A dynamic compensation strategy to correct patient-positioning errors in conformal prostate radiotherapy

A. D. Lauve, J. V. Siebers, A. J. Crimaldi, M. P. Hagan, and P. J. Keall

Department of Radiation Oncology, Virginia Commonwealth University, Richmond, Virginia 23298-0058

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Traditionally, pretreatment detected patient-positioning errors have been corrected by repositioning the couch to align the patient to the treatment beam. We investigated an alternative strategy: aligning the beam to the patient by repositioning the dynamic multileaf collimator and adjusting the beam weights, termed dynamic compensation. The purpose of this study was to determine the geometric range of positioning errors for which the dynamic compensation method is valid in prostate cancer patients treated with three-dimensional conformal radiotherapy. Twenty-five previously treated prostate cancer patients were replanned using a four-field technique to deliver 72 Gy to 95% of the planning target volume (PTV). Patient-positioning errors were introduced by shifting the patient reference frame with respect to the treatment isocenter. Thirty-six randomly selected isotropic displacements with magnitudes of 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 cm were sampled for each patient, for a total of 5400 errors. Dynamic compensation was used to correct each of these errors by conforming the beam apertures to the new target position and adjusting the monitor units using inverse-square and off-axis factor corrections. The dynamic compensation plans were then compared with the original treatment plans via dose-volume histogram (DVH) analysis. Changes of more than 5% of the prescription dose, 3.6 Gy, were deemed significant. Compared with the original treatment plans, dynamic compensation produced small discrepancies in isodose distributions and DVH analyses. These differences increased with the magnitudes of the initial patient-positioning errors. Coverage of the PTV was excellent: $D_{95}$ and $D_{mean}$ were not increased or decreased by more than 5% of the prescription dose, and $D_2$ was not decreased by more than 5% of the prescription dose for any of the 5400 simulated positioning errors. $D_3$ was increased by more than 5% of the prescription dose in only three of the 5400 positioning errors, all three occurring with a positioning error of 10.0 cm. Dose increases for adjacent organs at risk were more common. $D_{33}$ of the rectum and the periprostatic rectum was increased by more than 5% of the prescription dose in 235 (4.4%) and 212 (3.9%) of the 5400 positioning errors, respectively. $D_{10}$ of the right femoral head increased by more than 5% of the prescription dose in 444 (8.2%) positioning errors, and the degree of change was highly related to individual patient anatomy and simulation position. For the bladder $D_{20}$, there were three increases of more than 5% of the prescription dose. These data demonstrate the robustness of dynamic compensation for correction of patient-positioning errors in four-field conformal prostate radiotherapy, with minimal deviation from the original treatment plans even for errors greatly exceeding those commonly encountered in the clinic. Dynamic compensation can be performed remotely, thus eliminating errors that may result from unnecessary increases in treatment time or from secondary patient motion induced by couch motion during the repositioning process. Further, the ability of dynamic compensation to correct large positioning errors has implications for the accuracy necessary during the initial patient setup and, hence, patient throughput for prostate radiotherapy. © 2006 American Association of Physicists in Medicine. [DOI: 10.1118/1.2198967]

Key words: dynamic compensation strategy, patient-positioning errors, prostate

I. INTRODUCTION

Online image-guided therapy strategies allow for daily alignment of the radiation beam with the target. The dosimetric benefits of online image guidance for prostate radiotherapy have been quantified to allow on average a 10%–15% target dose increase. Typically, this process is accomplished by detecting the patient position error and moving the patient on the treatment couch to correct the error. The advent of remote couch control, which is becoming increasingly available, makes this correction a reasonably streamlined process.

An alternative strategy to aligning the patient to the beam is to align the beam to the patient, as investigated here. The premises for this study’s investigation of beam adjustment rather than couch motion were: (1) moving the patient after positioning error detection may introduce a secondary positioning error based on the response of the patient to the motion, and (2) target deformation (though not part of this study) cannot be compensated for by couch motion alone.

The system of aligning the beam to the patient by adjusting the dynamic multileaf collimator (MLC), as opposed to
aligning the patient to the beam, is termed dynamic compensation. Dynamic compensation is essentially an online implementation of the offline adaptive strategy described by Yan et al. Assuming negligible measurement error and thus obviating the need for Kalman filtering. The advantage of the online strategy is that both systematic and random interfraction variations are corrected, whereas only systematic errors are corrected in the offline strategy, though it is acknowledged that systematic errors are significantly more deleterious than random errors, and that online strategies increase the treatment time compared with offline strategies. A proof-of-principle study of this technique for IMRT was published for tomotherapy by Olivera et al. and for linac-based IMRT by Court et al., though the quantitation of the sensitivity of this technique for a significant cohort of patients and systematically varying patient positioning errors was not studied.

The purpose of this study was to investigate the practical utility of dynamic compensation and to determine the geometric range of patient-positioning errors, for which the method is valid, by comparing the resulting dosimetry with the couch-corrected plans. Note that only setup error was considered. Internal motion and deformation were not studied.

We chose to use a series of prostate cancer patients to evaluate this system because of the relatively well-defined, reproducible target volume and the proximity of dose-dependent radiation-sensitive organs at risk (OARs).

II. METHODS AND MATERIALS

The computed tomography (CT) simulations of 25 patients with intermediate-risk prostate cancer previously treated on an in-house IRB-approved IMRT protocol were used. CT images were acquired in the supine position at 3-mm slice separations using a CT simulator (Picker AcQsim, Cleveland, OH). All simulations included a retrograde urethrogram.

A. Treatment planning

A single physician contoured regions of interest (ROIs) on every CT slice using a commercially available planning system (Philips Pinnacle, Milpitas, CA) for treatment with a Varian (Palo Alto, CA) linear accelerator equipped with a Millennium 120-leaf MLC, which has 0.5-cm leaves for the central 20-cm field area of interest for this study. The clinical target volume (CTV) included the prostate and the proximal 2.1 cm of the seminal vesicles (seven CT slices from the prostate take-off). OARs included the rectum, the periprostatic rectum (that portion of the rectum adjacent to the prostate and extending 0.9 cm superiorly and inferiorly), the bladder, and the bilateral femoral heads.

To account for rotation, deformation, and intrafraction motion of the prostate during the course of radiotherapy, a planning target volume (PTV) was derived by expanding the CTV by 0.6 cm posteriorly and 1.0 cm in all other dimensions, with PTV-to-block margins of 0.5 cm radially and 1.0 cm superiorly and inferiorly. A MLC was used for the field blocking. A four-field plan was created using 18-MV photons with anterior-posterior, posterior-anterior (weighted ~20% each), and two lateral fields (weighted ~30% each).
without wedging. At least 95% of the PTV received the prescription dose of 72 Gy in 36 fractions. The plans were not altered in any way to limit the dose to adjacent OARs.

B. Inclusion of patient-positioning errors in correction strategy

Isotropic patient-positioning errors were introduced by randomly shifting the patient isocenter in three dimensions, such that

\[
\text{Setup error} = \sqrt{(\Delta \text{LAT})^2 + (\Delta \text{AP})^2 + (\Delta \text{SI})^2},
\]

where \(\Delta \text{LAT}\), \(\Delta \text{AP}\), and \(\Delta \text{SI}\) are the net lateral, anterior-posterior, and superior-inferior shifts, respectively. For each patient, 216 positioning errors were generated: 36 each of 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 cm from the original treatment isocenter, for a total of 5400 errors. Rotational errors were not included in the current study.

Figures 1 and 2 compare the conventional couch-correction and the dynamic compensation methods for correcting patient-positioning errors. The couch-correction method was simulated by repositioning the patient isocenter with the treatment isocenter exactly, i.e., reproducing the original treatment plan. Dynamic compensation consisted of MLC adjustments to conform to the altered PTV position and associated beam view projection, and monitor unit (MU) changes based on inverse-square (ISQ) and off-axis factor (OAF) corrections. The gantry angle remained fixed.

The corrected MU for each field, \(\text{MU}_{\text{corr}}\), was calculated from the equation

\[
\text{MU}_{\text{corr}} = \text{MU}_{\text{orig}} \times \text{ISQ} \times \text{OAF},
\]

where \(\text{MU}_{\text{orig}}\) is the MU derived for the original unshifted plan. The inverse-square (ISQ) correction was derived by

\[
\text{ISQ} = \left(\frac{\text{SAD} + \Delta z}{\text{SAD}}\right)^2,
\]

where SAD is the source-axis distance, and \(\Delta z\) is the net shift of the patient isocenter toward or away from the source defined by

\[
\Delta z = -\Delta \text{LAT} \times \sin(\text{gantry}) + \Delta \text{AP} \times \cos(\text{gantry}),
\]

where \(\text{gantry}\) is the gantry angle. Note that only integral MUs can be delivered on most linear accelerators, whereas typically the corrected MU values for each beam are not integers and are rounded to the closest integer value. This rounding is included in the results shown.

To account for radial output variations due to bremsstrahlung spectral variations, an OAF correction was incorporated

\[
\text{OAF} = \frac{d_{\Delta r}}{d_0},
\]

where \(d_{\Delta r}\) is the dose profile value measured at 15-cm depth in water at a radial distance of \(\Delta r\) from the central axis, and \(d_0\) is the central-axis profile value. \(\Delta r\) is the radial component of a given patient positioning error.

\[
\Delta r = \sqrt{(-\Delta \text{LAT} \times \cos(\text{gantry}) + \Delta \text{AP} \times \sin(\text{gantry}))^2 + (\Delta \text{SI})^2}.
\]

C. Dosimetric evaluation

The plans generated for each of the 5400 patient-positioning errors corrected using dynamic compensation were compared with the couch-corrected treatment plans via dose-volume histogram (DVH) analysis. Mean dose and point doses used to evaluate prostate treatment plans were used in the comparison, and changes of greater than 5% of the prescription dose (3.6 Gy) were considered significant. Throughout this manuscript, \(D_x\) is defined as the dose to \(x\%\) of volume of the ROI, and \(D_{\text{mean}}\) is the mean dose of the ROI.

PTV coverage was deemed adequate if \(D_{\text{95}}\) (dose delivered to 5% of the PTV volume), \(D_{\text{95}}\) (dose delivered to 95% of the PTV volume), and \(D_{\text{mean}}\) (mean dose) changed by <5% of the prescription dose when compared with the couch-corrected treatment plans. Similarly, for OARs, an increase of >5% of the prescription dose for any mean dose or evaluated point dose was considered significant. The OARs included bladder \((D_2, D_{10}, D_{\text{mean}})\), rectum and periprostatic rectum \((D_2, D_{33}, D_{\text{mean}})\), and the right femoral head \((D_2, D_{10}, D_{\text{mean}})\). Only one femoral head (right) was evaluated because (1) dosimetric changes of the femoral heads were similar due to patient and treatment symmetry, and (2) two patients had no left femoral head due to prior history of left hip replacements.

For each patient-positioning error corrected using dynamic compensation, the average change of each DVH parameter above was also calculated to determine trends of over- or underdosing.

III. RESULTS

Compared with the couch-corrected treatment plans, dynamic compensation produced small discrepancies in isodose distributions and DVH analyses. These differences increased with the magnitudes of the patient-positioning errors. An example isodose curve is shown in Fig. 3 for the patient repositioning and dynamic compensation (beam modification). The isodose curves for the two cases are almost identical around the prostate, though small differences are observed in the beam periphery. The DVHs for 36 positioning errors of
1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 cm for a single representative patient are shown in Fig. 4. The average dose-volume point and mean dose changes relative to the prescription dose for all patients are shown in Table I and in Fig. 5.

Coverage of the PTV was excellent for all positioning errors for every patient. When compared with the couch-corrected treatment plans, $D_{95}$ and $D_{\text{mean}}$ were not increased or decreased, and $D_3$ was not decreased by more than 5% of the prescription dose for any of the 5400 positioning errors (Table I). $D_3$ was increased by more than 5% of the prescription dose in only three of the 5400 positioning errors, with all three occurring with an error of 10.0 cm. The average change was $\leq 2.9\%$ of the prescription dose for all analyzed DVH parameters per incremental error and was $\leq 0.4\%$ for 1.0- and 2.0-cm positioning errors [Fig. 5(A)].

Dose increases for adjacent OARs were more common. $D_2$, $D_{33}$, and $D_{\text{mean}}$ of the rectum and periprostatic rectum were increased by more than 5% of the prescription dose in 1, 235 (4.4%), and 2 as well as in 1, 212 (3.9%), and 85 (1.6%) of the 5400 positioning errors, respectively (Table I). No positioning error resulted in an average change $>2.2\%$ of the prescription [Figs. 5(B) and 5(C)]. For errors of 1.0 and 2.0 cm, no change averaged more than 0.5% of the prescription dose.

$D_2$, $D_{20}$, and $D_{\text{mean}}$ of the bladder increased by more than 5% of the prescription dose in 2, 3, and 3 of the 5400 positioning errors, respectively—all occurring with errors of 8.0 or 10.0 cm (Table I). The average change for each positioning error was $\leq 2.4\%$ of the prescription dose [Fig. 5(D)].

Right femoral head dosimetry proved highly variable. $D_2$, $D_{10}$, and $D_{\text{mean}}$ of the right femoral head increased by more than 5% of the prescription dose in 498 (9.2%), 444 (8.2%), and 342 (6.3%) positioning errors (Table I). A wider range of changes occurred than was seen with other ROIs, especially with larger positioning errors. This was due to the peripheral location of the right femoral head, and because, for many patients, only a portion of the femoral head was included in the lateral fields of the original unshifted treatment plan. Thus, when using dynamic compensation to correct for a positioning error, a considerable volume of femoral head may be moved into or out of the treatment field. In our study, however, the increases and decreases tended to be balanced, with an average DVH parameter change of less than 2.0% of the prescription dose for all patient-positioning errors [Fig. 5(E)]. This is well demonstrated in Fig. 4.

The two patients with artificial left hips were planned using the same criteria as the remaining patients. The relative changes in PTV and OAR dosimetry seen with the correction of positioning errors using dynamic compensation were not measurably different than those seen with the remaining 23 patients (data not shown).

**IV. DISCUSSION**

The advent of image-guided patient-positioning error correction has improved treatment precision, with a corresponding reduction in the volume of irradiated tissue and an increase in the therapeutic ratio. Patient-positioning errors are typically corrected by compensatory couch movements, however, it has been suggested that couch corrections may result in further positioning error. The dynamic compensation scheme that aligns the treatment beam to the altered patient position (couch motion aligns the patient to the treatment beam) and is investigated here seems ideal in this context since it is performed rapidly, remotely, and without the risk of collision possible with remote couch adjustments.

We have shown that dynamic compensation is able to correct patient-positioning errors up to 10.0 cm, for an opposing beam setup, without compromising target coverage or sparing of adjacent OARs. This range far exceeds errors commonly encountered when using conventional techniques to position patients for pelvic radiotherapy. Dunscombe et al. examined 76 pairs of simulation and portal images for 29 patients treated for prostate cancer. The average orthogonal displacements were less than 0.36 cm, and the maximum displacement noted was 1.7 cm. In a retrospective review, Byhardt et al. found that although 37% of prostate setups included positioning errors of greater than 0.5 cm and 23% of all pelvic fields contained errors greater than 1.0 cm, the average displacement was only 1.5 cm, and errors greater than 2.5 cm were uncommon. Tinger et al. examined weekly portal images of seven fluoroscopically simulated...
Fig. 4. DVHs for a representative patient, showing changes with increasing patient-positioning errors corrected using the dynamic compensation strategy. The solid lines are the DVHs for a couch-corrected plan.
Table I. Dose-volume histogram changes by magnitude of patient-positioning error corrected using dynamic compensation.

<table>
<thead>
<tr>
<th>1 cm error</th>
<th>2 cm error</th>
<th>4 cm error</th>
<th>6 cm error</th>
<th>8 cm error</th>
<th>10 cm error</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of changes &gt;5% (%Rx dose)</td>
<td>No. of changes &gt;5% (%Rx dose)</td>
<td>No. of changes &gt;5% (%Rx dose)</td>
<td>No. of changes &gt;5% (%Rx dose)</td>
<td>No. of changes &gt;5% (%Rx dose)</td>
<td>No. of changes &gt;5% (%Rx dose)</td>
</tr>
<tr>
<td>(D_5)</td>
<td>0/0</td>
<td>0.8</td>
<td>-0.9</td>
<td>0/0</td>
<td>1.4</td>
</tr>
<tr>
<td>(D_{05})</td>
<td>0/0</td>
<td>0.7</td>
<td>-1.4</td>
<td>0/0</td>
<td>1.1</td>
</tr>
<tr>
<td>(D_{mean})</td>
<td>0/0</td>
<td>0.6</td>
<td>-1.1</td>
<td>0/0</td>
<td>1.0</td>
</tr>
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<td>PTV</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>(D_2)</td>
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<td>1.4</td>
<td>-1.5</td>
<td>0</td>
<td>2.2</td>
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<tr>
<td>(D_{33})</td>
<td>14</td>
<td>7.4</td>
<td>-7.2</td>
<td>12</td>
<td>7.3</td>
</tr>
<tr>
<td>(D_{mean})</td>
<td>0</td>
<td>2.3</td>
<td>-2.8</td>
<td>0</td>
<td>2.8</td>
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<tr>
<td>Rectum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(D_2)</td>
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<td>-1.4</td>
<td>0</td>
<td>2.1</td>
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<tr>
<td>(D_{33})</td>
<td>20</td>
<td>6.9</td>
<td>-8.1</td>
<td>21</td>
<td>7.0</td>
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<tr>
<td>(D_{mean})</td>
<td>0</td>
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<td>-4.5</td>
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<td>Prostate</td>
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<tr>
<td>(D_2)</td>
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<td>0</td>
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<tr>
<td>(D_{20})</td>
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<tr>
<td>(D_{mean})</td>
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<td>-1.9</td>
<td>0</td>
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<tr>
<td>Rectum</td>
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<td></td>
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<tr>
<td>(D_{30})</td>
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<td>1</td>
<td>5.5</td>
</tr>
<tr>
<td>Head</td>
<td>(D_{mean})</td>
<td>0</td>
<td>1.9</td>
<td>-2.1</td>
<td>0</td>
</tr>
</tbody>
</table>

Number of increases >5% of prescription dose/number of decreases >5% of prescription dose. All other changes denote number of increases >5% of prescription dose. Number of patients: 25. Isotropic positioning errors per offset: 36. Total number of errors (six offsets): 5400.
rectal cancer patients. The frequency of isocenter displacements greater than 1.0 cm was 3%, 16%, and 23% for mediolateral, craniocaudal, and anteroposterior displacements, respectively, but no displacement exceeded 2.4 cm.

When correcting patient-positioning errors of 1.0 and 2.0 cm, dynamic compensation reproduces the original treatment plan with excellent fidelity. Of the PTV and OAR DVH parameters evaluated, only the $D_{33}$ of the rectum and of the periprostatic rectum demonstrated more than 2 (of 1800 each) increases of greater than 5% of the prescription dose (Table I). This was due to the proximity of the rectum to the PTV. Although there are both high- and low-dose rectal circumference regions that are largely independent of changes made by dynamic compensation, there is a steep dose gradient across most of the volume, and this is more prone to change for any given correction (Fig. 4). Nevertheless, when correcting 1.0- and 2.0-cm patient-positioning errors, the rectal and periprostatic rectal $D_{33}$ were significantly increased in only 26 and 41 of 1800 patient-positioning errors, respectively (Table I); the maximum increase seen was only 7.4% of the prescription dose (5.3 Gy) (Table I); and the average change was no more than 0.5% of the prescription dose [Fig. 5(B)]. The latter indicates that a random positioning error is as likely to result in a $D_{33}$ decrease as an increase. Care should be taken to minimize systematic errors by using previous portal assessments to make appropriate corrections during each patient setup. Quality assurance should include a review of the cumulative DVH if there is concern that OARs may be at risk for inappropriate dosing.

We chose to use a series of prostate cancer patients to examine the utility of dynamic compensation because of the relatively well-defined, reproducible target volume and the proximity of dose-dependant radiation-sensitive OARs. We used a simple four-field technique still employed clinically in some centers. The MU adjustments required using inverse-square and off-axis factors that were modest when applying dynamic compensation to the small patient-positioning errors commonly encountered in the clinic (<4% per beam for a 2-cm shift), but these values gained significance when applied to larger positioning errors. Their inclusion, therefore, generalizes the potential applicability of dynamic compensation to include other beam arrangements, energies, and anatomic sites, as well as the use of IMRT. The generalization to beam modifiers such as wedges and physical compensators is questionable given that wedges can have field-size limitations that could be exceeded for a large positioning error correction with dynamic compensation, and that compensators cannot move with respect to the beam and have a fixed aperture. Although the use of dynamic compensation in other sites and/or treatment geometries may prove equally efficacious in providing appropriate coverage of the PTV, the relative sparing of adjacent OARs may prove highly variable and would require verification prior to clinical use. Using dynamic compensation for IMRT would involve the need for further software (including leaf-sequencing software and associated QA) at the treatment console.

![Fig. 5. Average DVH changes relative to the prescription dose (72 Gy) for 5400 patient-positioning errors (900 each of 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 cm) in 25 patients corrected using the dynamic compensation method. Error bars=1 sd. $D_x$=dose to $x\%$ of volume of region of interest. $D_{mean}$=mean dose of region of interest. PTV=planning target volume.](image-url)
This study serves as proof of principle confirming the utility of dynamic compensation in correcting patient-positioning errors in prostate cancer patients treated as shown, assuming that (a) only translational positioning errors are encountered, i.e., there is no significant rotational component, and that (b) the PTV is adequately derived to compensate for internal target motion and deformation.\textsuperscript{20} Further limitations of the study include the study of only one beam arrangement (four-field) and the use of a single CT anatomy per patient. The four-field technique conformal technique, in which the positioning of the OAR and PTV towards the anterior-posterior beams' axis, may be a best case scenario for dynamic compensation, and the efficacy of the application of this technique to other sites, field arrangements, and intensity modulation remains to be seen.

In its current form, there are limited advantages of dynamic compensation over couch shifts in correcting patient-positioning errors (Fig. 1): it can reduce treatment time (versus manual couch correction) and eliminate small positioning errors that may be introduced when physically shifting a patient (versus manual and remote couch correction). However, dynamic compensation itself introduces modest treatment plan deviations. Further, clinical implementation of dynamic compensation would require the development of software not currently commercially available as well as new quality assurance protocols. As the beam apertures are adjusted based on the beam view projections of the PTV, software to automatically perform this task and determine the new MLC positions (easily designed using modern software packages) would need to be included in the treatment console.

Despite these apparent shortcomings, however, the potential advantages of the dynamic compensation concept, beyond those explored herein, are compelling. Image-guided radiotherapy is emerging as a viable tool for real-time localization of target tissues and is accompanied by expectations of further improved therapeutic ratio and treatment outcomes. In order to fully realize these potential advantages, however, we must develop techniques to accommodate for changes in patient anatomy and target position “on the fly.” Intuitively, doing so will require more than simply placing the target within a fixed beam aperture (remotely or otherwise); it will require manipulation of the beam itself. As an initial trial of this concept, this study has demonstrated that static changes in patient position can be adequately compensated for through treatment beam changes alone, i.e., changing the MU and MLC positions, without the need to reposition the patient or couch. It is expected that similar techniques could be used to compensate for changes in patient anatomy resulting from both interfraction internal target motion, including rotation and deformation (where beam aperture modification is needed), and intrafraction target motion and deformation, e.g., those changes resulting from respiration. Finally, dynamic compensation has the potential for use in compensating for the differential movement of multiple targets in IMRT, e.g., prostate or lung primaries and the associated draining lymphatics.

V. CONCLUSION

When applied to setup error correction for four-field prostate cancer patient-treatment plans, we have shown that dynamic compensation does not significantly alter coverage of target tissues or sparing of adjacent OARs when compared with corrections made by performing couch shifts for patient-positioning errors up to 10.0 cm. Dynamic compensation can be performed remotely, thus eliminating positional errors that may result from unnecessary increases in treatment time or from movement of the patient. Further, the ability of dynamic compensation to correct large positioning errors has implications for the accuracy and time necessary during initial daily patient setup.

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\textsuperscript{4}Author to whom correspondence should be addressed. Electronic mail: Paul.Keall@stanford.edu


\textsuperscript{12}J. C. Stroom, H. C. de Boer, H. Huizenga, and A. G. Visser, “Inclusion of geometrical uncertainties in radiotherapy treatment planning by means of...


