Quantifying the effect of intrafraction motion during breast IMRT planning and dose delivery

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Respiratory motion during intensity modulated radiation therapy (IMRT) causes two types of problems. First, the clinical target volume (CTV) to planning target volume (PTV) margin needed to account for respiratory motion means that the lung and heart dose is higher than would occur in the absence of such motion. Second, because respiratory motion is not synchronized with multileaf collimator (MLC) motion, the delivered dose is not the same as the planned dose. The aims of this work were to evaluate these problems to determine (a) the effects of respiratory motion and setup error during breast IMRT treatment planning, (b) the effects of the interplay between respiratory motion and multileaf collimator (MLC) motion during breast IMRT delivery, and (c) the potential benefits of breast IMRT using breath-hold, respiratory gated, and 4D techniques. Seven early stage breast cancer patient data sets were planned for IMRT delivered with a dynamic MLC (DMLC). For each patient case, eight IMRT plans with varying respiratory motion magnitudes and setup errors (and hence CTV to PTV margins) were created. The effects of respiratory motion and setup error on the treatment plan were determined by comparing the eight dose distributions. For each fraction of these plans, the effect of the interplay between respiratory motion and MLC motion during IMRT delivery was simulated by superimposing the respiratory trace on the planned DMLC leaf motion, facilitating comparisons between the planned and expected dose distributions. When considering respiratory motion in the CTV-PTV expansion during breast IMRT planning, our results show that PTV dose heterogeneity increases with respiratory motion. Lung and heart doses also increase with respiratory motion. Due to the interplay between respiratory motion and MLC motion during IMRT delivery, the planned and expected dose distributions differ. This difference increases with respiratory motion. The expected dose varies from fraction to fraction. However, for the seven patients studied and respiratory trace used, for no breathing, shallow breathing, and normal breathing, there were no statistically significant differences between the planned and expected dose distributions. Thus, for breast IMRT, intrafraction motion degrades treatment plans predominantly by the necessary addition of a larger CTV to PTV margin than would be required in the absence of such motion. This motion can be limited by breath-hold, respiratory gated, or 4D techniques. © 2003 American Association of Physicists in Medicine. [DOI: 10.1118/1.1543151]

I. INTRODUCTION

Patient movement, inaccurate patient positioning, and organ motion are the three main reasons for variation of internal patient anatomy during the course of therapy.¹ Patient positioning, or setup error, is the difference in patient positioning between planning and treatment. Interfracion organ displacement deals with the day-to-day changes in the clinical target volume (CTV)¹-³ position. Intrafraction organ motion, which occurs while the patient is being irradiated, can be caused by respiration, cardiac motion, and the digestive system.¹ Methods that explicitly account for respiration-induced intrafraction motion include active breathing control,⁴⁵ voluntary breath-hold,⁶ deep inspiration breath-hold,⁷-¹⁰ respiratory gated techniques,¹¹-²⁵ and 4D or tumor-tracking techniques.²⁶-²⁸

Because dose heterogeneity is an important factor determining cosmesis in breast therapy,²⁹-³¹ the use of intensity modulated radiation therapy (IMRT) for breast treatment can be effective in attaining the desired homogeneity for the planning target volume (PTV),²,³ while minimizing the dose to heart and ipsilateral lung. Many patients have been treated with breast IMRT, and, in some institutions, breast IMRT is common practice, at least for early stage breast cancer.³²,³³ However, during breast radiotherapy planning, as with other sites, internal anatomy variations and setup errors need to be
included in the treatment planning process. To take into account these variations, we have to provide a sufficient CTV to PTV margin to include setup error and inter- and intrafraction motion. Large margins limit treatment planning in two ways: (1) an inadequate dose coverage of tumor volume can occur, and (2) healthy normal tissues receive a higher dose. There are several studies available that quantify setup and internal variation errors for breast radiotherapy.\textsuperscript{1,34–37} Another important consideration for IMRT is the relation between multileaf collimator (MLC) motion and CTV motion.\textsuperscript{27,38} This interplay leads to unplanned over- or under-dosage of the PTV.

A. Breast IMRT approaches

Many studies have been conducted on the effectiveness of using IMRT for breast cancer. IMRT techniques for breast cancer have been compared with various other conventional techniques used in different institutions. Since homogeneous dose distribution is an important issue for breast radiation technique, the use of IMRT has been proposed. Kestin et al. described the following IMRT technique:\textsuperscript{32} a segmental MLC (sMLC) approach was used to improve dose homogeneity and thus reduce acute toxicity. The auto blocking utility of the planning software formed MLC segments for each isodose surface. To reduce the excess transmission, additional block segments were added that conformed to the lung tissue. This technique was an effective method for achieving uniform dose throughout the breast. Acute skin toxicity was not experienced using this IMRT approach.

The benefit of IMRT for early stage breast cancer patients was also described by Hong et al.\textsuperscript{35} In this case, the beam parameters were the same as that of a standard plan. The inverse planning algorithm was used to obtain the optimized intensity profiles. This algorithm uses convolution-based dose calculation to determine the intensity distribution. The optimization process had two constraints: dose uniformity to the target volume and the maximum dose to the critical structures. Improvements in dose homogeneity throughout the target volume could be achieved by this method.

Various groups studied breast IMRT in comparison with other techniques. Cho et al. evaluated IMRT versus nonintensity modulated radiotherapy (non-IMRT) in the treatment of the left breast and the upper mammary lymph node chain.\textsuperscript{39} The non-IMRT techniques were of two types: (1) oblique electrons and (2) wide-split tangents. The IMRT technique treated using the same isocenter and gantry angle as the wide-split tangents with intensity modulated tangents. The conclusion of this study was that IMRT gave better dose homogeneity than the other two techniques. However, the process of IMRT was found to be more resource intensive and time consuming than most other methods studied, until now. An article by Antonella et al. compared intensity modulated photon beams with conventional photon beams and proton beams.\textsuperscript{40} The PTV coverage, which was comparable for IMRT and non-IMRT techniques, improved considerably with proton fields. This study, however, concluded that among the treatment techniques studied the differences between the photon techniques (IMRT and non-IMRT) were not significant. The proton technique was found to provide the most conformal dose distribution. Conformal radiotherapy, with and without intensity modulation, was studied by Hurkmans et al. to look at the possible reductions in cardiac and lung complications.\textsuperscript{41} The study also aimed at extending the maximum heart distance (MHD) as a criterion for selecting patients in whom rectangular and conformal tangential fields without IMRT would result in cardiac complications. The tangential IMRT techniques can reduce predicted NTCP (normal tissue complication probability) for late cardiac toxicity by a considerable amount (50%), as compared with rectangular fields.

Chui et al. presented a technique called sIMRT (simplified IMRT).\textsuperscript{42} The main aim of this technique was to produce a uniform dose distribution in the entire breast volume, and one of its advantages was an improvement in dose homogeneity throughout the volume. Other advantages included a dose reduction in the ipsilateral lung and the heart and the simplification of the planning process, which was achieved by eliminating the need to delineate contours on the full 3D CT image set. Since intensity distributions were determined during optimization, process variability between planners was eliminated. In addition, the total treatment planning time for sIMRT was comparable to the standard wedge technique.

The above-presented paragraphs show that IMRT techniques show promising dosimetric improvements over conventional breast radiotherapy treatments. However, the effect of intrafraction motion on breast IMRT planning and dose delivery has not been studied, and is the subject of the research described herein.

B. Intrafraction motion studies

The potential deleterious effects of intrafraction motion studies during IMRT delivery were first published by Yu et al.\textsuperscript{38} They used an analytical model to study the fundamental mechanism for creating the dosimetric variations in the target when both the beam aperture and the target move during irradiation. Yu et al. determined that for clinically realistic parameters, the magnitude of intensity variations in the target could be greater than 100% of the desired beam intensity.

Experimental demonstration of the dosimetric effects of intrafraction motion during IMRT were shown by Keall et al.,\textsuperscript{27} who used a mechanical sinusoidal oscillator to simulate target motion. Radiographic film was placed on the oscillator and irradiated under the conditions that the IMRT beam was not synchronized with the target motion, and that the IMRT beam was synchronized with the target motion. Their results showed dosimetric IMRT delivery errors of greater than 20% when the target motion was not explicitly accounted for.

The effect of intrafraction during motion delivery using a dynamic wedge was recently published by Pemler et al.,\textsuperscript{45} who state that extreme care must be taken when calculating dose distributions in regions where respiration-induced organ motion is present, together with dynamic wedges.\textsuperscript{43} Pemler et al. used parameters for the respiratory cycle and informa-
tion about respiration-induced motion for organs from the literature. The position as a function of time of the moving collimator jaw was obtained. These two motions were superimposed, and resulting monitor unit distributions were calculated. This technique can be applied to any organ that is undergoing motion due to respiration. Problems expected with IMRT delivery in the presence of respiratory motion are similar to those of dynamic wedge delivery in the presence of respiratory motion. In fact, a dynamic wedge can be considered an example of a large MLC leaf.

Bortfeld et al. have recently published a paper on the effects of intrafraction motion on IMRT dose delivery. The main aim of this paper was to evaluate the perceived concern that intrafraction organ motion could negate the potential benefit of IMRT. Using a theoretical approach, they calculated the expected dose values and dose variances of organs that move during the delivery of IMRT. This paper also looked at the overall influence of organ motion during the course of a fractionated treatment. Software was used to simulate the motion effects for IMRT delivery with a MLC, compensators, and a scanning beam. The expected dose value was found to be independent of the treatment technique. Also, it was seen that if the treatment is delivered in several fractions, the distribution of the dose around the expected value was close to Gaussian. This paper concluded that the main effect of organ motion in IMRT is an averaging of the dose distribution without motion over the path of the motion.

With this history in mind, our aims were to determine:

(a) The effects of respiratory motion and setup error during breast IMRT treatment planning.
(b) The effects of the interplay between respiratory motion and multileaf collimator (MLC) motion during breast IMRT delivery.
(c) The potential benefits of breast IMRT using breath-hold, respiratory gated, and 4D techniques.

### II. METHODS AND MATERIALS

#### A. Patients

Seven early stage breast cancer patient treatment plans (four with disease in the left breast, three with disease in the right) were used for this study. The volumes of the CTV, ipsilateral lung, and heart as contoured on the CT scan are shown in Table I. The prescription was to deliver 50 Gy in 25 daily fractions of 2 Gy.

#### B. Determining CTV to PTV margins

The CTV to PTV margin accounts for setup error, interfraction motion, and interfraction displacement of the PTV with respect to bony landmarks. For breast radiotherapy, the interfraction displacement of the breast is included in the setup error, since the beam is set up to the breast itself, rather than bony landmarks.

The CTV to PTV margin, $M$, was determined such that the CTV lies within the PTV for 95% of the treatment. Thus, a convolution of the setup error, $S$, and interfraction motion, $R$, yields $0.95$,

$$\int_{-M}^{M} S \otimes R = 0.95.$$  (1)

The setup error, $S$, was assumed to be Gaussian and isotropic. Two setup error values were included in the study, 0.1 and 0.3 cm. The 0.3 cm value was taken from Hector et al., as indicative of current practice. With the emergence of image-guided radiotherapy technology, a lower setup value (0.1 cm) was also included in the study as indicative of future practice.

The interfraction motion, $R$, was assumed to be in the anterior-posterior and in the medial-lateral directions only. These directions were chosen because Kubo and Hill observed that the chest wall of breast patients moves outward from the original position, but that the motion is almost constant along the superior-inferior edge of the radiation field.

The magnitude of the interfraction motion was obtained by using an infrared passive marker video tracking system (Real Time Position Management (RPM) system, Varian Medical Systems, Palo Alto, CA 94304.) developed for respiratory gated radiotherapy. This system senses the respiratory motion of the patient by tracking two reflective markers.

![Fig. 1. Setup for respiratory motion measurement. A block with infrared reflectors is placed directly on the breast (target volume) of a patient. The motion of the marker block is detected by a camera-based video tracking system.](image-url)
fixed to a block. Figure 1 shows the setup for respiratory motion measurement. The block with the infrared reflectors is placed directly on the anterior-medial part of the breast of the patient where the skin surface is approximately horizontal. A difference between measuring the respiration signal for breast radiotherapy and lung radiotherapy is that with the breast, there is a direct correlation between the respiratory signal and target breast motion. For lung radiotherapy, the target motion is implicitly assumed to correlate with the respiratory signal.

The motion of the marker block is detected by a camera-based video tracking system. By tracking the marker, we can determine the vertical component of motion. The acquired respiratory displacement versus time is shown in Fig. 2. Note that this respiratory trace, obtained from one patient, was used as the respiratory trace for all patients in this study. To study smaller and larger magnitudes of respiratory motion, the displacement of this respiratory trace was multiplied by 0.5 to simulate shallow breathing and by 2.0 to simulate heavy breathing. Using breath-hold, respiratory gated, and 4D techniques, the intrafraction motion is explicitly accounted for during the delivery, and no or a negligible intrafraction motion component of the CTV to PTV margin is necessary. Thus, the respiratory motions (relative to the actual respiration) studied were no breathing (0), shallow breathing (0.5), normal breathing (1.0), and heavy breathing (2.0).

To convert the respiratory signal into a function that can be used to obtain the CTV to PTV margin, the respiratory signal (displacement versus time) needs to be in the form of a probability distribution. The intrafraction probability distribution, \( R \), and the convolution of the intrafraction probability distribution with the setup error \( S \) are given in Fig. 3.

Table II lists the different margins obtained after following the above-mentioned method. As seen in Table II, there are four respiratory motions (no breathing, shallow breathing, normal breathing, and heavy breathing) and two setup errors for each respiratory motion, and, thus, eight plans per patient were performed as described in the following.

### Table II. Different CTV to planning target volume (PTV) margins used for variations in respiratory motion and setup error.

<table>
<thead>
<tr>
<th>Respiratory motion</th>
<th>Setup margin (cm)</th>
<th>AP margin (cm)</th>
<th>ML margin (cm)</th>
<th>SI margin (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No breathing</td>
<td>0.1</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Shallow breathing</td>
<td>0.1</td>
<td>0.41</td>
<td>0.41</td>
<td>0.20</td>
</tr>
<tr>
<td>Normal breathing</td>
<td>0.1</td>
<td>0.74</td>
<td>0.74</td>
<td>0.20</td>
</tr>
<tr>
<td>Heavy breathing</td>
<td>0.1</td>
<td>1.34</td>
<td>1.34</td>
<td>0.20</td>
</tr>
<tr>
<td>No breathing</td>
<td>0.3</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>Shallow breathing</td>
<td>0.3</td>
<td>0.74</td>
<td>0.74</td>
<td>0.60</td>
</tr>
<tr>
<td>Normal breathing</td>
<td>0.3</td>
<td>0.99</td>
<td>0.99</td>
<td>0.60</td>
</tr>
<tr>
<td>Heavy breathing</td>
<td>0.3</td>
<td>1.58</td>
<td>1.58</td>
<td>0.60</td>
</tr>
</tbody>
</table>

C. IMRT methodology

For each patient, a 3D CT data set was obtained for treatment planning. The prescribed dose and dose homogeneity criteria were defined for the PTV (uniform to 50 Gy), lung (no dose), and heart (no dose). An IMRT system that utilizes dynamic MLC delivery and had been described by Wu and Mohan was used. The dosimetric effects of the delivery device were explicitly included during IMRT optimization using the method described by Siebers et al. [46]
D. Studies performed

The studies performed were separated into two categories: (a) the effect of respiratory motion and setup error on the PTV and the lung and heart dose during treatment planning and (b) the effect of the interplay between respiratory motion and MLC motion during IMRT delivery.

1. Evaluation of the effects of varying respiratory motion on the planned dose distribution

The effect of respiratory motion and setup error on the PTV and lung and heart dose during treatment planning was determined by performing treatment plans with four values for the four different respiratory motions (no breathing, shallow breathing, normal breathing, and heavy breathing) and with two values for setup error (0.1 and 0.3 cm). Thus, eight plans were performed for each patient. For each plan of each patient, the 3D dose distributions and dose–volume histograms (DVHs) for the PTV, CTV, lung and heart were stored. Following some of the recommendations of the National Cancer Institute (NCI) IMRT Collaborative Working Group, from these DVHs for the PTV and CTV, the dose covering 95% of the volume ($D_{95}$), mean dose ($D_{\text{mean}}$), and the dose covering 5% of the volume ($D_{05}$) were obtained. For the lung and heart, the mean dose ($D_{\text{mean}}$) was collected.

2. Evaluation of the effect of varying respiratory motion on the expected dose distribution

The effect of the interplay between respiratory motion and MLC motion during IMRT delivery was calculated by simulating respiratory motion during IMRT delivery for each fraction (i.e., 25 times per plan). This simulation was performed by superimposing the IMRT leaf-sequence file on the breathing motion trace to create a new leaf-sequence file. In general, there is no synchronization of the radiation delivery initiation with the respiratory cycle, and, thus, the superposition of the breathing motion on the leaf-sequence file should occur with a random starting time. This random starting time was sampled independently for each fraction to simulate a course of treatment. The dose was recalculated using the new leaf-sequence file for each fraction henceforth, termed “dose per fraction”) and summed over all fractions to yield the expected dose. A flowchart of this process is shown in Fig. 4. Thus, instead of the patient moving with respect to the beam, the beam moves with respect to the patient, as shown schematically in Fig. 5. In our

For breast IMRT, the PTV extends outside the skin. Most treatment planning systems assign a zero dose to regions outside the skin. Thus, an iterative IMRT calculation will fail, as the intensities will continually be increased at each iteration to try to increase the dose to the prescription level. One solution to this problem is to add an artificial bolus during optimization, as suggested in ICRU 62. A problem with adding the bolus is that the IMRT algorithm will find the best solution for the plan with the artificial bolus, even though this is not present during treatment. To compromise between adding a bolus during IMRT optimization and not adding a bolus, so as not to perturb the dose calculation without bolus, an artificial bolus of low density (0.3 g cm$^{-3}$) was added to encompass the PTV with a 5 mm margin in the superior, inferior, anterior, and lateral dimensions. This artificial bolus addition occurred automatically via a script. Dose results in this manuscript are computed with the artificial bolus on, as suggested in International Commission on Radiation Units and Measurements (ICRU) Report 62.

Fig. 4. Flowchart describing the procedure followed to obtain the expected dose.

Fig. 5. In the beam reference frame, respiratory motion causes the patient anatomy to move as shown in (a). In the anatomy reference frame, the beam is observed to move as shown in (b). Our approach to account for respiratory motion was to use the anatomy reference frame.
studies, we assumed that breathing motion is constant from day to day. Our approach also assumed that the intrafraction motion does not deform patient geometry.

For each of the eight planned dose distributions obtained per patient as explained in the section above, a corresponding expected dose distribution was also calculated. Because the data collected for the expected dose distributions was the same as that for the planned distributions, direct comparisons between the planned and expected dose distributions were performed.

III. RESULTS AND DISCUSSION

The results obtained are presented as tables, isodose plots, and DVHs. Isodose line and DVH comparisons are presented for a typical patient, and the results of all seven patients are given in tabular form.

The results for the studies detailed in Sec. II are presented here as two parts: (a) an evaluation of the effects of varying respiratory motion on the planned dose distribution and (b) an evaluation of the effects of varying respiratory motion on the expected dose distribution. In both parts, the results are presented for a single patient case, and the similarities and variations observed for all seven patient cases are discussed. Results shown are for a setup error of 0.3 cm, unless explicitly stated.

A. Evaluation of the effects of varying respiratory motion on the planned dose distribution

The effects of varying respiratory motion on the PTV DVHs are shown in Fig. 6. The respiratory motions simulated are no breathing (representing a breath-hold, respiratory gated, or 4D technique), shallow breathing, normal breathing, and heavy breathing. From Fig. 6, it can be observed that PTV dose heterogeneity increases as the motion factor increases. The respiratory motion of the “no breathing” DVH shows the optimum coverage. This increase in heterogeneity with respiration motion is primarily due to the increase in the PTV volume required to account for this motion. The increase in heterogeneity with large breasted women has previously been described.29–31

The effects of the different respiratory motions (no breathing, shallow breathing, normal breathing, and heavy breathing) on the CTV DVHs are shown in Fig. 7. Figure 7 shows that CTV dose heterogeneity decreases as respiratory motion increases. It is interesting to note that the reverse trend is shown for the CTV DVHs, rather than the PTV DVHs of Fig. 6. An explanation for this is that the CTV to PTV margins increase with respiratory motion [see Eq. (1) and Table II], and, thus, with a greater margin, the CTV is less affected by the electron disequilibrium and dose-gradient effects that occur at the PTV boundary.

The effects of the different respiratory motions (no breathing, shallow breathing, normal breathing, and heavy breathing) on the lung and heart DVHs are seen in Fig. 8. This plot shows that as respiratory motion increases, the dose to these critical structures also increases. Because the CTV to PTV margin is lowest for no breathing corresponding to respiratory gated, breath-hold, and 4D techniques, such techniques allow maximum dose sparing of the lung and heart.

Specific dose points of the PTV, lung, and heart DVHs plotted in Figs. 6 and 8, along with dose points for the plans with a 0.1 cm setup error, are tabulated in the “Planned”
columns of Table III. (The “Expected” columns of Table III are discussed in the following.) Table III shows that the trends observed for the 0.3 cm setup error—the PTV dose heterogeneity and mean lung and heart dose increase with respiratory motion—are also observed with the 0.1 cm setup error value. However, as the setup error decreases, the respiratory motion dominates the CTV to PTV margin, and thus the magnitude of these trends increases as setup error is reduced. Note that not all of the values in Table III follow these trends. We attribute these discrepancies to the known existence of local minima in the IMRT planning process due to the filtering and inclusion of the MLC leaf sequence conversion during every optimization iteration.46

Analysis of the dosimetric differences caused by varying respiratory motion and setup errors with the other six patients showed a similar magnitude of the patterns discussed above.

### B. Evaluation of the effect of varying respiratory motion on the expected dose distribution

The effect of varying respiratory motion on the expected dose distribution is best displayed by providing comparisons between the “planned” dose distributions (where the interplay between respiratory motion and MLC motion was ignored) and the “expected” dose distributions that explicitly account for the interplay between respiratory motion and MLC motion.47

Planned and expected isodose plots on the central axis slice for the respiratory motions of shallow breathing, normal breathing, and heavy breathing are shown in Figs. 9, 10, and 11, respectively. The “no breathing” case is not shown, because the expected dose is the same as the planned dose. Though the isodose lines between the planned and expected plots differ, little quantitative information can be gleaned. However, one observation is that the distance between the 20 and 40 Gy lines passing through the lung is larger in the expected plots. This increase in the penumbra is due to the smoothing effect that occurs when explicitly accounting for respiratory motion. This smoothing is similar to that found by others when explicitly accounting for setup errors or organ motion during dose calculation.48–54

Note that the isodose lines extend outside to the skin due to the addition of a bolus per ICRU 62 recommendations as described in Sec. II.

The difference in the dose distributions observed in Figs. 9–11 can be quantified by examining the resultant DVHs. The planned, expected, and dose-per-fraction—expected PTV DVHs for the three different respiratory motions—shallow breathing, normal breathing, and heavy breathing—are shown in Fig. 12. The dashed line represents the planned dose, the solid line represents the expected dose, and the lighter lines represent the doses per fraction of radiation. For shallow breathing, as shown in Fig. 12(a), the planned and expected DVHs are very similar, as are the doses per fraction. In Fig. 12(b), which illustrates normal breathing, differ-

![Fig. 9. Isodose lines show a comparison between (a) the planned and (b) the expected dose distributions for the shallow breathing respiratory motion. The 20, 40, 50, and 52 Gy lines are shown.](image1)

![Fig. 10. Isodose lines show a comparison between (a) the planned and (b) the expected dose distributions for the normal breathing respiratory motion. The 20, 40, 50, and 52 Gy lines are shown.](image2)
ences between the planned and expected doses are observed. Some variation is seen between the doses per fraction. In general, these doses per fraction follow the expected dose more than the planned dose. The expected DVH is more heterogeneous than the planned DVH, indicating that the dose received by the patient is less optimal than that seen during treatment planning. The variation between the planned and expected doses is the largest for the heavy breathing case; see Fig. 12(c). It can be concluded that as respiratory motion increases, the difference between planned and expected doses increases, and the PTV dose heterogeneity increases.

It is interesting to note that in all the plots of Fig. 12, the summed expected dose distribution (solid line) is not in the center of the individual fraction doses (lighter lines). This indicates that the hot spots caused by the interplay between respiratory motion and MLC leaf motion are in different positions on different days. Thus, different parts of the anatomy receive a different dose per fraction, which may have radiobiological significance.

The CTV DVHs for planned and expected doses are shown in Fig. 13. For an increase in respiratory motion, the planned versus expected DVH variation increases. Similar trends are observed for the CTV, as shown for the PTV in Fig. 12; namely, the difference between the planned and expected DVHs increases with respiratory motion, the dose heterogeneity of the expected dose increases as the respiratory motion increases, there is a variation in the doses per fraction expected, and the hot spots of these doses per fraction vary in position from day to day.

Planned versus expected lung and heart DVHs for different respiratory motions are given in Fig. 14. For shallow breathing, the expected DVH is similar to that planned. The normal breathing DVHs start to show some variation between planned and expected, and, as with the PTV and CTV, most variation is observed for heavy breathing DVHs. The doses per fraction were seen to follow the expected dose rather than the planned dose. The rationale for having the lung and heart dose higher or lower, when comparing planned and expected dose distributions, is due to the geometric relation between the PTV and the critical organs. Respiratory motion tends to blur the dosimetric edges of the field. Specific dose points of the planned and expected DVHs for the PTV, lung, and heart that are plotted in Figs. 12 and 14, along with dose points for the plans with a 0.1 cm setup error, are tabulated in Table III. This table shows that the difference between planned and expected doses is relatively small, except when respiratory motion approaches heavy
breathing. There is more difference between the planned doses for no breathing, shallow breathing, and normal breathing, than the planned and expected doses at each respiratory motion value.

A summary of the expected versus planned doses for all seven patients is given in Table IV. The data in this table were produced assuming that the respiratory motion was normal breathing and that the setup error was 0.3 cm. For the PTV, the expected $D_{05}$, $D_{\text{mean}}$, and $D_{95}$ values were all less than or equal to the corresponding planned values. This reduction in dose can be attributed to the smearing effect of explicitly accounting for respiratory motion. The mean expected lung dose was lower than the planned dose, whereas...
for the heart, the planned and expected mean doses were similar. However, none of the differences between planned and expected doses in Table IV were statistically significant.

IV. CONCLUSIONS

When considering respiratory motion as a factor during treatment planning for breast IMRT, the results presented show that PTV dose heterogeneity increases as respiratory motion increases. The lung and heart dose also increases with respiratory motion.

Due to the interplay between respiratory motion and MLC motion during IMRT delivery, the planned and expected doses are different. This difference increases with respiratory motion. The expected dose varies from fraction to fraction. However, for the seven patients studied and the respiration trace used, for no breathing, shallow breathing, and normal breathing, there were no statistically significant differences between planned and expected doses.

These results suggest that for breast IMRT, intrafraction motion degrades dose distributions predominantly by the necessary addition of a larger CTV to PTV margin, which would be required in the absence of such motion. This motion can be limited by breath-hold, respiratory gated, or 4D techniques.

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