Dosimetric evaluations of the interplay effect in respiratory-gated intensity-modulated radiation therapy

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(Received 31 March 2008; revised 18 December 2008; accepted for publication 19 December 2008; published 20 February 2009)

The interplay between a mobile target and a dynamic multileaf collimator can compromise the accuracy of intensity-modulated radiation therapy (IMRT). Our goal in this study is to investigate the dosimetric effects caused by the respiratory motion during IMRT. A moving phantom was built to simulate the typical breathing motion. Different sizes of the gating windows were selected for gated deliveries. The residual motions during the beam-on period ranged from 0.5 to 3 cm. An IMRT plan with five treatment fields from different gantry angles were delivered to the moving phantom for three irradiation conditions: Stationary condition, moving with the use of gating system, and moving without the use of gating system. When the residual motion was 3 cm, the results showed significant differences in dose distributions between the stationary condition and the moving phantom without gating beam control. The overdosed or underdosed areas enclosed about 33% of the treatment area. In contrast, the dose distribution on the moving phantom with gating window set to 0.5 cm showed no significant differences from the stationary phantom. With the appropriate setting of the gating window, the deviation of dose from the respiratory motion can be minimized. It appeals that limiting the residual motion to less than 0.5 cm is critical for the treatments of mobile structures. © 2009 American Association of Physicists in Medicine. [DOI: 10.1118/1.3070542]

Key words: gating, intensity modulation, dosimetry, respiratory motion, interplay effect

I. INTRODUCTION

Intensity-modulated radiation therapy (IMRT) has been used to deliver highly conformal dose to irregular targets. One of the major and unique characteristics of IMRT is that each field is composed of many subfields or segments to be delivered in sequence. Several publications have shown that the motions caused by respiration can be as large as 3 cm.1–5 During the delivery of IMRT, the interplay between the multileaf collimator (MLC) movement and the motion of internal structures may introduce distortion to the desired dose distribution. These motion artifacts during imaging or treatment have been reported by several authors.6–9 The common solution is to increase the margin of the target volume to enclose the maximum range of motion. However, these expanded margins may inevitably include the adjacent healthy tissue or critical structures into the treatment fields and increase the possibility of radiation-related complications.

A variety of alternative methods have been proposed to reduce the issues from respiratory motion.10–13 An effective approach to resolve it without increasing margins is to “gate” or “synchronize” the radiation to specified phases of respiratory cycle. A few studies have demonstrated the effectiveness of the camera-based respiratory gating system from Varian Medical System (real-time position management system [RPM™]).14,15 In our experience, one of the prerequisites of the gating system is that patients have to be able to follow the audio/video coaching and exhibit a regular breathing pattern during simulation and treatment. As a result, the patients with serious chronic obstructive pulmonary disease would not be considered to receive any gating treatments in our institution.
Although the gating system can reduce the motion during radiation therapy, the interplay between residual organ motion and leaf movements still exists. The larger residual motion exists in the IMRT delivery, the more motion artifacts will be seen in the resultant dose distribution. The question to be answered is “how much residual motion is acceptable during gated IMRT?” The published data focused on the difference between the dose deliveries with and without gating system.\(^\text{16–18}\) There was not much information about the effects of residual motion on the delivered dose. Therefore, we designed three experiments to investigate the dosimetric effects between the stationary and moving targets. Furthermore, the appropriate gating window may be determined for gated IMRT. Several gating windows were used in gated deliveries to examine their impacts on the dose distributions.

## II. MATERIAL AND METHODS

A Varian 23EX linear accelerator equipped with RPM gating system and a custom-designed moving phantom were used in this study. The setup in this experiment is shown in Fig. 1. The phantom was made of polystyrene with a dimension of \(25\times25\times18\text{ cm}^3\). The phantom-marker assembly was connected to a drive mechanism that could generate a periodic motion up to 3 cm. The direction of motion was along the longitudinal axis of the treatment couch and the pattern of motion was designed to mimic a normal respiratory pattern. In this representative pattern, the sinusoidal part simulated the inhaled and exhaled motion. A short flat part simulated the short rest period at exhalation.

The movement of the phantom was monitored by observing a marker block mounted on the top of the phantom. The marker block is made of lightweight plastic in rectangular shape with two circular reflectors located on one side of its surface. An infrared camera captures the real-time positions of the reflectors at the rate of 30 frames/s and sends the video signal to the RPM computer. The RPM computer then tracks the position of the marker block and plots the trace of its motion, which in fact represents the movement of the phantom from the camera’s perspective. A threshold or window can be set on the trace of the motion. When the trace of the marker moves in or out of the gating window, a corresponding on or off signal is sent to the beam control box. The beam control box, in turn, enables or disables the radiation beam depending on the marker’s position. When the trace of the marker moves to the peaks of the curve, the position of the phantom should be in its most superior position. Conversely, when the marker moves to the valleys of the curve, it corresponds to the most inferior position of the phantom. This cyclical motion of the marker was divided into 100 phases ranging from 0\% to 99\% phase, which evenly covers the entire cycle from peak to peak on the waveform. Each phase in the entire cycle corresponds to each of the phantom positions. In this study, the term “gating window” is defined by a sequence of phases as the beam-on period in each cycle. The mean motion of the phantom for a range of phases was calculated using the following equation:

\[
\text{Mean motion} = \frac{\sum [\text{phantom displacement at each phase}]}{[\text{No. of phases}]}.
\]

Dosimetric studies on absolute doses, dose profiles, and dose distributions were performed for all three experiments. Each of the field arrangements were delivered to (i) stationary phantom, (ii) moving phantom without gating control, and (iii) moving phantom with gating control. The results on the stationary phantom always serve as references for comparison. All the experiments were performed on the same moving phantom. The maximum movement was always 3 cm, but the residual motion during beam-on period was controlled by the gating window. The brief descriptions of all three types of field arrangements are as follows.

### II.A. Simple step-and-shoot field

This test was designed to show the effectiveness of the gating system. A simple static step-and-shoot IMRT with two \(5\times10\text{ cm}^2\) segmental fields was used to irradiate the stationary and moving phantoms. This simple step-and-shoot field was designed to simulate a uniform \(10\times10\text{ cm}^2\) field. A Kodak EDR2 x-ray film was placed at 5 cm depth in the phantom. The beam direction was perpendicular to the plane of the film. The direction of motion was parallel to the motion of the MLC leaves. The gating window was set to 1 cm residual motion during beam-on period. In order to evaluate the dose distortion under large motion, the same fields were also delivered to the moving phantom without the use of gating system. The results obtained from the stationary phantom served as a reference for comparison.

### II.B. Single dynamic MLC field

A dynamic sliding-window IMRT field was designed to generate a dose distribution with highly modulated fluence. Similar to the previous test, the beam direction was perpendicular to the Kodak EDR2 film which was placed at 5 cm
FIG. 2. The eight gating windows used in this study were (a) 29%–68% phases, (b) 35%–73% phases, (c) 84%–16% phases, (d) 24%–74% phases, (e) 23%–77% phases, (f) 20%–78% phases, (g) 18%–81% phases, and (h) 75%–25% phases. The beam-on periods are shown with dashed lines on the curves.
depth in the phantom for both stationary and moving conditions. Three measurements were performed with three different gating windows. The first window setting was set to limit the residual motion during the beam-on period ranged from 0 to 0.6 cm and the mean motion was about 0.1 cm. For the second gating window, the phantom residual motion ranged between 0 and 0.8 cm with the mean motion of about 0.2 cm. For the third window setting, the motion during the beam-on period ranged from 0 to 1 cm and the mean motion was about 0.25 cm. The result obtained from the stationary phantom served as a reference for the comparison.

### II.C. Multiple dynamic MLC fields

A clinical lung IMRT plan was randomly chosen for the investigation. In this plan, there were five sliding-window dynamic fields at the gantry angles of 40°, 155°, 180°, 210°, and 343°. The same moving phantom was used for this experiment. The results obtained from the static phantom served as a reference for comparison.

To investigate the effects of the target motion, eight different gating windows were determined for the dose deliveries. These were 29%–68%, 35%–73%, 84%–16%, 24%–74%, 23%–77%, 20%–78%, 18%–81%, and 75%–25% phases. The beam-on periods of the gating windows were similar, but the motion patterns were different. For those gating windows at the inhalation part of the breathing cycle, the beams were aligned with the center of the phantom when it reached the end of inhalation. For those gating windows at the exhalation part of the cycle, the beam centers were aligned with the center of the phantom when it reached the end of exhalation.

All films were processed according to the film dosimetry guideline and then scanned with Vidar® 12 scanner (Vidar Systems Corporation, 365 Herndon Parkway, Herndon, VA 20170). The analysis was done with RIT 113® radiation dosimetry software Version 4.1 (Radiological Imaging Technology, Inc., 637 Elkton Drive, Colorado, CO 80907).

### III. RESULTS

#### III.A. Simple step-and-shoot field

Figures 3(a) and 3(b) show the radiation field image and the dose profiles when the film-phantom combination was irradiated with simple step-and-shoot field without using gating system. Figures 3(c) and 3(d) show the results when gating system was used. In Figs. 3(b) and 3(d) the solid lines represent the dose profile obtained from the film under stationary condition and the dashed lines represent those obtained from moving conditions. The differences between the two sets of profiles are shown with thin blue lines. As large as 50% discrepancies were observed when the film was irradiated without the gating system. In contrast, differences of less than 3% inside the field were observed when the gating system limited the residual motion to less than 1 cm.

#### III.B. Single dynamic MLC field

This experiment demonstrated the impacts of different gating windows, which directly related to the motion magnitude in the beam-on period. As previously stated, the direction of motion was parallel to the motion of the MLC in this test. The film exposed in the stationary phantom is shown in Figs. 4(a). The comparison of the dose profiles between the stationary and the moving conditions with three different gating windows (as described in Sec. II) are shown in Figs. 4(b)–4(d). The dose profiles from the gating windows, which corresponded to the 0.6 and 0.8 cm maximum residual motions, were close to the stationary condition. The dose differ-

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**Table I. The properties of nine different gating windows and percentages failing gamma test from film analysis.**

<table>
<thead>
<tr>
<th>Gating window</th>
<th>% Duty cycle</th>
<th>Beam-on part of the breathing cycle</th>
<th>Mean motion (cm)</th>
<th>Maximum motion (cm)</th>
<th>% Area failing gamma</th>
<th>Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>29%–68%</td>
<td>40</td>
<td>Exhalation</td>
<td>0.10</td>
<td>0.5</td>
<td>0.0</td>
<td>Yes</td>
</tr>
<tr>
<td>35%–73%</td>
<td>39</td>
<td>Exhalation</td>
<td>0.15</td>
<td>1.0</td>
<td>0.3</td>
<td>Yes</td>
</tr>
<tr>
<td>84%–16%</td>
<td>33</td>
<td>Inhalation</td>
<td>0.26</td>
<td>1.0</td>
<td>0.0</td>
<td>Yes</td>
</tr>
<tr>
<td>24%–74%</td>
<td>51</td>
<td>Exhalation</td>
<td>0.25</td>
<td>1.1</td>
<td>0.5</td>
<td>Yes</td>
</tr>
<tr>
<td>23%–77%</td>
<td>55</td>
<td>Exhalation</td>
<td>0.31</td>
<td>1.4</td>
<td>5.1</td>
<td>No</td>
</tr>
<tr>
<td>20%–78%</td>
<td>59</td>
<td>Exhalation</td>
<td>0.38</td>
<td>1.5</td>
<td>5.5</td>
<td>No</td>
</tr>
<tr>
<td>18%–81%</td>
<td>64</td>
<td>Exhalation</td>
<td>0.48</td>
<td>1.9</td>
<td>11.4</td>
<td>No</td>
</tr>
<tr>
<td>75%–25%</td>
<td>51</td>
<td>Inhalation</td>
<td>0.67</td>
<td>2.1</td>
<td>8.5</td>
<td>No</td>
</tr>
<tr>
<td>0%–100%</td>
<td>100</td>
<td>Inhalation</td>
<td>1.72</td>
<td>3.0</td>
<td>33.2</td>
<td>No</td>
</tr>
</tbody>
</table>

*a The criteria used for gamma test were 5% dose difference and 5 mm distance-to-agreement.*
ences at the top of the peaks were about 3% in the 0.6 cm, 6% in the 0.8 cm and 12% in the 1.0 cm residual motion case.

III.C. Multiple dynamic MLC fields

Figures 5–7 demonstrate the impacts of different gating windows on the IMRT delivery that involved multiple dynamic fields. Figure 5 shows the results obtained with the gating window that was set to 29%–68% phases and the residual motion was less than 0.5 cm. In both the profile and isodose comparisons, the solid lines represent the results from stationary condition and the dashed line is from the moving condition. The differences between two profiles are shown with thin lines.

FIG. 3. Results from the single step-and-shoot field test. (a) The radiation field image from the moving phantom delivered without gating control. (b) The dose profile comparison between the stationary condition and the moving condition without any gating control. (c) The radiation field image from the moving phantom delivered with 84%–16% gating window. (d) The dose profile comparison between the stationary phantom and the moving phantom delivered with 84%–16% gating window. In each profile comparison graph, solid line is the profile from the stationary condition and dashed line is from the moving condition. The differences between two profiles are shown with thin lines.
along the direction of motion. However, by looking at the isodose curves, all the corresponding isodose lines almost overlap on top of each other. The central dose profiles along the longitudinal and lateral directions are also matched well.

Figure 6 presents the results with 23%–77% gating window, which allowed up to 1.4 cm motion in the beam-on period. The deviations in the longitudinal margins are easy to see in the dose difference map. Compared to the gating window 29%–68% case, this gating window allowed for larger motion during the beam-on period, so the corresponding isodose lines do not seem to match well. Figure 7 shows the dose differences, isodose overlays, and central axis profiles of gating windows that allowed 3.0 cm residual motion. These cases demonstrated large motion artifacts in IMRT delivery. The dose distribution was obviously distorted by the phantom motion. Apparently, the larger the motion allowed during the beam-on period, the larger area would be overdosed or underdosed. An objective tool called “gamma-index” proposed by Low and co-workers\textsuperscript{19,20} was used to compare the dose distributions from different conditions. This quantity provides a numerical quality index that serves as a measure of disagreement that compares to the acceptance criteria. A gamma-index distribution can be generated and displayed, providing a quantitative assessment of the similarity of two dose distributions. We adapted 5% dose difference and 5 mm distance-to-agreement to his gamma equations to determine the pixels in those images were passed or failed. Generally speaking, if the dose difference is less than 5% or the distance-to-agreement is less than 5 mm, then that pixel would be identified as a passed pixel; otherwise it would be marked as failed pixel. For the detailed definition of Gamma index, please refer to Refs. 19 and 20.

Figure 8 shows the gamma pass-fail maps for all the nine gating windows in this study. Table I summarized the percentage area that failed the gamma test, which is the percentage of area failed 5% dose-difference and 5 mm distance-to-agreement criteria. The failing percentage of 0.5 cm residual motion case was 0%. The maximum failing percentage of 1.0
cm group was about 0.5%, while the maximum failing percentage of 1.5 cm group was much higher at 5.5% and the maximum percentage of 2.0 cm group had about 10% area over the criteria. The 3.0 cm residual motion case had about 33% of the pixels, over the criteria.

It is important to point out that all the dose deviations seem to appear in the regions of borders along the direction of motion. The doses delivered to the central parts of the films had not been affected significantly even when the residual motion was as large as 3.0 cm. The results of the chamber measurements shown in Table II demonstrate very little differences from the static to moving cases. All the chamber measurements were displayed in the forth column of Table II, and they have been normalized to the reading from the stationary case. All appeared to have less than 2% dose deviations from the stationary phantom.

IV. DISCUSSION

The movements of the internal structures in the thorax or abdomen can be as large as 3 cm even under quiet breathing. The organ motions might potentially compromise the efficacy of IMRT. An effective way to resolve this problem without increasing margins of the targets is to gate the radia-

Fig. 5. Results of the multiple dynamic MLC irradiation technique with 29%–68% phases gating window that allowed up to 0.5 cm residual motion. (a) The dose difference between stationary phantom and moving phantom with gated delivery. (b) The isodose comparison between stationary phantom (solid lines) and moving phantom with gated delivery (dashed lines). The isodose levels shown are 95%, 90%, 70%, 50%, and 30%. (c) The comparison of central longitudinal profiles taken from stationary phantom (solid line) and the gated delivery (dashed line). (d) The comparison of central lateral profiles taken from stationary phantom (solid line) and the gated delivery (dashed line).
tion beam with the respiratory signal. Respiratory gating has been successfully applied to patient treatments in Japan and the United States. The study conducted by Mageras et al.\textsuperscript{14} showed that the average patient diaphragm excursion could be reduced from 1.4 cm (range of 0.7–2.1 cm) without gating to 0.3 cm (range of 0.2–0.5 cm) with breathing instruction and gating beam control.

The magnitude of residual motion within the gating window is an important factor to change the dose distributions, the pattern of target motion may also affects the dose delivered to the target. If we consider two cases with the same residual motion, for the first case, the target stays at the expected location during 80% of the beam-on period and moves in the rest of the time in a breathing cycle; for the other case, the target spends 20% of the beam-on time at the expected position and moves in the remaining 80% of the time. Although they may have the same maximum residual motion, the dose distributions from the above two cases will be different. Therefore, the motion pattern within the gating window should also affect the delivered dose. We tried to calculate the mean motion in the gating window to see if there is a correlation between the mean motion and perturbation of the dose. But, it did not show a direct correlation to the percentage of failing/passing pixels in the gamma evalu-

FIG. 6. Results of the multiple dynamic MLC irradiation technique with 23%–77% phases gating window that allowed up to 1.4 cm residual motion. (a) The dose difference between stationary phantom and moving phantom with gated delivery. (b) The isodose comparison between stationary phantom (solid lines) and moving phantom with gated delivery (dashed lines). The isodose levels shown are 95%, 90%, 70%, 50%, and 30%. (c) The comparison of central longitudinal profiles taken from stationary phantom (solid line) and the gated delivery (dashed line). (d) The comparison of central lateral profiles taken from stationary phantom (solid line) and the gated delivery (dashed line).
ation. However from one group to another, both the mean and maximum motion displayed the increases in failing pixels when these two quantities increased.

Based on the results from our experiments, we believe that dose distribution on a moving target will be considerably different from those in the stationary condition if there is no motion management applied to the treatment. With an appropriate gating window, the gated delivery should significantly reduce the dose deviations from motion. In the single dynamic MLC field test, the dose profiles from 0.6 and 0.8 cm residual motions were not dramatically changed by the motion artifacts. However, the dose deviation increased with the increase in motion magnitude within the gating window. It appeared that the target motion smeared the dose in the direction of movement and reduced the dose gradient inside the field. In all of our measurements, the results showed that the dose deviations between the stationary and moving phantom cases were closely correlated with the size of gating window. When the residual motion was less than 0.5 cm, the dose distribution appeared to be almost unchanged. If the

Fig. 7. Results of the film analysis from the multiple dynamic MLC fields test without gating beam control. There was up to 3.0 cm motion during the beam-on period. (a) The dose difference between stationary phantom and moving phantom with gated delivery. (b) The isodose comparison between stationary phantom (solid lines) and moving phantom with gated delivery (dashed lines). The isodose levels shown are 95%, 90%, 70%, 50%, and 30% for both cases. (c) The comparison of central longitudinal profiles taken from stationary phantom (solid line) and the gated delivery (dashed line). (d) The comparison of central lateral profiles taken from stationary phantom (solid line) and the gated delivery (dashed line).
maximum residual motion was about 1.0 cm, the area failing gamma test appeared to be less 1%. When the residual motion was 1.5 cm or larger, the dose distributions appeared to be dramatically deteriorated.

V. CONCLUSION

In conclusion, it is critically important to manage the target motion during the IMRT delivery. Adaptation of respiratory gating system achieved the desired results successfully on a moving phantom. The residual motion in the gating window is critical in the delivery of the IMRT. Although we consider the results from a 1 cm residual motion group as acceptable, we should also keep in mind that patients will not breathe as regularly as a moving phantom. There are some other factors, such as the change in breathing pattern or baseline shift may introduce additional errors to the delivery of
IMRT. It is recommended that a residual motion of 0.5 cm should be used for the selection of gating windows in the respiratory-gated IMRT.

Table II. The ion chamber measurements at the isocenter for all the gating windows.

<table>
<thead>
<tr>
<th>Gating window</th>
<th>Phantom</th>
<th>Chamber dose (cGy)</th>
<th>Chamber dose ratio (Relative to static phantom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29–68</td>
<td>Moving</td>
<td>209.8</td>
<td>0.997</td>
</tr>
<tr>
<td>35–73</td>
<td>Moving</td>
<td>210.0</td>
<td>0.998</td>
</tr>
<tr>
<td>84–16</td>
<td>Moving</td>
<td>211.0</td>
<td>1.003</td>
</tr>
<tr>
<td>24–74</td>
<td>Moving</td>
<td>211.0</td>
<td>1.003</td>
</tr>
<tr>
<td>23–77</td>
<td>Moving</td>
<td>207.3</td>
<td>0.985</td>
</tr>
<tr>
<td>20–78</td>
<td>Moving</td>
<td>211.6</td>
<td>1.006</td>
</tr>
<tr>
<td>18–81</td>
<td>Moving</td>
<td>209.2</td>
<td>0.994</td>
</tr>
<tr>
<td>75–25</td>
<td>Moving</td>
<td>212.6</td>
<td>1.010</td>
</tr>
<tr>
<td>00–100</td>
<td>Moving</td>
<td>213.9</td>
<td>1.016</td>
</tr>
</tbody>
</table>

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