion compensation were shifted downward compared with those when the target was static. Moving average tracking shows the γ -test results between those of no compensation and real-time tracking. Figure 4 shows the dose distributions obtained for sIMRT beam delivery to a target moving with the regular motion with a gradual baseline drift trace, with and without motion compensation. A relatively large isodose line shift in the left part of the dose distribution of no compensation beam delivery was corrected with moving average tracking, which is comparable with that of real-time tracking. Table IV shows dosimetric errors listing γ -test failing rates for various motion traces, treatment plans, and motion compensated delivery types. The percentage of dosimetric points failing the γ -test ranged from 4 to 30% for moving average tracking, 0%–23% for real-time tracking, and 10%–47% for no compensation beam delivery. This indicates that, compared to no compensation, a large efficiency gain can be made compared to real-time tracking while maintaining substantial dosimetric improvements. Further study is needed to determine if the additional dosimetric errors compared with real-time tracking are worth the decreased treatment time.

Also notable in Table IV is the increase in the number of points failing the γ -test for dynamic vs step and shoot delivery for all motion compensation types. This variation is likely due to the modulation of the individual field rather than general results, as the modulation of the field affects the magnitude of the interplay effect.³² Geometric uncertainties during tracking (moving average or real-time) will be subject to the interplay effect, though to a lesser extent.

IV. DISCUSSION

In this study, the moving average algorithm, a class of mean position estimation algorithms, was implemented into a DMLC tracking system and experimentally investigated in terms of delivery efficiency and geometric and dosimetric accuracies. The results were also compared with (1) real-time tracking and (2) no compensation beam delivery. The moving average algorithm is useful for target tracking in two

FIG. 3. Dosimetric comparison of moving average tracking with real-time tracking and no compensation beam delivery for the conformal treatment plan with the synthetic motion trace (with a peak-to-peak displacement of 8 mm, a respiratory period of 2.5 s, and a baseline drift of 10 mm). The dose distribution for each beam delivery (solid isodose lines) is compared with that when the target was static (dashed isodose lines). Red rectangles indicate the points where the γ -test failed.

FIG. 4. Dosimetric comparison of moving average tracking with real-time tracking and no compensation beam delivery for the step-and-shoot IMRT treatment plan with the regular motion with a gradual baseline drift trace. The dose distribution for each beam delivery (solid isodose lines) is compared with when the target was static (dashed isodose lines). Red rectangles indicate the points where the γ -test failed.

TABLE IV. Dosimetric accuracy of moving average tracking, real-time tracking, and no compensation beam delivery: the accuracy was defined as the percentage of points failing the 3%/3 mm γ -test.

Type of motion trace	Percentage of points failing the 3%/3 mm γ -test (%)								
	Conformal			sIMRT			dIMRT		
	MA	RT	NC	MA	RT	NC	MA	RT	NC
Synthetic trace	11.0	6.7	14.0	6.0	3.8	10.3	25.0	22.9	27.1
Regular motion with a gradual baseline drift	15.6	11.9	23.0	3.8	3.8	15.1	29.2	20.8	32.3
Regular motion with an abrupt baseline shift	15.6	9.6	28.9	3.8	2.2	26.0	22.9	19.8	37.5
Irregular motion with varying baseline shifts	17.8	3.7	34.8	4.9	0.0	20.5	29.2	18.8	41.7
Regular motion with a small baseline drift	16.3	11.1	31.1	4.9	2.7	41.0	30.2	22.9	46.9

Note: MA: moving average tracking; RT: real-time tracking; NC: no compensation beam delivery.

ways. First, it can substantially reduce systematic errors associated with target motion, particularly baseline drifts, which have a large impact on clinical target volume to planning target volume margins.²¹ Second, it provides an alternative solution to circumvent mechanical constraints in MLC leaf motion during real-time tracking. The target motion parallel to the MLC leaf travel direction can be compensated for using real-time tracking and the motion perpendicular to the MLC leaf travel direction can be managed by the moving average algorithm.

There are a number of factors related to the delivery efficiency of DMLC tracking, including respiratory cycle, magnitude of target motion, complexity of MLC aperture shape, and leaf sequences in IMRT delivery. Moving average tracking showed higher delivery efficiency than real-time tracking because moving average tracking follows the slowly changing baseline of the target motion, while real-time tracking attempts to correct for the entire real-time target motion.

The effect on the geometric accuracy of moving average tracking is shown well in the synthetic trace result, where moving average tracking reduces geometric errors by compensating the baseline drift, which causes large geometric errors in no compensation beam delivery. Compared with the no compensation technique, moving average tracking showed little improvement in reducing geometric errors resulting from regular motion. The geometric accuracy of DMLC tracking is affected by several factors such as systematic time delay of the DMLC tracking system, the physical size of leaf width, the leaf velocity, the complexity and magnitude of the target motion, and the fidelity of the position monitoring system. An abrupt baseline change or irregularity in target motion may introduce errors in estimating the target mean position with the moving average algorithm. Other mean position estimation algorithms may help in solving this drawback of the moving average algorithm.²³

The dosimetric accuracy is affected by similar factors to those of geometric accuracy, as well as the interplay effect of leaf sequences and target motion in IMRT delivery.³² The moving average algorithm is incorporated to account for target motion perpendicular to the MLC leaf travel direction with the other motion components compensated in real time. The synthetic motion trace has only a motion component perpendicular to the MLC leaf travel direction, so that geometric errors for the other motion components are absent in evaluating dosimetric errors. However, compared with the synthetic trace, the selected patient tumor motion traces have other motion components with a small displacement contributing to large dosimetric errors without motion compensation. Compared with real-time tracking, it is expected (but not shown here) that as the motion perpendicular to the MLC leaf motion increases, the dosimetric accuracy of the moving average algorithm decreases. It is also expected that the efficiency of the real-time tracking would decrease.

V. CONCLUSION

The moving average algorithm was implemented into a DMLC real-time target tracking system to account for target

motion perpendicular to the MLC leaf travel direction. Geometric and dosimetric accuracy results were between those of real-time tracking and no compensation beam delivery. The moving average algorithm maintained high efficiency ($\geq 89\%$) for all of the delivery scenarios investigated.

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