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A Cone Beam CT-Based Study For Clinical Target Definition Using Pelvic Anatomy During Post-Prostatectomy Radiotherapy

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BODINE JOURNAL

A Cone Beam CT-Based Study For Clinical Target Definition Using Pelvic Anatomy During Post-Prostatectomy Radiotherapy

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Introduction
Radiation therapy (RT) is delivered after radical prostatectomy (RP) either as salvage treatment for an elevated prostate-specific antigen (PSA) level or as adjuvant therapy for patients with high-risk pathologic features. Recent prospective data demonstrated a disease-free survival benefit of adjuvant RT for pathologic T3N0 prostate cancer. Despite literature supporting the delivery of post-RP RT to the prostatic fossa (PF), no clear target definition guidelines exist for intensity modulated radiation therapy (IMRT) or image-guided RT (IGRT).

Visualization of the PF is limited on standard CT images, with significant interobserver variability and uncertainty in CTV definition. Efforts to incorporate complementary imaging modalities such as MRI for PF target volume definition have generated neither demonstrably more reliable PF delineation, nor practical contouring guidelines. Regardless of the imaging modality, direct visualization and delineation of the PF clinical target volume (CTV) is fraught with uncertainty. On the other hand, it is possible to distinguish the borders of important nearby pelvic structures, namely the bladder and the rectum. The reliability of rectal volume definition on helical CT is supported by analysis of rectal contours defined in a prospective trial, suggesting the feasibility of rectal dose-volume data collection in a multicenter setting. Fiorino et al have described the utility of online CBCT imaging during definitive, primary RT for prostate cancer using equipment similar to that utilized in the current study. These studies support the reliability of CT-defined rectum contours and a limited correlation between PF CTV and anterior rectal wall, an important tenet in the current study.

The data reported by Fiorino et al. are limited by the infrequency of image collection and the acquisition of images at a time and place separate from the treatment couch. Though PTY margin recommendations are not provided by Fiorino et al., they state eloquently that 1), the anterior-posterior movements of rectum and bladder are more important than lateral motion; 2), the rectum trends anteriorly during an RT course; 3), there is significant correlation between the posterior CTV border and the anterior rectal wall for the cranial half of the rectum. Through the use of CBCT images obtained during post-prostatectomy RT, the interfraction movement of the dose-limiting pelvic organs may be characterized further. This information may be used for the careful extrapolation of information regarding motion of the PF target volume. Prior reports have described the utility of online CBCT imaging during definitive, primary RT for prostate cancer using equipment similar to that utilized in the current study.

In our study, we approach the problem of PF target definition through analysis of real-time CBCT images during post-RP RT, studying the motion of the critical normal tissue structures that approximate the anterior and posterior anatomical boundaries of the prostatic fossa. Cone-beam CT images, obtained during a definitive course of RT, provided information regarding rectal and bladder movement. For the purpose of estimating appropriate anterior and posterior PF PTV definition guidelines, the posterior bladder border and the anterior rectum border were considered as radiographic surrogates for the anterior and posterior PF borders, respectively.

Methods and Materials
The pelvic anatomy of 10 consecutive prostate cancer patients undergoing post-RP RT was studied retrospectively using CBCT images obtained during the course of treatment. All patients received a radiation dose of 68.4 Gy (1.8 Gy/fraction), delivered with a four-field conformal RT plan. Planning CT (CTv) scans, with 3 mm slice thickness, were obtained in the supine position with contrast dye cystograms and urethrograms. Patients were instructed to follow a strict preparatory regimen before the CTv and during RT in order to ensure consistent filling and emptying of the bladder and rectum, respectively. The attending physician (R.V.) reviewed and approved CTV, rectum, and bladder CTv volumes on the helical CT scans for each patient as a component of standard RT planning and delivery. At our institution, a standard 1.0 cm PTV margin is added to the prostatic fossa CTV, an empirically chosen guideline. The standard post-RP treatment policy in our department includes at least every-other-day CBCT scans for position verification, with corrective shifts for 5 mm or more. Image registration using CBCT scans is performed based upon bony anatomy including femoral heads, pubic arch, sacrum, ischium and ilium. CBCT images were obtained 2-5 times weekly immediately before treatment using the Elekta Synergy cone beam system. CBCT scans (exported with a 1 mm slice thickness) were registered in relation to the planning CT using the mutual information algorithm on the CMS FocalSim. The automatically co-registered images were evaluated for accuracy by a single observer (T.S.); manual adjustments

Figure 1. Rectum and bladder motion were recorded at three points along the distance from seminal vesicle stump to bladder-urethral junction.
were made when necessary to produce an optimal fusion of images in relation to the bony pelvic anatomy. The same observer contoured bladder and rectal volumes on all CBCT images of satisfactory quality for the identification of the rectal and bladder borders. Rectal and bladder motion was measured from the seminal vesicle stump (SVS) to the bladder-urethral junction (BUJ) (Figure 1). This region was chosen since it represents the volume at risk for subclinical disease and it includes the relevant, potentially dose-limiting organs-at-risk (OAR). For each patient, 3 cross-sectional levels were studied: 1) superior (SUP), one slice caudal to the SVS; 2) inferior (INF), one slice cranial to the BUJ; and 3) middle (MID), midway between SUP and INF levels. In the cross-sectional plane, midsagittal coordinates were measured at the anterior rectal border and the posterior bladder border and compared to the planning CT volumes and the mean organ position to obtain interfraction motion. Lateral shifts were not assessable with this technique, and were not studied due to minimal impact on RT dose delivered to adjacent organs at risk (bladder and rectum) relative the anterior and posterior shifts. Inter-organ distance (IOD), the midsagittal difference between bladder and rectum, was also recorded at each measurement level, as this quantity may approximate crudely the anteroposterior PF distance. Data regarding organ volume and movement were collected for each CTref and CBCT. The mean and the standard deviation of organ border motion were calculated relative to both CTref and mean organ position.

In order to assess the reproducibility of the rectum and bladder by volume definition, repeat contours of the rectum and bladder were performed for 2 patients. In separate contouring sessions, the same observer (T.S.) repeated the organ definition steps using all CBCT scans for both patients. Repeat measurements of the anterior rectal border and the posterior bladder border were recorded, and movement relative to CTref was collected. The difference between the two sets of CBCT organ contours was calculated to determine the intraobserver variability for bladder and rectum motion measurements. A similar process was followed for rectum and bladder volume measurements to determine intraobserver variation in organ volume.

Anterior and posterior PTV margins were calculated by applying a formula (2Σ + 0.7σ) that includes systematic error (Σ) and random error (σ) of target volume position17, using measured organ border shifts relative to CTref for each CBCT scan. Interfraction motion of the posterior bladder border and the anterior rectum border were used in the analysis as substitutes for anterior and posterior PF motion in order to calculate estimated margin recommendations.

Results
Ten patients undergoing prostate fossa RT to 68.4 Gy in 38 fractions were evaluable for this study. Demographic data is displayed in Table 1. A total of 176 CBCT study sets obtained 3-5 times weekly were analyzed. The rectal and bladder borders were reliably identified in 166 of 176 (93%) of CBCT images. Figure 2 shows a representative CBCT image. Figure 3 contains a typical CT image obtained for planning purposes.

Table 1. Characteristics of 10 patients receiving radiotherapy to PF after radical prostatectomy

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>Mean 57, Range 44-69</td>
</tr>
<tr>
<td>Time from surgery to RT</td>
<td>Median (months) 8.2, ≤ 9 months (6), &gt; 9 months (4)</td>
</tr>
<tr>
<td>Pre-RT PSA (ng/mL)</td>
<td>≤ 0.4 (6), &gt; 0.4 (4)</td>
</tr>
<tr>
<td>Gleason Score</td>
<td>≤ 6 (2), ≥ 7 (8)</td>
</tr>
<tr>
<td>Pathologic Tumor Stage (n)</td>
<td>pT2 (5), pT3 (5)</td>
</tr>
<tr>
<td>Extracapsular extension (n)</td>
<td>No (6), Yes (4)</td>
</tr>
<tr>
<td>Margin status</td>
<td>Positive (4), Negative (6)</td>
</tr>
</tbody>
</table>

Validation of Methods
Ten patients undergoing prostate fossa RT to 68.4 Gy in 38 fractions were evaluable for this study. Demographic data is displayed in Table 1. A total of 176 CBCT study sets obtained 3-5 times weekly were analyzed. The rectal and bladder borders were reliably identified in 166 of 176 (93%) of CBCT images. Figure 2 shows a representative CBCT image. Figure 3 contains a typical CT image obtained for planning purposes.

Validation of Methods
Repeat contours and measurements for two patients reveal an average organ movement measurement discrepancy between contour sets of 1.2 ± 1.7 mm for bladder and 1.1 ± 1.0 mm for rectum for each of thirty CBCT
Volume and Motion Relationships

For rectum and to 40.7 mL for bladder.

Table 2. Pearson correlation coefficients among mean organ motion and mean organ volume.

<table>
<thead>
<tr>
<th>Relative to</th>
<th>SUP</th>
<th>MID</th>
<th>INF</th>
<th>AVG</th>
<th>INF</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bladder Motion</td>
<td>-0.13</td>
<td>0.07</td>
<td>-0.44</td>
<td>0.53</td>
<td>0.15</td>
<td>0.26</td>
</tr>
<tr>
<td>Rectum Motion</td>
<td>0.08</td>
<td>-0.15</td>
<td>-0.44</td>
<td>0.45</td>
<td>0.14</td>
<td>0.26</td>
</tr>
<tr>
<td>IOD</td>
<td>-0.12</td>
<td>0.14</td>
<td>0.13</td>
<td>0.33</td>
<td>0.04</td>
<td>0.33</td>
</tr>
<tr>
<td>Rectum Motion</td>
<td>0.02</td>
<td>0.18</td>
<td>0.01</td>
<td>0.15</td>
<td>0.18</td>
<td>0.28</td>
</tr>
<tr>
<td>SUP</td>
<td>0.04</td>
<td>0.26</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MID</td>
<td>-0.07</td>
<td>0.30</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INF</td>
<td>0.04</td>
<td>0.30</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVG</td>
<td>0.01</td>
<td>0.28</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussion

The normal tissue anatomy (bladder and rectum) adjacent to the PF CTV was readily definable throughout the course of post-RP RT using CBCT. Relative to the planning CT, a mean posterior shift of the anterior rectal wall was observed on the CBCT images. The mean rectal volume as contoured on CBCT images during RT was less than the mean CTref volume. The rectum border shift and rectal volume change noted in this study may be related to a trend towards reduced rectal volume over time during prostate RT.

Our adjusted analysis of rectum volumes, which showed smaller mean variations in rectum volume after the removal of two large, outlying values, suggests that strict adherence to the bowel preparatory regimen may produce a planning CT that is more representative of the rectum during RT. The recommendation that patients in the current study present to clinic for RT with a full bladder and an evacuated rectum may have contributed to the small level of rectum volume variation observed.

In our study of nine patients receiving weekly CT scans during post-RP RT, Furtins et al reported a mean anterior shift of the anterior rectal wall throughout the caudal half of the rectum, but no shift within the cranial half of the rectum. In their study, measurements of rectum and bladder motion were acquired weekly using weekly CT scans. In our study, measurements of rectum and bladder motion were acquired weekly using weekly CBCT images. We also observed a mean anterior shift of the anterior rectal wall throughout the cranial half of the rectum, but no shift within the caudal half of the rectum. The difference in the results between our study and the study of Furtins et al may be related to the difference in the CT scanning frequency and the difference in the CT scanning protocol.

Table 3. Pearson correlation coefficients among mean organ motion and mean organ volume.

<table>
<thead>
<tr>
<th>Observed Motion</th>
<th>Bladder Motion</th>
<th>Rectum Motion</th>
<th>IOD</th>
<th>Rectum Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative to</td>
<td>SUP</td>
<td>MID</td>
<td>INF</td>
<td>SUP</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.13</td>
<td>0.07</td>
<td>-0.44</td>
<td>0.53</td>
</tr>
<tr>
<td>Bladder Motion</td>
<td>0.04</td>
<td>0.26</td>
<td>X</td>
<td>X</td>
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<td>0.30</td>
<td>X</td>
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<td>0.30</td>
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<td>Rectum Motion</td>
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<td>X</td>
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</tr>
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<td>SUP</td>
<td>0.01</td>
<td>0.28</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 4. Scatter plot of rectum motion and change in rectum volume.
bladder shifts were performed only at levels that included the PT CTV. The mean posterior shift of the anterior rectum wall relative to CTVp in the current study (1.6-2.7 mm) was small. The standard deviation of the rectal wall position on CBCT relative to the CTVp (5.6-8.3 mm) demonstrates important interfraction variation in rectal wall position, noted throughout the region of rectum relevant to the PT CTV, despite the small average shift observed. Variations in rectal volume appear to impact the position of the anterior rectum wall (Figure 4). In addition, the interorgan distance, which may serve as a rough approximation of the prostatic fossa, correlates more strongly with anterior rectal motion than with other factors (Table 3), supporting the influence of rectal border motion on PT CTV delineation.

We recommend the use of a nonuniform margin for PTV definition, consisting of a 5.9 to 7.1 mm bladder border margin and an 8.6 to 10.2 mm rectal border margin. A published report of significant correlation between the anterior rectal wall and the prostatic fossa CTV supports, in part, the rationale of the current study’s approach, through the reported relationship between rectal and CTV motion occurring only with the cranial portion of the rectum12. Although the influence of OAR motion on PT PTV definition seems sensible, the extrapolation of target information from organ motion should be approached with caution. The use of 3D conformal RT after RP has been shown to reduce toxicity relative to conventional delivery techniques30. In addition, rectal dose-volume histograms (DVHs) for patients undergoing post-RP RT have been correlated significantly with risk for late complications21. Retrospective analyses of patients undergoing salvage post-RP RT suggest a benefit from RT doses 64.8 Gy or higher2-3. As higher RT doses are delivered to the prostatic fossa, the ability to minimize toxicity of adjacent tissues rests upon an understanding of motion of both CTV and OARs during treatment. Intensity-modulated radiation therapy (IMRT) may allow safe dose-escalation for post-RP RT22, but its application requires detailed target definition guidelines. CBCT may allow tighter RT margins when used to construct IMRT with daily corrections23, potentially allowing for higher doses without parallel increases in OAR dose and treatment-related toxicity.

The current study provides anterior and posterior margins for PTV definition based on calculations using pelvic organ motion information. Lateral margins were not calculated, as lateral movement is less significant than anteroposterior motion and is unlikely to influence dose delivered to the adjacent organs at risk (bladder and rectum). Due to uncertainty in direct definition of the PT CTV, an indirect approach was utilized based on interaction rectal and bladder motion. This approach acknowledges the uncertainty of CTV-definition15 while incorporating the additional anatomic information provided by on-line CBCT imaging during the RT course. The bladder and the rectum were easily identified on most CBCT images in the current study. A small number of CBCT images collected in the current study (7%) were unusable for organ definition due to poor image quality, which may be attributed to technical errors in image acquisition. The use of CBCT and rectum movements as determinants for PTV margin guidelines may provide a reliable approach, as rectal contouring has been shown to be reproducible using helical CT scans30. These data and similar future studies should be pursued to better define target-definition guidelines for post-RP conformal RT. Avenues for future applications of CBCT images in post-RP RT may include daily online localization with manual soft-tissue registration and subsequent corrective shifts in patient position, as well as online adaptive radiation therapy, following a strategy similar to that described previously by Yan et al24. The current work may be used in future attempts to develop off-line adaptive strategies for RT that rely upon conformal avoidance of the rectum and bladder to target the PT CTV for post-prostatectomy patients.

In conclusion, normal tissue anatomy (bladder and rectum) used to define the anterior and border of the prostatic fossa was readily definable by CBCT imaging throughout the course of post-RP RT. In the absence of direct, target-based treatment guidelines, CBCT definition of bladder and rectum volumes may be used to pursue anterior and posterior PTV margin recommendations.

References