Determination of maximum leaf velocity and acceleration of a dynamic multileaf collimator: Implications for 4D radiotherapy

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The dynamic multileaf collimator (MLC) can be used for four-dimensional (4D), or tumor tracking radiotherapy. However, the leaf velocity and acceleration limitations become a crucial factor as the MLC leaves need to respond in near real time to the incoming respiration signal. The aims of this paper are to measure maximum leaf velocity, acceleration, and deceleration to obtain the mechanical response times for the MLC, and determine whether the MLC is suitable for 4D radiotherapy. MLC leaf sequence files, requiring the leaves to reach maximum acceleration and velocity during motion, were written. The leaf positions were recorded every 50 ms, from which the maximum leaf velocity, acceleration, and deceleration were derived. The dependence on the velocity and acceleration of the following variables were studied: leaf banks, inner and outer leaves, MLC-MLC variations, gravity, friction, and the stability of measurements over time. Measurement results show that the two leaf banks of a MLC behave similarly, while the inner and outer leaves have significantly different maximum leaf velocities. The MLC-MLC variations and the dependence of gravity on maximum leaf velocity are statistically significant. The average maximum leaf velocity at the isocenter plane of the MLC ranged from 3.3 to 3.9 cm/s. The acceleration and deceleration at the isocenter plane of the MLC ranged from 50 to 69 cm/s² and 46 to 52 cm/s², respectively. Interleaf friction had a negligible effect on the results, and the MLC parameters remained stable with time. Equations of motion were derivable derived to determine the ability of the MLC response to fluoroscopy-measured diaphragm motion. Given the present MLC mechanical characteristics, 4D radiotherapy is feasible for up to 97% of respiratory motion. For the largest respiratory motion velocities observed, beam delivery should be temporarily stopped (beam hold).

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I. INTRODUCTION

Maximum leaf velocity for multileaf collimator (MLC) radiotherapy is an important factor for conventional dynamic intensity modulated radiation-therapy delivery.1–5 However, with the potential ability of the MLC to be used for dynamic multileaf collimator (DMLC)-based four-dimensional (4D), or tumor tracking radiotherapy,6–10 will require a new treatment delivery mechanism where the MLC is continuously communicating with a separate controller, which is supplying leaf positions at 20 Hz. In DMLC-based 4D radiotherapy leaf acceleration becomes an important factor, since the multileaf collimator leaves need to respond within a fraction of the respiratory cycle, to the incoming respiratory motion signal. The delay between the acquisition of the respiratory motion signal and the activation of the delivery system is called the response time. The response time is composed of several components, such as respiratory signal acquisition, signal processing, determination of leaf trajectories based on the treatment plan and respiratory signal, communication of the leaf trajectories to the MLC, and the mechanical response time of the MLC in following the leaf trajectory instructions.11 Our research focused on the latter component, the mechanical response time of the MLC to leaf-trajectory instructions. The aims of this research were to

1. Measure the average maximum velocity, acceleration and deceleration of the MLC leaves,
2. Derive equations of motion to determine the mechanical response times of the MLC, and
3. Determine the capability of the MLC to track respiratory motion in DMLC-based 4D radiotherapy.

II. MATERIALS AND METHODS

This section consists of the following seven subsections: basics of DMLC operation, creating leaf-sequence files, delivering leaf-sequence files at the linear accelerator, extracting Dynalog files, determining the isocenter positions of the leaves, calculating mechanical characteristics of the leaves, and determining the capability of the MLC to track respiratory motion. The details of each subsection are explained below.

A. Basics of DMLC operation and dynalog files

For the measurements described in this paper, three Varian (Varian Medical Systems, Palo Alto, CA) 120-leaf Millennium multileaf collimator systems with a Clinac model 21EX accelerator were used. The Millennium MLC system provides mechanically variable beam collimation using individually motorized leaves to shape treatment fields. There are two carriages with two banks of leaves each carrying 60 leaves. The MLC controller drives the MLC leaves using instructions from a leaf-sequence file. During a dy-
dynamic treatment, through a communication link, the MLC controller records information related to MLC motion—dose fraction, tolerance, gantry angle, beam-hold flag, gantry position, and the positions of each leaf—and places it in a “Dynalog” file every 50 ms.\textsuperscript{12} Recording continues until the dynamic treatment is completed or terminated.

B. Creating leaf-sequence files

A leaf-sequence file (referred to throughout as “synchronous,” because the leaves move together) was generated such that all the leaves were initially positioned at $-5$ cm (all positions described here are projections to the isocenter). All B (right) leaves were requested to travel to $+5$ cm in 0.001 fraction of the overall delivery, (20 MUs delivered at a dose rate of 300 MU/min). At 0.499 of the overall delivery, the A (left) leaves were requested to travel to $+5$ cm, finishing at 0.500 of the overall delivery. Thus, in the absence of acceleration and maximum leaf-velocity constraints, each leaf moved 10 cm in 0.004 s, corresponding with an average velocity of 250 cm/s, well beyond the capabilities of the MLC as will be shown. However, such a request, which exceeds the MLC’s capabilities, will cause the MLC to drive the leaves with maximum acceleration, velocity, and deceleration during this period. There was no MLC motion over the final half of delivery; however, inclusion of the extra delivery time was required to ensure that the Dynalog file, which records the leaf-position information, was complete. A reverse leaf-sequence file, identical to that described above, was also created, except that leaf starting positions and directions were reversed. In order for the measurements to illustrate the effects of friction, another set of four leaf-sequence files (referred to throughout as “asynchronous,” because only every other leaf moves) was created. With this set, every other leaf was intended to move from both leaf banks (odd-even and even-odd), simultaneously starting from an open configuration and ending in a closed configuration and vice versa. In all the leaf sequence files, a leaf position tolerance at the iso center of 0.2 cm was used.

Figure 1 shows a typical leaf motion pattern for the three cases we considered in this measurement. Panels (a): 1, 2, 3, and 4 show the synchronous motion of leaves with leaf bank B moving first, followed by the leaf bank A motion. Panel (b) [panel (c)]: 1, 2, and 3 show the asynchronous leaf motion starting with the closed (open) configuration and ending with the open (closed) configuration. Here, every other leaf was moved at a given time to quantify the effects of friction on leaf motion from the adjacent leaves.

C. Delivering leaf-sequence files at the linear accelerator

To investigate the dependence of inner versus outer leaves, temporal stability, MLC-MLC variations, influence of gravity, and friction on the motion parameters the following measurements were taken.

1. Comparison of leaf banks and inner and outer sets of leaves and the stability with time

Each leaf-sequence file for the synchronous case was delivered three times in a single measurement; this procedure was repeated three times over a period of three weeks and after one year, with MLC 1 to examine the stability of leaf-motion characteristics with time.

2. MLC-MLC variations

Each leaf sequence file for the synchronous case was delivered on three different MLCs (all Millennium 120 leaf) to determine the MLC dependence of the leaf motion parameters.

3. Influence of gravity

To determine the effects of gravity on the leaf motion three other such data sets were obtained on a single MLC with the gantry angle set at 90, 180, and 270 deg; keeping the collimator angle at 0 deg; and the gantry angle set at 90 and 270 deg, while the collimator angle was changed from 90 to 270 deg.

4. Influence of friction

Leaf-sequence files for the asynchronous case were delivered once for each of the four setups shown in Table I, with MLC 1, with a gantry angle of 0 and 90 deg for a collimator angle of 0 deg, to determine the effects of friction with and without the effects of gravity. A summary of the experiments performed is shown in Table I.

D. Extracting dynalog files

After the dynamic treatment, the MLC controller stores the Dynalog data files (one for each bank of leaves). By analyzing these Dynalog files for each of the experiments, extracting the leaf positions, and assuming the time interval to be 50 ms, it was possible to evaluate leaf-motion characteristics under different criteria. Hence, the recording time, 50 ms, is crucial for the results discussed in this paper. Furthermore, the Dynalog readings were assumed to be accurate representations of the relative leaf positions, and the variation of acceleration with time was assumed to be a step function. Recent publications on the verification of dynamic MLC controller and log files support the above assumption.\textsuperscript{13–15}

E. Determining leaf positions at the isocenter plane

Dynalog files were converted to leaf-sequence files as follows: First, the positions were converted from Dynalog format (units of positions are in hundredths of a millimeter) to leaf-sequence-file format (units are in centimeters); then, the positions were converted to the beam coordinate system; and, finally, the MLC positions were transferred from the elevation of the MLC to the isocenter plane of the linac using a conversion table “mlctable.txt” by Varian.\textsuperscript{16} This takes care...
of both the magnification and the off-axis light field shift due to the round edge. All velocity and acceleration measurements were those projected to the isocenter.

F. Calculating mechanical characteristics of the leaves

Leaf velocity was obtained from using laws of motion from successive position readings. Figure 2 is a plot of maximum velocities versus time for an inner and outer leaf. The maximum leaf velocity reported in this paper is the average of all maximum leaf velocities calculated for all the leaves for a given set. Since the recording time interval of the Dynalog file is large, relative to the time taken for the leaves to reach their maximum velocity from rest or vice versa, there is an uncertainty in initial/final times for the acceleration/deceleration portion of the motion. Most of these points have spent part of their time in a zero-acceleration region. To precisely measure such high accelerations, it is necessary to record leaf positions at a higher rate. In our study, a chi-squared minimization was performed for the time differences of positions, recorded versus fit, assuming the following constraints: constant acceleration and that the leaves started from zero velocity and ended with the measured maximum velocity. Observed uncertainties were used as the limits on these variables in the fit. The fit results yielded two parameters: the acceleration (deceleration) and the initial (final) times for the motion of each leaf in each experiment. Since we do not have enough degrees of freedom, it was impossible to determine both the initial and the final times from the fit. Such obtained fit results for a single leaf from a measurement from machine 1 for the acceleration portion are shown in Fig. 3.

![Fig. 1](image-url) MLT leaves in motion showing the distinction of motion between inner (0.5-cm thick) and outer (1.0-cm thick) leaves. Panels (a), (b), and (c) show synchronous and asynchronous leaf motion, starting from the closed position, and asynchronous, starting from the open positions. In Panel (a), leaf motion is from left to right; first, the B bank moves from -5 to +5 followed by bank A moving from -5 to +5. In panel (b): asynchronous leaf motion for the odd A leaves and even B leaves. Odd leaves in bank A move from +5 to -5 while even leaves stay stationary at -5. Even leaves from bank B move from -5 to +5 while odd leaves stay stationary at +5. In panel (c): asynchronous leaf motion for the odd A leaves and even B leaves. Odd leaves from bank A move from -5 to +5, while the even leaves stay stationary at -5. Even leaves from bank B move from +5 to -5, while the odd leaves stay stationary at +5. In all images, the isocenter is shown by a blank square.
leaves (inner or outer) from a particular experiment, only the leaves that performed a reasonable fit were included (99% of the input data set). Time versus position plot for an event that was not included is shown in the top plot of Fig. 4. As an example, if the variables in the fit did not remain well within the limits assigned to them, such an event is unable to find a minimum under the given constraints such as constant acceleration. Another example would be, leaves were not moving monotonically in one direction as they should be, but we do not have the resolution to discard the event prior to the fit. In preparing the input files with position/time data for the fit, only the leaves that had positions in the acceleration/deceleration region were included. It was observed that 18% of the event set had failed to record positions monotonically in one direction as shown in the bottom plot of Fig. 4, suggesting that these leaves are bouncing back or jittering back and forth in an effort to come to rest at a required position. These data points were discarded from the fit sample. Furthermore, it appears that there are two sets of deceleration fit values within the inner or outer leaves; as a result, we could not clearly identify criteria for discarding one value, hence, the large standard-deviation variation depicted in the decelerations. One speculation is that the lower deceleration value from the two values might have already undergone jittering even though we did not have the temporal resolution to observe it. Since we did not correct for the time when the leaf was at its maximum velocity, both the acceleration and the deceleration values reported in this paper are the best estimates of the lower limits that will be the closest to reality. Error is a combination of the resolution of the measurements as well as the stability of the measurements and will represent an upper limit.

G. Determining the capability of the MLC to track the respiratory motion

There are different aspects of the 4D delay, that need to be considered, such as mechanical, communication, image pro-

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**Table I.** Types of measurements performed with variables that may affect maximum leaf velocity, acceleration, and deceleration.

<table>
<thead>
<tr>
<th>Type of measurement</th>
<th>Leaf-sequence file type</th>
<th>MLC used</th>
<th>Gantry angle (deg)</th>
<th>Collimator angle (deg)</th>
<th>Number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time dependence</td>
<td>Synchronous</td>
<td>MLC 1</td>
<td>0</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLC 2</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLC 3</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLC 1</td>
<td>90</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLC 1</td>
<td>180</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLC 1</td>
<td>270</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Machine dependence</td>
<td>Synchronous</td>
<td>MLC 1</td>
<td>90</td>
<td>90</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLC 1</td>
<td>90</td>
<td>270</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLC 1</td>
<td>270</td>
<td>90</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLC 1</td>
<td>270</td>
<td>270</td>
<td>3</td>
</tr>
<tr>
<td>Gravitational</td>
<td>Synchronous</td>
<td>MLC 1</td>
<td>0 and 90</td>
<td>0</td>
<td>1 Close → open (odd A/even B)</td>
</tr>
<tr>
<td>Gravitational</td>
<td>Synchronous</td>
<td>MLC 1</td>
<td>0 and 90</td>
<td>0</td>
<td>1 Close → open (even A/odd B)</td>
</tr>
<tr>
<td>Gravitational</td>
<td>Synchronous</td>
<td>MLC 1</td>
<td>0 and 90</td>
<td>0</td>
<td>1 Close → open (odd A/even B)</td>
</tr>
<tr>
<td>Friction dependence</td>
<td>Asynchronous</td>
<td>MLC 1</td>
<td>0 and 90</td>
<td>0</td>
<td>1 Open → close (even A/odd B)</td>
</tr>
<tr>
<td>Friction dependence</td>
<td>Asynchronous</td>
<td>MLC 1</td>
<td>0 and 90</td>
<td>0</td>
<td>1 Open → close (even A/odd B)</td>
</tr>
</tbody>
</table>

Note: MLC: multileaf collimator.
cessing, motion prediction, etc. In this paper we focus only on one but important portion of the total delay, the mechanical response time. Furthermore, the actual control of motion via control loop software is not part of this study, this study simply determined if the MLC was mechanically capable of tracking motion of the magnitude of respiration. However the work in this manuscript provides essential information for the development of the 4D controller. There is significant concern that there may occur dosimetric errors when operating the MLC in an environment which it was not designed for. However, there is some published data for 4D conformal radio therapy and intensity modulated radio therapy (IMRT) dosimetry that indicates that the errors, if present, are not significant.

The measured acceleration/maximum velocity/deceleration values were subsequently used to obtain the limits on the mechanical response time for the aforementioned MLC unit. General formulas for the mechanical response time derived from the equations of motion are

\[
\Delta t = \frac{\Delta x}{v_{\text{max}}} + \frac{(v_{\text{max}} - v_f)^2}{2a v_{\text{max}}} + \frac{(v_{\text{max}} - v_i)^2}{2d v_{\text{max}}},
\]

if \( \Delta x \geq \left| \frac{(v_{\text{max}}^2 - v_f^2)}{2a} + \frac{(v_{\text{max}}^2 - v_i^2)}{2d} \right| \).

Here \( v_{\text{max}}, a, \) and \( d \) are the maximum leaf velocity, constant leaf acceleration, and deceleration obtained from measurements, respectively. \( v_i \) and \( v_f \) are any arbitrary initial and final velocities for the leaf. \( \Delta x, \Delta t \) are the requested leaf displacement and the time taken for the displacement, respectively. Equation (1) corresponds with the scenario in which the leaf goes through the maximum velocity at some portion of its motion, while Eq. (2) corresponds with the scenario in which the leaf does not reach the maximum velocity at any portion of its motion. The lower limit on the second equation is to avoid overshooting of the leaf during motion. We can organize position-change operations into different classes. Several examples, ordered by the response time and including the best and worst case scenarios for the initial/final boundary conditions considered, are

1. \( v_i = v_{\text{max}}, v_f = v_{\text{max}} \)
2. \( v_i = v_{\text{max}}/2, v_f = v_{\text{max}}/2 \)
3. \( v_i = 0, v_f = v_{\text{max}}, v_f = v_{\text{max}}, v_f = 0 \)
4. \( v_i = 0, v_f = 0 \)
5. \( v_i = -v_{\text{max}}, v_f = v_{\text{max}} \)
6. \( v_i = -v_{\text{max}}, v_f = 0 \)

The best case scenario is when the leaf is already moving with the maximum velocity toward the desired location. A more difficult scenario occurs when the leaf is initially moving away from the desired location with maximum velocity. The worst possible scenario occurs when the previous situation is combined with a zero final velocity requirement.

The mechanical response times derived from the equations of motion were compared with patient respiratory signal data, collected and analyzed from over 20 respiratory motion data sets obtained from five patients under visual breathing training using fluoroscopy, as discussed by Vedam et al. The respiratory data was recorded every 100 ms as opposed to every 50 ms, corresponding to the MLC controller operating frequency of 20 Hz. The diaphragm displacements between each consecutive fluoroscopic image frame were calculated from the data set linearly interpolated to 50 ms. From this displacement distribution, the corresponding quartile positions (positions at which the sample distribution is divided into four equal samples) were obtained.

### III. RESULTS AND DISCUSSION

Prior to a discussion of our results, it should be noted that the real-time behavior of the machine control system also affects the ability of the MLC to deliver a given dynamic sequence. According to the findings of Litzenberg, Moran, and Fraass, maximum operational velocity, which is always...
less than the maximum possible leaf velocity of the MLC leaves, is directly proportional to the leaf-position tolerance and inversely proportional to the time delay in the communication system. In 4D radiotherapy, it would be necessary to quantify and weigh the dosimetric effects associated with following the tumor in real time versus having a better leaf—positioning accuracy before deciding upon the appropriate settings. Litzenberg, Moran, and Fraass also found that due to the control system-enforced minimum gap (0.5 mm) between leaves, which is required in Varian machines to ensure collision avoidance in leaf pairs, acceleration/deceleration changes may occur. According to the leaf sequence file initial and final leaf positions, this arises as an issue only with decelerations. This may or may not be the reason for our observation of jittering effects on deceleration cases.

We analyzed the acceleration, deceleration (second order term) and maximum velocity ($v_{max}$—first-order term) of each leaf for each of 64 experiments. In analyzing the data, we grouped the data as follows: leaf banks A and B; inner and outer sets of leaves; machine used to acquire the data with MLC 1, MLC 2 or MLC 3; motion direction with respect to gravity; and effect of friction.

Even though higher-order terms may have an effect on the response time, here we assumed the acceleration to have a step function (not unrealistic to consider motors designs giving constant torque). The reason for not attempting to measure higher-order terms was twofold: Due to the limited time sampling (50 ms), the acceleration measurements were poorly resolved, and thus the errors for higher-order derivatives would be compounded. Further, the effect of these terms is increasingly small.

A. Comparison of leaf banks and inner and outer sets of leaves and the stability with time

Figure 5 (top), (middle), and (bottom) shows the comparison of maximum leaf velocities, accelerations, and decelerations for the two leaf banks A and B for inner and outer leaves from MLC 1 at both the gantry angle and the collimator angle at 0 deg. As shown, it was observed that the A and B banks of leaves behave similarly within the statistical uncertainties for both observables of interest. Therefore, in presenting the remaining data, we do not make a distinction between the two banks.

In all scenarios, the inner set of leaves moves faster than the outer set of leaves. Two distinctions are observed between inner and outer leaves: the inner leaves (leaf numbers 11 to 50) have a width of 0.5 cm, while the outer leaves (leaf numbers 1 to 10 and 51 to 60) have a width of 1.0 cm. Also the inner set of leaves is driven by motors with a resistance
of 33 to 43 Ω, while the outer set is driven by motors with a resistance of 14 Ω. Due to these differences, the outer leaves which probably require more torque do not get enough to keep up with the inner leaves. There is a statistically significant difference in maximum velocities for inner and outer leaves for all scenarios. Normally, inner leaves move with a maximum velocity of $3.9 \pm 0.5$ cm/s, while the outer leaves have a maximum velocity of $3.3 \pm 0.1$ cm/s. Accelerations for the inner and outer sets of leaves are $66 \pm 5$ and $52 \pm 3$ cm/s$^2$, respectively, while the decelerations for the inner and outer sets of leaves are $-52 \pm 4$ and $-50 \pm 5$ cm/s$^2$, respectively. Within an individual MLC, the maximum velocity is very stable with time. An additional measurement with MLC 1 was performed after one year of time lag to verify the stability of the motion characteristics, and the values are very stable with time [maximum velocity for inner (outer) leaves were $3.9 \pm 0.2$ cm/s ($3.3 \pm 0.1$ cm/s), acceleration for inner (outer) leaves were $60 \pm 2$ cm/s$^2$ ($55 \pm 6$ cm/s$^2$), and deceleration for inner (outer) leaves were $-55 \pm 6$ cm/s$^2$ ($-52 \pm 7$ cm/s$^2$)].

B. Comparison of MLCs

A comparison of MLCs 1, 2, and 3, as depicted in Fig. 6 (top), shows a maximum variation of 10% on maximum velocity from MLC to MLC. In Fig. 6 (middle), there are variations up to 13% in acceleration from MLC-MLC. Statistical accuracy of the data set hinders us from commenting on the dependence of the deceleration on the MLC, as shown in Fig. 6 (bottom).

C. Influence of gravity

Influence of gravity on maximum leaf velocity was studied using MLC 1. The results are shown in Fig. 7 (top). Gantry angle rotation measurements show that while the set of inner (outer) leaves that move against gravity are approximately $6.6\%$ ($6\%$) lower in velocity than the case when the leaves move orthogonally to gravity, the set of inner (outer) leaves that move with gravity are approximately $2.3\%$ ($1.5\%$) standard deviation higher velocity than the case when leaves move orthogonal to gravity. This effect is independent of the gantry angle or the collimator angle. Influence of gravity on the accelerations is shown in Fig. 7 (middle). Similar behavior is observed here. When the inner set of leaves moves with (against) gravity, it has a 6% higher (8% lower) in acceleration than when it is moving orthogonally to gravity. Figure 7 (lower) again shows that we do not have the resolution to comment on the gravitational dependence on the decelerations.
D. Influence of friction

In all two cases of motion orthogonal to gravity, when every other leaf was moved, (asynchronous with no gravity as shown in Table II), starting from the initial open/closed positions to final closed/open positions, both leaf banks give maximum velocities similar to the case where there is no friction (synchronous with no gravity), showing no dependence on friction for the maximum velocity. The acceleration and deceleration values were in general reduced in the presence of friction, though not significantly. In both cases of motion with and against gravity, when every other leaf was moved (asynchronous with gravity, asynchronous against gravity), the three observables of motion did not show significant deviations from the case where only gravity was operated (synchronous with gravity, synchronous against gravity). This shows that while gravity plays an observable difference in leaf characteristics, interleaf friction does not.

E. Influence of MLC mechanical limitations on mechanical response time

In Fig. 8, we aim to relate the operating range of the measurement-derived MLC mechanical response to measured respiratory motion data. 50 ms is the cycle frequency of the MLC, and thus this is the time interval of interest. Figure 8 shows the mechanical response time versus distance traveled for three initial/final velocity constraint combinations. Since there is only a minimal difference between the inner and the outer sets of leaves for the mechanical response times, only the case for the outer set of leaves is shown here (the inner leaves can respond slightly faster). This figure shows that given the acceleration and deceleration values, only certain boundary conditions could achieve the required criteria of satisfying the initial and final velocity conditions in a 50 ms timing window. Given the measured maximum leaf velocity, acceleration, and deceleration values for the MLC, the achievable range of possible distance is observed as 0 to 1.7 mm within the MLC cycle frequency time of 50 ms. Bar shown in Fig. 8 is the probability of patient respiratory displacements per 50 ms, obtained from fluoroscopic data. The fact that most of the respiratory motion data is within the operating range of the MLC means that the current MLC is mechanically capable of tracking respiratory motion. However, the other sources of time delays must also be addressed prior to clinical implementation. For the case where both the initial and the final velocities are the maximum velocity, the MLC will achieve the required displace-
ment 97% of the time. Small uncertainties in maximum velocity will not significantly affect the mechanical response time. Beam hold will need to be asserted for high velocities and fast directional changes, since acceleration and decelerations are involved in such processes. However, in 4D radiotherapy, directional changes occur only at the endpoints where respiratory motion signal turns around, and since it is shown at the endpoints that the displacements are also small per each 50-ms window, such changes can also be easily achieved from the current MLC.

<table>
<thead>
<tr>
<th>Measurement type</th>
<th>Maximum leaf velocity (cm/s)</th>
<th>Leaf acceleration (cm/s²)</th>
<th>Leaf deceleration (cm/s²)</th>
</tr>
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<tbody>
<tr>
<td>Synchronous with no gravity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner leaves</td>
<td>3.9±0.5</td>
<td>66±5</td>
<td>−52±4</td>
</tr>
<tr>
<td>Outer leaves</td>
<td>3.3±0.1</td>
<td>53±3</td>
<td>−50±5</td>
</tr>
<tr>
<td>Synchronous with gravity</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Inner leaves</td>
<td>4.0±0.2</td>
<td>65±3</td>
<td>−49±15</td>
</tr>
<tr>
<td>Outer leaves</td>
<td>3.3±0.1</td>
<td>49±4</td>
<td>−48±7</td>
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<tr>
<td>Synchronous against gravity</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Inner leaves</td>
<td>3.6±0.2</td>
<td>60±3</td>
<td>−45±10</td>
</tr>
<tr>
<td>Outer leaves</td>
<td>3.1±0.1</td>
<td>47±6</td>
<td>−43±3</td>
</tr>
<tr>
<td>Asynchronous with no gravity (close → open)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Inner leaves</td>
<td>3.9±0.2</td>
<td>59±3</td>
<td>−48±7</td>
</tr>
<tr>
<td>Outer leaves</td>
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<td>−48±1</td>
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<td>Asynchronous with no gravity (open → close)</td>
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<td>Inner leaves</td>
<td>3.9±0.2</td>
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<td>−46±6</td>
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<tr>
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<td>−46±6</td>
</tr>
<tr>
<td>Asynchronous with gravity (close → open)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner leaves</td>
<td>4.0±0.2</td>
<td>63±2</td>
<td>−51±11</td>
</tr>
<tr>
<td>Outer leaves</td>
<td>3.3±0.1</td>
<td>49±6</td>
<td>−49±5</td>
</tr>
<tr>
<td>Asynchronous against gravity (close → open)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner leaves</td>
<td>3.7±0.2</td>
<td>57±2</td>
<td>−48±10</td>
</tr>
<tr>
<td>Outer leaves</td>
<td>3.1±0.1</td>
<td>46±6</td>
<td>−47±6</td>
</tr>
</tbody>
</table>

Fig. 8. Mechanical response time for the operational region (nonhashed time/distance space) for the dynamic multileaf collimator (DMLC) operating cycle time of 50 ms for the outer set of leaves for several initial and final boundary conditions of leaf motion. (Initial, final) boundary conditions \((v_{max}, v_{max}), (v_{max}/2, v_{max}/2), (0, 0)\) are considered. Error bars shown correspond to one standard deviation. The shaded region indicates displacements that cannot be achieved at the requested time for the current hardware. Thus a beam hold will be required for these cases. The stem and leaf plot at the top of the figure represents the quartiles for the displacement at a 50-ms timing window due to the breathing motion extracted from 20 fluoroscopy data sets of five patients. The inner set of leaves will take a slightly shorter time to respond to a position change request.
The efficacy of 4D radiotherapy is dependent on the stability of the mechanical characteristics of each MLC leaf involved in the treatment. Since we have experimentally verified that over a period of one year the MLC system’s characteristics are stable with time, incorporating the measurement of leaf-motion characteristics into a monthly quality assurance program would be useful for monitoring leaf performance and identifying leaf motors that may need to be replaced.

It is likely that future MLC designs will have much higher accelerations, decelerations, and maximum velocities and perhaps more constancy in these observables, since MLCs specifically designed for DMLC-based 4D radiotherapy are being developed. Fluctuations in accelerations and decelerations play an important role in mechanical response time when the leaves are not moving with the maximum velocity, because some delivery times will always be spent under such conditions. The importance of having smaller variations of accelerations from leaf to leaf as well as with time is noted. It is also observed that to accurately measure such high accelerations and decelerations the recording frequency of the leaf positions should be increased, or alternate measurement techniques employed, such as the fast camera method described by Dempsey et al.\textsuperscript{15}

IV. CONCLUSIONS

The maximum leaf velocity, acceleration, and deceleration for the millennium MLC system with 120 leaves have been measured for three different MLC units. There are statistically significant differences in maximum leaf velocity and accelerations; these occur between inner and outer MLC leaves, between MLC units and with gravity. Due to the large fluctuations observed in deceleration (even for each leaf) and due to limited time resolution, compared to the deceleration time of the Dynalog file, no conclusions could be made regarding the dependency of deceleration on machine, gravity, or friction. Only a lower limit with an upper limit on the error is reported for the leaf accelerations and decelerations. However, the small fluctuations in maximum leaf velocity have only a small impact on the mechanical response time of the MLC for DMLC-based 4D radiotherapy. The mechanical response time calculated from the measured acceleration and maximum leaf velocity data is deemed adequate for 4D radiotherapy, provided a beam hold is available for the rare occasions when the respiration motion exceeds the mechanical limitations of the MLC.

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\textsuperscript{12}Dynalog file viewer, Reference Guide (Varian Medical Systems, 2002).


\textsuperscript{16}Millennium MLC, Systems and Maintenance Guide (Varian Medical Systems, 2001).