Towards image-guided radiotherapy of prostate cancer

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THE INFLUENCE OF A DIETARY PROTOCOL ON CONE-BEAM CT-GUIDED RADIOTHERAPY FOR PROSTATE CANCER PATIENTS

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ABSTRACT

PURPOSE To evaluate the influence of a dietary protocol on cone-beam computed tomography (CBCT) image quality, which is an indirect indicator for short-term (intrafraction) prostate motion, and on interfraction motion. Image quality is affected by motion (e.g., moving gas) during imaging and influences the performance of automatic prostate localization on CBCT scans.

PATIENTS AND METHODS Twenty-six patients (336 CBCT scans) followed the dietary protocol and 23 patients (240 CBCT scans) did not. Prostates were automatically localized by using three-dimensional (3D) grey-value registration (GR). Feces and (moving) gas occurrence in the CBCT scans, the success rate of 3D-GR, and the statistics of prostate motion data were assessed.

RESULTS Feces, gas, and moving gas significantly decreased from 55%, 61%, and 43% of scans in the nondiet group to 31%, 47%, and 28% in the diet group (all p < 0.001). Since there is a known relation between gas and short-term prostate motion, intrafraction prostate motion probably also decreased. The success rate of 3D-GR improved from 83% to 94% (p < 0.001). A decrease in random interfraction prostate motion also was found, which was not significant after Bonferroni's correction. Significant deviations from planning CT position for rotations around the left-right axis were found in both groups.

CONCLUSIONS The dietary protocol significantly decreased the incidence of feces and (moving) gas. As a result, CBCT image quality and the success rate of 3D-GR significantly increased. A trend exists that random interfraction prostate motion decreases. Using a dietary protocol therefore is advisable, also without CBCT-based image-guidance.
INTRODUCTION

Throughout the treatment process of external beam radiotherapy for patients with prostate cancer, geometric uncertainties limit the accuracy of treatment, such as setup error and interfraction and intrafraction organ motion, which is a major source of concern\(^1\). The position of prostate and seminal vesicles (prostate in remainder of report) is affected mostly by physiologic changes in rectum volume\(^2-3\). To account for these uncertainties, margins are used. However, large margins result in more dose treatment to the bladder and rectum, which increases toxicity\(^4\). To reduce toxicity, intensity-modulated radiotherapy\(^5\) and offline and online image-guided radiotherapy (IGRT) techniques (correcting prostate motion) are used\(^6-7\). Many institutes use implanted fiducials\(^6\) to correct for interfraction prostate motion. Kupelian et al.\(^7\) made use of a continuous prostate tracking device that provides real-time positional feedback to detect intrafraction prostate motion. To correct for interfraction prostate motion, cone-beam computed tomography (CBCT)-IGRT strategies can be used in combination with adaptive radiotherapy protocols\(^8-9\). These techniques increase the precision of treatment delivery and lead to a decrease in the required margins\(^10\), providing opportunities for dose escalation and increasing the probability of disease control\(^11\).

With the introduction of linear accelerators equipped with kilovoltage CBCT imaging, soft-tissue registration is feasible\(^12\). Therefore, we previously developed an automatic rigid three-dimensional (3D) grey-value registration (GR) algorithm for fast prostate localization that could be used for online and offline IGRT\(^13-14\). For conventional CT scans, 3D-GR had a success rate of 91%. On CBCT scans, the success rate was only 65%, increasing to 83% with an adapted procedure. The main cause for unsuccessful prostate registration on CBCT scans was the presence of reconstruction artifacts in the images caused by motion of large gas pockets during acquisition of the CBCT scan (taking ~2 minutes), which are not present in conventional CT scan.

Contrary to the development of IGRT techniques for prostate radiotherapy, less effort has been concentrated on introducing methods, such as a dietary protocol, to decrease changes in rectal volume and associated prostate motion. To our knowledge, there are no published data about the effect of
laxatives or dietary means on prostate motion during radiotherapy. However, several institutes mentioned the use of protocols to achieve empty rectums during the course of radiotherapy\(^{(15-16)}\). Others used mild laxatives before acquisition of the planning CT scan to minimize rectal content\(^{(17)}\). The potential advantages of a routine dietary protocol are two-fold. First, a dietary protocol would decrease the occurrence of moving gas pockets during image acquisition and the related reconstruction artifacts in the CBCT images, thus increasing the image quality of the CBCT scans and the 3D-GR success rate. Second, decreased rectal volume changes during the course of treatment may decrease interfraction motion, whereas fewer moving gas pockets may decrease intrafraction prostate motion.

The aim of this study is to evaluate the influence of a dietary protocol on CBCT image quality, which influences performance of automatic 3D-GR prostate localization on CBCT scans, and on interfraction prostate motion.

**PATIENTS AND METHODS**

**PATIENT DATA**

Twenty-six patients with prostate cancer (336 CBCT scans) treated at The Netherlands Cancer Institute–Antoni van Leeuwenhoek Hospital (2005) subject to a dietary protocol were compared with a retrospective data set (2004) of 23 patients (240 CBCT scans) who were not subject to the dietary protocol. All patients had a planning CT scan and CBCT scans made according to a routine offline bony anatomy setup correction protocol for translations\(^{(18)}\); i.e., CBCT scans were obtained on average for 12 fractions. No correction per protocol motion was made at this time.
PROTOCOLS

STANDARD PROTOCOL
Patients with prostate cancer were instructed to have a full bladder and empty rectum during simulation and irradiation by emptying the bladder and bowels and drinking 250 cm$^3$ of liquid approximately 1 hour before planning CT scan acquisition and treatments. For the nondiet group, the standard protocol was followed and there was no rule about treatment time.

DIETARY PROTOCOL
Next to the standard protocol, the diet group followed a dietary protocol (FIGURE 1). The dietary guidelines prescribed how to reduce intestinal gas and obtain a reproducible rectum volume, starting 1 week before acquisition of the planning CT scan until the end of treatment. The intake of a daily mild laxative, two magnesium-oxide tablets (each 500 mg), was to start on the evening 2 days before acquisition of the planning CT scan and 2 days before treatment up to the end of treatment. In consultation with the radiation oncologist, the dose of laxative could be adjusted. To facilitate regular meals and a regular schedule of bowel movements, the treatment schedule was intended to be regular, as well. Treatments were planned for after 10:00 AM because it was expected that most people defecate in the morning.

FIGURE 1. Dietary protocol.
CT = computed tomography.
INCIDENCE OF FECES, GAS, AND MOVING GAS

The incidence of feces and (moving) gas in the CBCT scans at the level of the prostate was visually assessed and scored by an observer (Figure 2) for both groups. Moving gas pockets during CBCT scan acquisition cause streak artifacts in the reconstructed CBCT scan and therefore could be visually recognized.

Figure 2. Transverse slices of cone-beam computed tomography scans with (A) empty rectum (visible prostate); (B) rectum containing feces and small gas pockets (visible prostate); the very small gas pockets within the feces were not scored; (C) rectum with moving gas pocket (streak artifacts; hardly visible prostate); and (D) rectum with feces and a slightly moving gas pocket (white streak artifacts at gas pocket edges; large part of prostate is visible).
SUCCESS RATE OF 3D-GR AND PREDICTIVE FACTORS FOR 3D-GR OUTCOME

The success rate of automatic rigid 3D-GR prostate localization on CBCT scans was compared between the diet and nondiet groups. The 3D-GR starts with a bony anatomy registration, followed by a 3D-GR prostate registration of CBCT scan and planning CT scan (normal GR: three rotations and three translations). In case normal GR failed, registration was repeated starting from the bony anatomy registration, with the prostate fixed at the apex (fixed apex GR: three rotations, no translations), i.e., the apex of the prostate was used as a rotation point for 3D-GR. The term combined GR is used for the combination of normal GR and fixed apex GR. Translations and rotations were expressed relative to the center of mass of the clinical target volume (CTV) contour of the prostate defined in the planning CT. The CTV contours of the planning CT were expanded to obtain a help line for visual evaluation by 3.6 mm (Note: this was not the margin used for the planning target volume; i.e., the width of two pixels in a 256 x 256 image, which takes into account the finite accuracy of 3D-GR, the partial volume effect, and allowing slight deformation of prostate and seminal vesicles). An experienced observer visually assessed the registrations in transverse, coronal, and sagittal planes by using the expanded CTV contours overlaid on the registered CBCT scan. A registration was marked as successful if the prostate fit within the expanded CTV contours. To test whether the presence of feces and/or (moving) gas in the rectum was predictive for 3D-GR outcome, all CBCT scans were divided into groups related to their rectum content. Because CBCT scans that contained moving gas were a subset of the scans with gas, the following groups were considered: feces, nonmoving gas, and moving gas.

PROSTATE MOTION

Prostate motion for the diet and nondiet groups was calculated for the successful 3D-GR registrations, and motion between groups was compared. Motion was expressed as the difference between 3D-GR and bony anatomy registration and evaluated for translations and rotations along and around the left-right (LR), craniocaudal (CC), and anteroposterior (AP) axes through the rotational center of the prostate.
STATISTICS

Differences in observed feces and/or (moving) gas and success rates of 3D-GR between diet and nondiet groups were tested by using Pearson’s chi-square test\(^{(19)}\).

To find possible predictive factors for 3D-GR outcome, it was first tested whether feces correlated with nonmoving gas and moving gas using cross-tabulations in combination with Pearson’s chi-square test. Subsequently, univariate and multivariate logistic regression analyses were performed\(^{(19)}\).

For prostate motion analysis, group means, systematic errors, and random errors (calculated as the root mean square of the SDs per patient) were calculated for translations and rotations. Only patients with five or more successful registrations were included for statistical analysis to increase the reliability of statistical analysis. We tested whether group means significantly deviated from zero, i.e., the position of the prostate in the planning CT scan (one-sample t-test). Furthermore, we tested whether group means significantly differed between groups (independent-samples t-test), as well as systematic errors (Levene’s test for equality of variance) and random errors (Mann-Whitney test)\(^{(19)}\).

SPSS software for Windows (SPSS Inc., Chicago, IL) was used for statistical analyses. For most significance tests, \(p = 0.05\) was used. However, for prostate motion analysis, six parameters (three translations, three rotations) were tested, increasing the chance to find a significant value by chance. Therefore, Bonferroni’s correction was applied to correct the \(p\)-value for the number of parameters used (\(N = 6\)), i.e., \(p = 0.05/N = 0.008\).

RESULTS

PROTOCOL COMPLIANCE

In the nondiet group, treatment times ranged between 7:12 AM and 4:19 PM. The average time was 11:09 AM ± 2:26 hours (1 SD). Of all 240 CBCT scans in the nondiet group, 43% were acquired before 10:00 AM. Treatment times in the diet group ranged between 7:49 AM and 7:09 PM. The average
time was 13:57 PM ± 1:51 hours (1 SD). Despite the aim of regular treatment times in the diet group, the SD exceeded 3:00 hours for 3 of the 26 patients. For the remaining patients, the SD was 1:36 hours. Only 3% of 336 CBCT scans in the diet group were acquired before 10:00 AM.

**RATING OF FECES, GAS, AND MOVING GAS**

Observer scores for feces and (moving) gas in the CBCT scans are listed in Table 1. The presence of feces and (moving) gas was less in the diet group, and the difference was significant for all three parameters (all p ≤ 0.001).

<table>
<thead>
<tr>
<th></th>
<th>Nondiet (23 patients, 240 CBCTs)</th>
<th>Diet (26 patients, 336 CBCTs)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feces</td>
<td>55%</td>
<td>31%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Gas pocket</td>
<td>61%</td>
<td>47%</td>
<td>0.001</td>
</tr>
<tr>
<td>Moving gas pocket</td>
<td>43%</td>
<td>28%</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

**SUCCESS RATE OF 3D-GR AND PREDICTIVE FACTORS FOR 3D-GR OUTCOME**

The success rate of automatic prostate 3D-GR on CBCT scans in the diet group was significantly higher than in the nondiet group (Table 2), for normal and combined GR. In addition, we found that of all successful GRs, there was a shift from 78% normal GRs and 22% fixed apex GRs in the nondiet group to 89% normal GRs and 11% fixed apex GRs in the diet group. Because it was expected that most people defecate in the morning, one would expect the success rate to be higher for scans acquired after 10:00 AM. In the diet group, we found a significant difference in success rates (60% against 95%) between scans acquired before and after 10:00 AM (p <
However, only 10 of 336 scans were obtained before 10:00 AM in this group. In the nondiet group, the success rate was also lower before 10:00 AM (78% against 87%; p = 0.07), in which 104 of 240 scans were acquired before 10:00 AM. If only scans acquired after 10:00 AM are evaluated, a higher success rate was still found for the diet group: 95% vs. 87% for the nondiet group (p = 0.003).

<table>
<thead>
<tr>
<th>TABLE 2. Success rate of normal and combined automatic three-dimensional GR method in the nondiet and diet groups and results of significance tests between groups.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-diet (23 patients, 240 CBCTs)</td>
</tr>
<tr>
<td>Normal GR</td>
</tr>
<tr>
<td>Combined GR</td>
</tr>
</tbody>
</table>

**ABBREVIATIONS.** CBCT = cone-beam computed tomography; GR = grey-value registration.

**FIGURE 3** shows the relations of rectum content and CBCT scans with 3D-GR failures. Because the CBCT scans containing moving gas were a subset of those with gas, the following groups were made: feces and nonmoving gas, feces and moving gas, feces, nonmoving gas, moving gas, and empty rectum. In the nondiet group (**FIGURE 3A**), many scans contained a combination of feces and nonmoving gas or feces and moving gas. In the diet group (**FIGURE 3B**), more scans had an empty rectum, and the amount of 3D-GR failures for CBCT scans with feces and moving gas was much lower than in the nondiet group. The presence of feces in the rectum significantly correlated with the presence of nonmoving gas and moving gas (both p < 0.001). From univariate analyses, feces and moving gas appeared to be predictive factors (both p < 0.001), whereas nonmoving gas was not (p = 0.4). Multivariate analysis showed that moving gas was the higher significant predictive factor (p for moving gas < 0.001) compared with feces (p for feces = 0.023).
**Figure 3.** Distributions in the nondiet and diet groups of rectum content in relation to three-dimensional grey-value registration (3D-GR) outcome. Error bars denote the error for the failures in a group with specific rectum content. CBCT = cone-beam computed tomography; F = feces; NMG = nonmoving gas; MG = moving gas.

**Prostate Motion**

The results for prostate motion are listed in Table 3. Only patients with five or more successful registrations were used, i.e., for the nondiet group, 192 (of 240) registrations (i.e., 80% of all registrations) of 21 (of 23) patients, and
for the diet group, 315 (of 336) registrations (i.e., 94% of all registrations) of all 26 patients were used.

**Table 3.** Prostate motion data in the nondiet group and diet group.

<table>
<thead>
<tr>
<th></th>
<th>Nondiet (21 patients, 199 registrations)</th>
<th>Diet (26 patients, 315 registrations)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TRR (mm)</td>
<td>TRC (mm)</td>
</tr>
<tr>
<td>μ</td>
<td>0.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Σ</td>
<td>0.4</td>
<td>1.8</td>
</tr>
<tr>
<td>σ</td>
<td>0.8</td>
<td>2.9</td>
</tr>
</tbody>
</table>

**Abbreviations.** T = translations; R = rotations; LR = left-right; CC = craniocaudal; AP = anteroposterior; μ = group mean; Σ = systematic error (1 SD); σ = random error (1 SD).

Negative values for mean rotations around the LR axis indicate the prostate in the CBCT scan is rotated to the posterior side with respect to the planning CT scan (the definition of directions is described by Hoogeman et al. (21)). Positive values for mean translations along the CC and AP axis mean that the prostate moved to the cranial and anterior side, respectively. This is consistent with a larger rectum in the planning CT scan.

* Significant differences (p < 0.008; Table 4) from zero (the planning CT scan).

Significant deviations from the planning CT scan for rotations around the LR axis were found for both groups (p = 0.005 and p = 0.001, respectively; Table 4). Group mean values and systematic and random errors for rotations and translations were not significantly different after Bonferroni's correction (Table 5). However, a trend exists that prostate motion decreased in the diet group, mainly for random variations (Tables 3 and 5).
TABLE 4. Prostate motion: results (p) of significance test on group mean values for the nondiet group and diet group with respect to 0 (= planning CT scan).

<table>
<thead>
<tr>
<th></th>
<th>Nondiet</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T_{LR}</td>
<td>T_{CC}</td>
<td>T_{AP}</td>
<td>R_{LR}</td>
<td>R_{CC}</td>
<td>R_{AP}</td>
<td>T_{LR}</td>
<td>T_{CC}</td>
<td>T_{AP}</td>
<td>R_{LR}</td>
<td>R_{CC}</td>
<td>R_{AP}</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>0.003</td>
<td>0.6</td>
<td>0.005*</td>
<td>0.9</td>
<td>0.2</td>
<td>0.7</td>
<td>0.6</td>
<td>0.9</td>
<td>0.001*</td>
<td>0.9</td>
<td>0.03</td>
</tr>
</tbody>
</table>

ABBREVIATIONS. CT = computed tomography; T = translations; R = rotations; LR = left-right; CC = craniocaudal; AP = anteroposterior.

* Significant differences (p < 0.008) from zero (the planning CT scan).

TABLE 5. Prostate motion: results (p) of significance tests between the nondiet group and diet group on \( \mu \), \( \Sigma \), and \( \sigma \) values.

<table>
<thead>
<tr>
<th></th>
<th>T_{LR}</th>
<th>T_{CC}</th>
<th>T_{AP}</th>
<th>R_{LR}</th>
<th>R_{CC}</th>
<th>R_{AP}</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>0.7</td>
<td>0.1</td>
<td>0.6</td>
<td>0.5</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td>( \Sigma )</td>
<td>1.0</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>0.06</td>
<td>0.02</td>
<td>0.6</td>
<td>0.03</td>
<td>0.04</td>
<td>0.6</td>
</tr>
</tbody>
</table>

ABBREVIATIONS. T = translations; R = rotations; LR = left-right; CC = craniocaudal; AP = anteroposterior; \( \mu \) = group mean; \( \Sigma \) = systematic error (1 SD); \( \sigma \) = random error (1 SD).

No significant differences (p < 0.008) in \( \Sigma \) and \( \sigma \) were found between groups.
DISCUSSION

FECES, GAS, AND MOVING GAS

The percentage of scans with feces, gas, and moving gas (i.e., gas that moves during CBCT acquisition, deteriorating image quality of the scans) decreased significantly by using the dietary protocol. Although visual assessment is a subjective way of scoring, it is very useful for evaluating the influence of the dietary protocol on CBCT image quality.

The effect of the dietary protocol on rectal volume was evaluated in another study at our institute (9), in which the rectums of 20 patients were delineated. The variation in rectum volume in the diet group was found to be smaller than in an older repeated CT data study (20). The negative time trend in rectal volume reported by several studies (e.g., 20) was not observed in the diet group. This is unexpected because for the diet group, mean rotations around the LR axis still significantly deviated from the planning CT scan position.

SUCCESS RATE OF AUTOMATIC PROSTATE LOCALIZATION

The dietary protocol had a positive effect on the outcome of automatic 3D-GR for prostate on CBCT scans (Table 2). The success rate of the combined GR method increased from 83% in the nondiet group to 94% in the diet group, which was significant. If only normal GR is considered, the nondiet group had a success rate of 65% and the diet group had a success rate of 84%, which is still lower than the success rate found for conventional CT scans (91%) with normal GR (13). However, when using CBCT scans the combined GR method in combination with the dietary protocol leads to a success rate similar to that found for conventional CT scans. In addition, there was increased normal GR in the diet group: 89% vs. 78% success in the nondiet group, indicating that CBCT image quality improved.

The change in mean treatment time from 11:09 AM of the nondiet group to 13:57 PM had its influence on 3D-GR success rate. Also, more patients in the nondiet group were treated and underwent scanning before 10:00 AM, presumably therefore having a larger probability of a full rectum and gas in the rectum. The 3D-GR success rate was higher for scans acquired after...
10:00 AM for both the diet group and nondiet group (95% against 87%). In addition, the difference between success rates for scans acquired before and after 10:00 AM strongly suggests that part of the better success rate in the diet group can be explained by the later treatment time, and patients in the diet group might have more regular bowel movements.

The dietary protocol significantly decreased the amount of failure scans that had rectums with a combination of moving gas and feces; from 11.3% failures in the nondiet group to 1.5% in the diet group (Figure 3). From univariate analysis, it was found that feces and moving gas both were significant predictive factors for the outcome of 3D-GR. Multivariate analysis of feces and moving gas showed that moving gas was the more significant predictive factor.

These findings clearly show that the dietary protocol reduces the presence of feces and (moving) gas and improves CBCT image quality, thereby facilitating CBCT image-guidance. The dietary protocol and the 3D-GR algorithm for CBCT scans currently is in clinical use in an adaptive radiotherapy protocol in our clinic. By the reduction in moving gas, very likely also intrafraction prostate motion decreases because a relation between rectal gas and prostate motion has been established before. Ghilezan et al. found for patients with a full and empty rectum using cine magnetic resonance imaging that the status of rectal filling was the most significant predictor for prostate intrafraction organ motion. Stroom et al. reported that gas pockets occurred in 23% of patients, and about 50% of the interfraction rectal wall shifts were larger than 5 mm, implying internal prostate motion. Currently, we are investigating how to increase the performance of 3D-GR for the remaining scans that are determined by moving gas. Remaining 3D-GR failures seem to be caused mostly by very large differences in rectum volume between planning CT scans and CBCT scans which may cause prostate deformations that our rigid 3D-GR algorithm cannot take into account.

**Prostate motion**

Mean prostate rotations around the LR axis in the CBCT scans deviated significantly from planning CT scan position for both groups. Rotation was in the posterior direction, which might indicate that the rectum becomes emptier during the course of treatment. The situation may improve if one
would start earlier with the diet and/or use laxatives to have more effect on the planning CT situation. There were no more significant differences in mean values and systematic and random errors between groups. However, a trend exists that random prostate motion decreased in the diet group for almost all parameters.

To calculate prostate motion, 2 patients were excluded from the nondiet group because they did not meet the constraint of more than five successful registrations. In addition, registrations for which 3D-GR failed were not used to calculate prostate motion. Therefore, it is not unlikely that prostate motion is underestimated, possibly introducing a bias in statistical results. For example, we found that the dietary protocol reduced the SD of random rotations around the LR axis to 58% (2.8º/4.8º x 100%) compared with the nondiet group. This difference is almost significant (p = 0.008) (Table 5). However, because a small percentage of scans was not scored (6% in the diet group and 17% in the nondiet group), the magnitude of motion might be underestimated, and this effect is stronger in the nondiet group than in the diet group. Assuming a Gaussian distribution and assuming that only the largest prostate rotations would have been deleted, the effect would be that the SD in the diet group would be 48% of the nondiet group (corrected SDs of 3.3º and 6.9º, respectively). Thus, the effect of the diet might be underestimated. However, it cannot be determined whether the scans with the largest rotations have been deleted because scans become unreadable due to the short-term motion, which has an unknown correlation with long-term motion.

With regard to introduction of a possible bias in our statistical results, we also compared our nondiet data with a previous prostate motion study at our institute on repeat CT data (21). We found slightly larger random errors (4.8º vs. 3.6º for rotations around the LR axis, and 2.4 vs. 1.4 mm for translations around the AP axis) in our nondiet group than in the study by Hoogeman et al. (21) This may indicate that the introduced bias is not very high. Conversely, systematic errors in our nondiet group are smaller (e.g., 2.5º vs. 5.1º for rotations around the LR axis). However, the uncertainty in calculating the systematic error is much larger than in the random error because it depends on the number of patients, whereas random error depends on the total number of scans used. Based on the behavior of the prostate from continuous tracking data by Kupelian et al. (7), one may also conclude that the introduced bias is low. They distinguished several motion patterns, from which the probability of obtaining a CBCT scan with poor image quality for which large excursions exist could be estimated. With continuous target drift,
high-frequency excursions and erratic-behavior CBCT scan image quality will become poor, whereas prostate motion is small on average. For transient and persistent excursions, CBCT image quality will only be poor if scanning occurs exactly at the time of the excursion, whereas otherwise, the large excursions will be detected. However, these patterns seem to occur infrequently: radiation delivery was stopped in 0.4% of fractions and delayed in 2.7% of fractions waiting for a spontaneous resolution of the prostate gland motion. The patient was realigned in 8.2% of all fractions.

Compared with previous prostate motion studies at our institute on a repeated CT data set by Van Herk et al.\(^{(22)}\) and Hoogeman et al.\(^{(21)}\), our study also showed that the main rotation was around the LR axis, and AP and CC translations were larger than along the LR axis. These latter findings were confirmed by other prostate motion studies\(^{(e.g., 1)}\). Prostate motion in our diet group was smaller than in earlier studies\(^{(21)}\), indicating that the diet has some influence on prostate motion. However, our nondiet group also showed fairly small prostate motion, except for random rotations around the LR axis. These differences may be attributed to the difference in registration technique or an improved planning CT protocol, which requires that patients exceeding a certain rectum volume must be rescanned. Hoogeman et al.\(^{(21)}\) used contour-based registration, for which delineation variation adds uncertainty. The largest registration differences between the two studies occurred for rotations around the LR axis (2.4° (1 SD)), whereas for translations, the difference is up to 1.3 mm\(^{(13)}\).

Compared with prostate motion studies in other institutes\(^{(e.g., 1)}\), most SDs of the diet group are smaller or similar. Regardless of the different registration techniques used, this indicates that the dietary protocol decreases prostate motion somewhat. To make a definitive statement about the impact of the dietary protocol, a randomized clinical trial would be required. However, in our institution, such a trial is not considered feasible because the improved image quality of the CBCT scans is essential for our adaptive radiotherapy protocol.
CONCLUSIONS

Introduction of a dietary protocol for prostate cancer radiotherapy significantly reduced the incidence of feces and (moving) gas in the rectum. As a result, CBCT image quality and the success rate of automatic prostate localization were significantly increased. Also, a trend exists that interfraction prostate motion is reduced. Intrafractional prostate motion might also be reduced because it is known that CBCT image quality is an indirect indicator for intrafractional prostate motion. It therefore is advised to use a dietary protocol in the treatment of patients with prostate cancer with or without CBCT-IGRT.
REFERENCES

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