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Adaptive off-line protocol for prostate external radiotherapy with cone beam computer tomography

Conformal radiation therapy is routinely used in radical treatment of prostate cancer. Several studies have shown that dose escalation may improve the clinical outcome of prostate radiotherapy [8]. Dose escalation almost inevitably leads to increasing probability of rectum injury unless technologically advanced techniques are used. For a given total dose, the dose delivered to the rectum depends on the margin between the clinical target volume (CTV) and the planning target volume (PTV). In general, the smaller the margin, the smaller the rectum dose. The CTV–PTV margin depends on target motion, patient setup, and target delineation uncertainty. To reduce the CTV–PTV margin required for setup errors and organ motion, several adaptive radiation therapy protocols have been introduced. For compensation of the setup uncertainty the Shrinking Action Level or No Action Level protocols are widely used [1, 3]. In centers where these protocols are implemented, the typical CTV–PTV margin is 1.0 cm. However, some reports suggest larger margins should be added, especially if extracapsular invasion of tumor is suspected [15]. Further diminishing the CTV–PTV margin requires controlling of the prostate movement in relation to bony structures. New radiotherapy technologies introduced in the late 1990s enabled measuring the interfraction of prostate movement. These were computer tomography on rails installed in the treatment room and cone beam computer tomography systems (CBCT) [7, 10, 11, 12]. Using these technologies, the first adaptive strategies were introduced. According to these strategies, the treatment was initiated with a conventional CTV–PTV margin, e.g., 1 cm [6]. Next volumetric imaging was performed during the first few fractions (first 4–6 fractions). Based on the image data, the average CTV was defined, and a new adapted plan was prepared with a smaller CTV–PTV margin. If this adaptive protocol was used, the typical CTV–PTV margin was 0.7 cm in each direction. Only systematic error is corrected in these strategies. In Munich where helical tomotherapy is used supported by the daily megavoltage computerized tomography prior to irradiation the CTV–PTV margin is decreased to 3 mm in all directions and to 5 mm in the craniocaudal direction [4].

In the newest adaptive procedures, online techniques were implemented. They enabled compensation of both systematic and random errors. In these techniques, the position of the prostate is identified by the position of the gold markers inserted into the prostate gland [2]. Using this method, the CTV–PTV margin was decreased to 0.5 cm (0.3 cm dorsally) in Charité–University of Berlin [5]. Nearly continuous localization of prostate in relation to the machine isocenter may be obtained with electromagnetic active markers (transponders) implanted into the prostate. The idea is analogous to those procedures where gold seeds are used. However, in this case a wireless magnetic system has been developed. The system enables localization of the few implantable transponders. Information about the position of all transponders is obtained at least ten times per second during treatment. Using this system different adaptive protocols were proposed which differ concerning the reaction on the prostate displacement observed during irradiation. In the most demanding protocols, the users claim that the CTV–PTV margins may be reduced to less than 0.3 cm. Depending on the technology and implemented adaptive protocols different CTV–PTV protocols may be safely used. In this paper, we describe the adaptive protocol implemented in our center based on application of CBCT and conventional portal imaging techniques. The results confirming the clinical value of this protocol are presented.

Materials and methods

Treatment technique

This study included 10 patients with a localized prostate carcinoma (T2–3 N0 M0) who were treated in our center in 2010. The median age of treated patients was 71 years and 6 months, PSA median 7.9 ng/ml (range 4.8–22.7 ng/ml), and Gleason score median 4.0 (range 3–7). During CT treatment simulation, patients were positioned supine with a knee-wedge for a better comfort and reproducibility. According to the protocol, images were taken with an empty rectum and full bladder. (All patients were asked to empty their rectum; some were prescribed mild laxative suppositories). To keep the bladder volume full, patients were asked to empty their bladder and drink half a liter of water 1 h prior to a planning CT scan. The same procedure was followed before each treatment session. CT treatment simulation was performed with a CT scanner (Somatom Open, Siemens) with a slice thickness of 3 mm. Three skin tattoos were marked during the simulation, and image data were sent to a contouring station (ROP, CompArt) where the prostate, seminal vesicles, rectum, bladder, and femoral heads were defined by a physician. The PTV consisted of a prostate gland CTV and seminal vesicles CTV with an additional uniform margin of 1 cm. The three-dimensional (3D) conformal prostate planning protocol was followed with a three field arrangement (anterior–posterior and two lateral opposed fields, with a wedge as required). All treatments were performed on a Varian Clinacs with 15 MV energy beams. The prescribed dose was 65 Gy delivered daily in 25 fractions during a 5-week treatment. During the planning process the recommendations of ICRU Reports 50 and 62 were followed; min PTV >95% and min CTV >97% of a prescribed dose.

Patient positioning control

During treatment, patients were positioned on the skin tattoos. Table position was then shifted according to the treatment plan. CBCT scans were taken during the first three fractions and then at least twice a week. A total of 162 CBCT images were collected. The prostate visualized on the CBCT was then manually matched to the planning CT; on-line registration was performed by radiography staff. Prior to irradiation, any displacement from the planning position of more than 0.2 cm was corrected. A soft registration procedure was repeated off-line by experienced physics staff. In the off-line registration CBCT images were also matched automatically to a planning CT based on the pubis symphisis (registration volume was limited to the pubis symphysis only).

Adaptive protocol

In the adaptive protocol, the off-line data were used. For each patient, the same protocol was used in each of the three main directions vertical, longitudinal, and lateral; however, for simplicity, the mathematical formalism of the protocol and the protocol itself is described for one patient and one direction. The reader is referred to the appendix, which provides a more general description of the mathematical formalism of the protocol. Let us describe the m-th registration result based on the pubis symphisis (bones) and on prostate (soft tissue) with b_m and s_m, respectively.

Both the bone and soft registrations describe the change of the pubis symphysis and prostate positions with respect to an external system in a single fraction, respectively. These displacements are known as setup error and internal error, respectively. In this work, bony anatomy means the pubis symphysis. Having b_m and s_m, a change in the prostate position in relation to the pubis symphysis may be calculated as follows:

$$\Delta sb_m = S_m - b_m$$

The term Δsb_m describes the position of the prostate with respect to the pubis symphisis in the m-th fraction, i.e., how much the position of the prostate differs from its planning position if the position of a patient is corrected by a setup uncertainty. To analyze the movement of the prostate with respect to the pubis symphysis for all patients (the data for each single patient is denoted with subscript "k"), frequency histograms of $\Delta(sb_m)_k$ were calculated for each direction separately.

Adaptive protocol

There are four main steps in an adaptive protocol developed in our center.

1. Prior to irradiation during the first three fractions, the CBCT is taken. CBCT images are registered on-line on the prostate gland by radiography staff. Based on the on-line soft registration, if any displacement larger than 0.2 cm is observed for any direction, the appropriate change of table position is made before irradiation.
2. CBCT images are registered off-line to a planning CT based on bones and prostate gland (soft registration). After the first free fractions, the average displacement in each direction of the prostate position with respect to the pubis symphysis is calculated according the following formula:

$$\langle \Delta sb \rangle_{mean} = \frac{1}{3}\left[\Delta sb_1 + sb_2 + \Delta sb_3\right]$$

3. From the fourth treatment session onwards two orthogonal portal images were taken and the table position was shifted to localize the pubis symphysis in the same position in relation to the isocenter as during the planning. This is achieved by the on-line registration of the portal images with DRRs.
4. In the next step, the table is also adjusted by the following vector

$$\left(\langle \Delta sb \rangle^{vert}_{mean}, \langle \Delta sb \rangle^{long}_{mean}, \langle \Delta sb \rangle^{lat}_{mean}\right)$$

and the irradiation is started. Superscripts "vert", "long", and "lat" denote the three main directions vertical, longitudinal, and lateral, respectively.

The adaptive protocol was tested for 10 patients. For these patients, the CTV–PTV margin was 1 cm. With this data, the prostate shifts from its initial position were evaluated. For a single patient, the m-th fraction, and one main direction, the corrected displacement was calculated according to the formula:

$$\langle \Delta sb_m \rangle_{corr} = \Delta sb_m - \langle \Delta sb \rangle_{mean}$$

The population cumulative frequency histogram of the prostate positions in relation to its average position in each direction was calculated. The assumption was made that in the first three sessions the position of the prostate was identical or nearly identical with the planning position. According to the procedure, displacement should not be greater than 0.2 cm. Based on the results the CTV–PTV margin was changed to 0.7, 0.7, and 0.4 cm for the vertical, longitudinal, and lateral directions, respectively.

In order to evaluate the validity of the adaptive procedure, data was collected for 30 consecutive patients treated according to the protocol. For this group of patients, CBCT were taken in the 10th and 21st fraction, followed by the position adjustments. The off-line soft registration was performed and displacement of the prostate in relation to the planning isocenter was obtained. The results are present-

Abstract · Zusammenfassung

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Adaptive off-line protocol for prostate external radiotherapy with cone beam computer tomography

Abstract

Purpose. The goal of this work was to prepare and to evaluate an off-line adaptive protocol for prostate teleradiotherapy with kilovoltage cone beam computer tomography (CBCT).

Patients and methods. Ten patients with localized prostate carcinoma treated with external beams underwent image-guided radiotherapy. In total, 162 CBCT images were collected. Position of prostate and pubis symphysis (PS) with respect to the isocenter were measured off-line. Using the CBCT scans obtained in the first three fractions the average position of prostate in relation (AvPosPr) to PB was calculated. On each CBCT scan, the position of prostate with respect to AvPosPr was calculated and cumulative histogram of prostate displacement with respect to AvPosPr was prepared. Using this data, the adaptive protocol was prepared in which (1) based on the CBCT made in the first three fractions the AvPosPr to PS is obtained, (2) in all other fractions two orthogonal images are acquired and if for any direction setup error exceeds 0.2 cm the patient's position is corrected, and (3) additionally, the patient's position is corrected if the AvPosPr exceeds 0.2 cm in any direction. To evaluate the adaptive protocol for 30 consecutive patients, the CBCT was also made in 10th and 21st fraction.

Results. For the first 10 patients, the results revealed that the prostate was displaced in relation to AvPosPr >0.7 cm in the vertical and longitudinal directions only on 4 and 5 images of 162 CBCT images, respectively. For the lateral direction, this displacement was >0.3 cm in one case. For the group of 30 patients, displacement was never >0.7, and 0.3 cm for the vertical and lateral directions. In two cases, displacements were >0.7 cm for the longitudinal direction.

Conclusion. Implementation of the proposed adaptive procedure based on the online set-up error elimination followed by a reduction of systematic internal error enables reducing the CTV–PTV margin to 0.7, 0.7, and 0.4 cm for the vertical, longitudinal, and lateral directions, respectively.

Keywords
Adaptive radiotherapy · Prostate · Cone beam computed tomography · Image-guided radiotherapy · Radiotherapy setup errors

Adaptives Offline-Protokoll mit digitaler Volumentomographie für die perkutane Strahlentherapie des Prostatakarzinoms

Zusammenfassung

Zielsetzung. Ziel dieser Studie war die Vorbereitung und Testung eines Offline-Protokolls mit digitaler Volumentomographie [“cone beam computed tomography“ (CBCT)] für die perkutane Strahlentherapie des Prostatakarzinoms.

Patienten und Methoden. Mit einer perkutanen, bildgesteuerten Strahlentherapie [“image-guided radiotherapy“ (IGRT)] wurden 10 Patienten mit einem lokalisierten Prostatakarzinom behandelt. Die Lage der Prostata und der Symphysis pubica in Relation zum Isozentrum wurde offline gemessen. Basierend auf Scanbildern der CBCT aus den 3 ersten Fraktionen wurde die mittlere Lage der Prostata (AvPosPr) in Beziehung zur Symphysis pubica berechnet. Auf jedem CBCT-Bild wurde die Lage der Prostata in Relation zur AvPosPr berechnet und das kumulative Histogramm der Verschiebung der Prostata zum AvPosPr gebildet. Das adaptive Protokoll wurde anhand dieser Daten vorbereitet. Das Protokoll beinhaltete erstens die AvPosPr zur PB, gemessen anhand der ersten 3 Fraktionen, zweitens eine Korrektur der Patientenlage, wenn der Set-up-Fehler, gemessen an 2 orthogonalen Bildern, um 0,2 cm in beliebiger Richtung abwich und drittens eine Korrektur der Patientenlage, wenn die AvPosPr um 0,2 cm in beliebiger Richtung abwich. Zur Evaluation des adaptiven Protokolls, wurde bei 30 aufeinanderfolgenden Patienten die CBCT zusätzlich während der 10. und 21. Fraktion durchgeführt.

Ergebnisse. Eine Messung der ersten 10 Patienten ergab, dass die Prostata nur in 4 von 162 CBCT-Bildern um 0,7 cm vertikal und in 5 Bildern um 0,7 cm longitudinal abwich. Eine laterale Abweichung von 0,3 cm wurde in einem Bild festgestellt. Für die Gesamtgruppe der 30 Patienten überschritt die Abweichung nie 0,7 cm vertikal und 0,3 cm lateral. In 2 Fällen lag die Abweichung in longitudinaler Richtung >0,7 cm.

Schlussfolgerung. Eine Implementierung der adaptiven Prozedur, die auf einer Online-Fehlereliminierung und der anschließenden Reduktion des internen systematischen Fehlers basiert, erlaubt es, die Grenze zwischen klinischem Zielvolumen und Planungszielvolumen um 0,7 cm in der vertikalen, 0,7 cm in der longitudinalen und 0,4 cm in der lateralen Richtung zu verringern.

Schlüsselwörter
Adaptive Radiotherapie · Prostata · Digitale Volumentomographie · Bildgesteuerte Strahlentherapie · Radiotherapeutische Positionierungsfehler

ed in the form of the population cumulative histograms of the changes of the prostate position with respect to the planning isocenter for the 10th and 21st fraction and for each direction separately.

Results

In **Fig. 1, 2 and** **Fig. 3,** the frequency distribution histograms of the values “Δsb_j” are presented. The “Δsb_j” is calculated with formula (1). Data in **Fig. 2 and** **Fig. 3** show significant reposition of the prostate in relation to the pubis symphysis for the vertical and longitudinal directions. In 5 out of 162 fractions prostate, displacement from its initial position was found to be >1.0 cm. Changes in the lateral position was found insignificant (<0.4 cm), which means the setup control based on bony structures, preferably on pubis symphysis, enables using a quite small CTV–PTV margin.

Fig. 4, 5 and **Fig. 6** show the frequency distribution histograms of the values $(\Delta sb_j)_{corr}$, i.e., the displacement of the prostate in relation to the average position of the prostate based on the image data obtained during the first three fractions. The average position is described in

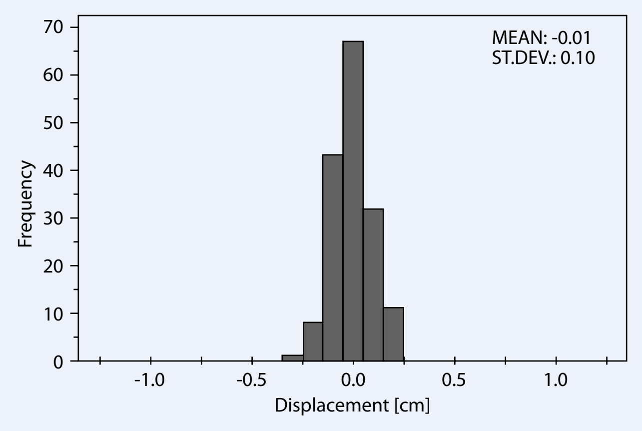

Fig. 1 ▲ Frequency distribution histograms of displacement of the prostate in relation to the pubis symphysis for the lateral direction

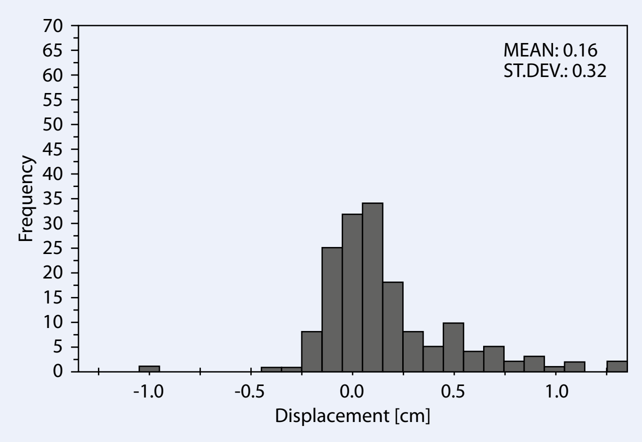

Fig. 2 ▲ Frequency distribution histograms of displacement of the prostate in relation to the pubis symphysis for the vertical direction

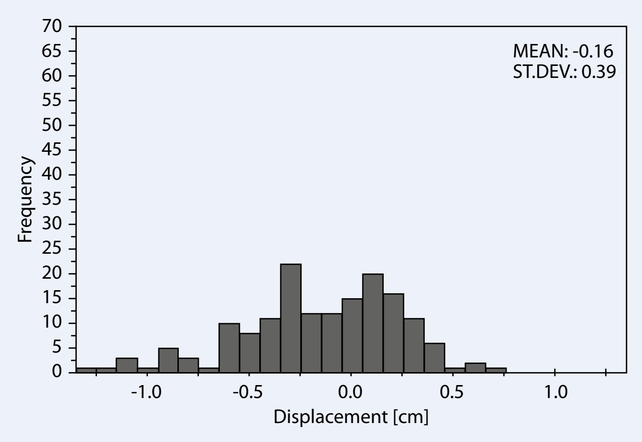

Fig. 3 ▲ Frequency distribution histograms of displacement of the prostate in relation to the pubis symphysis for the longitudinal direction

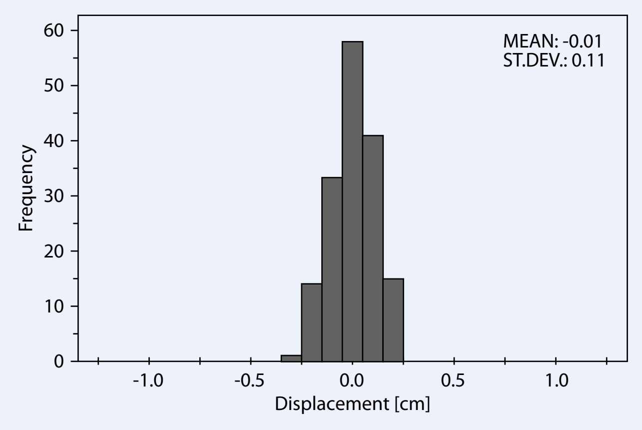

Fig. 4 ▲ Frequency distribution histograms of displacement of the prostate in relation to the average position of the prostate based on the image data obtained during the first three fractions for the lateral direction

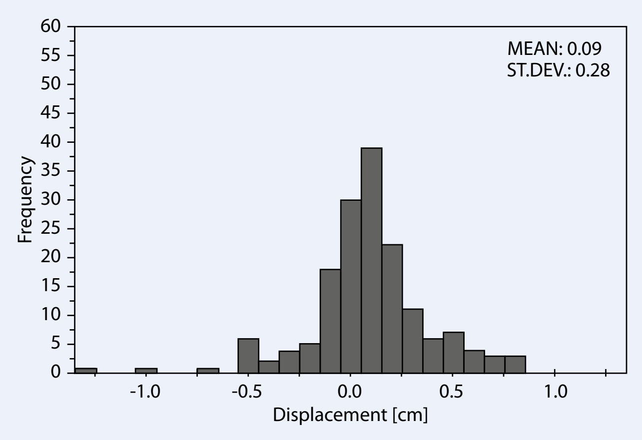

Fig. 5 ▲ Frequency distribution histograms of displacement of the prostate in relation to the average position of the prostate based on the image data obtained during the first three fractions for the vertical direction

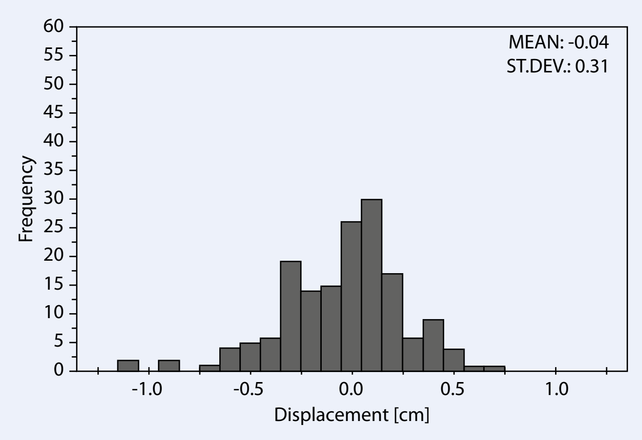

Fig. 6 ▲ Frequency distribution histograms of displacement of the prostate in relation to the average position of the prostate based on the image data obtained during the first three fractions for the longitudinal direction

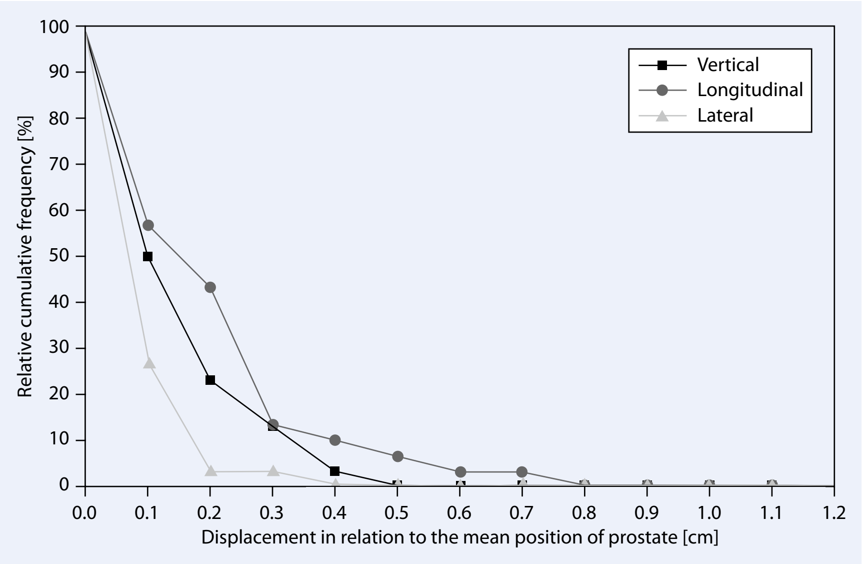

Fig. 7 ▲ Cumulative distribution of displacement of the prostate in relation to the average position of the prostate based on the image data obtained during the first three fractions collected during the 10th fraction

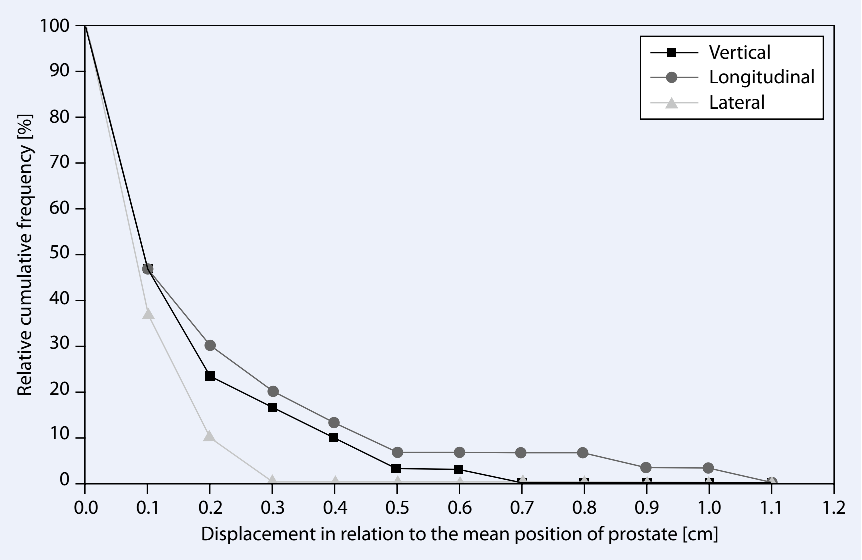

Fig. 8 ▲ Cumulative distribution of displacement of the prostate in relation to the average position of the prostate based on the image data obtained during the first three fractions collected during the 21st fraction

relation to the pubis symphysis for this direction.

For the vertical and longitudinal directions, the distribution of prostate displacement is not symmetrical. In relation to the planning position, the prostate moves more anteriorly and superiorly (mean displacements were 0.16±0.32 cm and −0.16±0.39 cm, respectively). If displacement is measured in relation to the average position the prostate moves symmetrically, the mean displacements were 0.09±0.28 cm for the vertical and 0.04±0.31 cm for the longitudinal direction).

Introducing correction of the isocenter with the average position of the prostate estimated based on the results obtained in the first three fractions enables improvement of the geometric accuracy of irradiation. In the vertical and longitudinal directions, only in 4 and 5 fraction (about 3%) was the displacement greater than 0.7 cm, respectively. For the lateral direction, displacement was found to be 0.3 cm in a single fraction.

In ◘ **Fig. 7 and** ◘ **Fig. 8,** the cumulative distribution of prostate displacement in relation to the average position are shown. Displacement was defined in relation to the pubis symphysis corrected for the average position of the prostate calculated with data obtained in the first three fractions. Data was collected for 30 consecutive patients in the 10th and 21st fraction. Significant results were obtained for all three directions. In 10th fraction displacements were always less than 0.7, 0.8, and 0.3 cm for vertical, longitudinal, and lateral directions. In the 21st fraction, only in two cases were displacements larger than 0.7 cm in the longitudinal direction (in one case 0.8 cm and in the other case 1.0 cm).

Discussion

There are two main sources of treatment position uncertainties; the variation in the daily patient setup and internal organ motion during treatment (interfraction and intrafraction prostate movement). Setup uncertainty influences the accuracy of treatment delivery. Therefore, if any setup correction protocol is used, quite large CTV–PTV margins should be applied. The margin may be reduced slightly if a positioning control procedure is implemented. We have implemented the online method of correction of a patient setup. We noticed that in the lateral direction that the prostate follows the pubis symphysis. Displacement of the prostate in this direction in relation to its planning position was always less than 0.4 cm, and when the adaptive protocol was tested in 60 treatment sessions, only once was the displacement 0.3 cm. In the lateral direction, the internal error was very small. Most important is that the setup error may be diminished considerably with pre-irradiation portal control. It should be emphasized that this result was obtained when the registration was performed on the pubis symphysis, the anatomical structure which is located with proximity to the prostate. Implementation of this procedure enabled decreasing the CTV–PTV margin from 1.0 cm to 0.4 cm only for the lateral direction.

Tab. 1 The mean values calculated with the data obtained for 10 patients: minimum dose ($D_{100\%}$), $D_{98\%}$ and the mean dose to the CTV. The data are for initial plan and plans in which the isocenter was shifted by ±0.9 cm. For the longitudinal (***Long***), and vertical (***Vrt***) directions + means that the isocenter was shifted towards a patient's head and towards treatment table, respectively

	Prostate			**Seminal vesicles**		
	$D_{100\%}$	$D_{98\%}$	**Mean**	$D_{100\%}$	$D_{98\%}$	**Mean**
Initial plan	98.4±0.6	98.9±0.9	100.6±0.3	99.2±0.6	99.5±0.6	100.3±0.5
Long +0.9	93.3±2.2	95.7±1.3	100.2±0.5	94.2±2.4	95.0±2.1	97.6±1.4
Long −0.9	92.6±1.2	95.5±1.1	99.7±0.5	99.3±1.2	99.6±0.9	10.4±0.6
Vrt +0.9	96.9±2.7	99.1±1.0	101.3±0.5	93.2±2.5	96.3±1.8	99.2±1.1
Vrt −0.9	94.8±2.5	97.7±0.5	99.5±0.5	98.9±0.9	99.1±0.9	100.0±0.8

The results show that the prostate does not necessarily follow the pubis symphysis along the vertical and longitudinal directions. The movement of the prostate depends on rectum and bladder filling and, as we suspected, from the tension of sphincters. If the rectum is distended, the prostate is shifted towards the pubis symphysis. Gas in the rectum may move the gland superiorly. Therefore, in case of prostate irradiation, the internal error for the vertical and longitudinal directions are greater, which explains the rationale behind extended CTV–PTV margins. Our results showed that the displacement of the prostate in relation to the pubis symphysis is greater than 0.9 cm for the anterior–posterior and cranial–caudal directions in almost 10% of fractions. Such large displacements were observed when the position of the prostate was measured with respect to its initial position, obtained during the planning CT. If the position of the prostate was not described in relation to its initial position but in relation to its average position and if the set-up error was negligible the number of significant displacements would have to be decreased considerably. Based on these observations, the adaptive protocol was formulated and tested. The protocol was initially tested on 30 patient cases during the process of clinical implementation. For these patients, the additional CBCT scans were acquired in the 10th and 21st fraction in order to verify the validity of the adaptive procedure. For all 30 patients, the prostate displacement with respect to the planning isocenter was less than 0.8, 0.4 cm for the vertical and lateral directions, respectively. For the longitudinal direction, only in two cases were displacements larger than 0.7 cm (in one case 0.8 cm and in the other case 1.0 cm). Therefore, statistically large displacements can be treated as outliers. More data are needed to identify patients for whom these large displacements may occur. However, results obtained for the group of 30 patients has proved validity of implemented adaptive procedure.

The usage of an adaptive protocol is not time consuming. In the first three fractions, when CBCT and soft tissue registration are made, the extra time required at the treatment machine is about 5 min (on average the CBCT takes 1.5 min and registration takes 3.5 min). In all other fractions when two perpendicular portal images, one MV and one kV images, are taken, an extra 2 min are needed. Occasionally, for some patients due to poor CBCT image quality, it is difficult to make registration. If this is the case, the procedure may be much longer and reliability of registration much poorer. However, one should remember that the average position of the prostate is calculated with the data obtained during an off-line procedure where the users are not limited in time.

We were aware that in some cases the displacement may exceed the value of the CTV–PTV margin. In order to evaluate how much the geometrical error deteriorates the dose distribution, we prepared treatment plans with an isocenter that was moved ±0.9 cm from its initial position along the vertical and longitudinal axes. All treatment plans were made with the Eclipse Varian system (version 9). Calculated dose distributions were compared with initial dose distributions in terms of the mean dose, minimum dose, $D_{98\%}$ to the PTV and standard deviation in the CTV. In **Tab. 1**, the results of this experiment are presented. Doses to the prostate and seminal visicles were calculated separately. For each index, the mean value and standard deviation were calculated for 10 patients. The mean value of minimum dose and $D_{98\%}$ were significantly smaller in all plans in which the isocenter was shifted when compared with the initial plans ($p<0.01$) for both the prostate and seminal vesicles. Very small differences were found between the mean dose to the CTV in the initial plan and for plans calculated with 0.9 cm shifts. In the majority of cases, the mean dose in the initial plans was slightly greater than obtained for the shifted plans. Only a few differences are statistically significant. The minimum dose to the CTV was in almost all cases greater than 95% which follows ICRU recommendations for conformal radiotherapy. We may conclude that larger displacements have no influence on the mean dose delivered to the target. This is partly because the dose distributions for the initial plans were very homogenous in the CTV (standard deviation was always below 1.5% of the mean dose). Hence, the mean dose seems to be a very good estimate of the equivalent uniform dose. Therefore, somewhat larger than expected displacements should not influence the probability of tumor control. If a more conservative attitude is preferred, we propose increasing the CTV–PTV margin for the longitudinal direction to 0.9 cm.

Nevertheless, we would like to emphasize the importance of the experience of the user who is responsible for CT registrations and CBCT images. Much easier is to register portal images and digitally reconstructed radiographs. Bones are usually very well visible on portal images. However, in some cases computerized methods of image quality improvements would be beneficial [9]. In the first few months after implementation of the protocol, due to difficulties in image registration, we decided to return to our previous 1.0 cm margin for some patients.

Similar adaptive techniques were described by other authors [13, 14]. In some cases, the pretreatment average CTV was defined based on diagnostic CT data. The treatment plan was prepared to the PTV constructed from the average CTV. In another study, the cone beam CT or CT on rails were performed during the first few fractions and average CTV was defined accordingly. A major disadvantage of the procedures is the necessity of multiple contouring. In the Netherlands Cancer Institute, a set of 5 CT scans was used to calculate the average prostate shape and position [13]. However, this procedure is time consuming and requires highly qualified staff. The advantage, on the other hand, is that contouring allows correction of translations and rotations of a prostate gland. It allows for constructing not only average prostate shape and position but also the average shape and position of the rectum. In our procedure, rotations were not considered. The importance of accounting for rotations depends on the conformity of the dose distributions. In case of very conformal dose distributions, like IMRT, the interfraction rotations which are not accounted for may deteriorate the dose distribution considerably.

Conclusion

A major source of treatment position uncertainty is the variation in the daily patient setup defined with respect to the external coordinate system. Therefore, implementation of the proposed adaptive procedure which on the on-line error elimination followed by a reduction of systematic errors enables the CTV–PTV margin to be reduced to 0.7, 0.7, and 0.4 cm for the vertical, longitudinal, and lateral directions, respectively. The procedure is easy to implement and has a little effect on the treatment time.

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Conflict of interest. On behalf of all authors, the corresponding author states that there are no conflicts of interest.

References

1. Bel A, Herk M van, Bartelink H, Lebesque JV (1993) A verification procedure to improve patient set-up accuracy using portal imaging. Radiother Oncol 29:253–260
2. Beaulieu L, Girouard LM, Aubin S et al (2004) Performing daily prostate targeting with a standard V-EPID and an automated radio-opaque marker detection algorithm. Radiother Oncol 73:61–64
3. Boer HC de, Heijmen BJ (2001) A protocol for the reduction of systematic patient setup errors with minimal portal imaging workload. Int J Radiat Oncol Biol Phys 50:1350–1365
4. Geier M, Astner ST, Duma MN·et al (2012) Dose-escalated simultaneous integrated-boost treatment of prostate cancer patients via helical tomotherapy. Strahlenther Onkol 188:410–416
5. Graf R, Bohmer D, Budach V, Wust P (2010) Residual translational and rotational errors after kV X-ray image-guided corrections of prostate location using implanted fiducials. Strahlenther Onkol 10:544–550
6. Hoogeman MS, Herk M van, Bois J de et al (2005) Strategies to reduce the systematic error due to tumor and rectum motion in radiotherapy of prostate cancer. Radiother Oncol 74:177–185
7. Jaffray D, Siewerdsen JH, Draka DG (2002) Flat-panel cone-beam tomography for image-guided radiation therapy. Int J Radiat Oncol Biol Phys 53:1337–1349
8. Kuban DA, Levy LB, Cheung MR et al (2011) Long-term failure patterns and survival in a randomized dose-escalation trial for prostate cancer: who dies of disease? Int J Radiat Oncol Biol Phys 79:1310–1317
9. Looe HK,·Uphoff Y,·Harder D·et al (2012) Numerical deconvolution to enhance sharpness and contrast of portal images for radiotherapy patient positioning verification. Strahlenther Onkol 188:185–190
10. Martin JM, Bayley A, Bristow R et al (2009) Image guided dose escalated prostate radiotherapy: still room to improve. Radiat Oncol 4:65
11. Ma CM, Paskalev K (2006) In-room CT techniques for image-guided radiation therapy. Med Dosim 31:30–39
12. Morin O, Gillis A, Chen J et al (2006) Megavoltage cone-beam CT: system description and applications. Med Dos 31:51–61
13. Nijkamp J, Pos FJ, Nuver TT et al (2008) Adaptive radiotherapy for prostate cancer using kilovoltage cone-beam computed tomography: first clinical results. Int J Radiat Oncol Biol Phys 70:75–82
14. Nuver TT, Hoogeman MS, Remeijer P et al (2007) An adaptive offline procedure for radiotherapy of prostate cancer. Int J Radiat Oncol Biol Phys 67:1559–1567
15. Rasch C, Steenbakkers R, Van Herk M (2005) Target definition in prostate, head, and neck. Semin Radiat Oncol 15:135–145

Appendix

Let us denote a patient with index n ε {1,2, …, N}, each treatment with CBCT with index m ε {1,2, …, M_N}, each registration result with $(b_{n,m})_k$ and $(s_{n,m})_k$, where “b” indicates the registration based on the pubis symphisis (bones) and “s” indicates the registration on prostate (soft tissue). Subscript “k” denotes one of the three main axes, namely 1: vertical, 2: longitudinal, 3: lateral.

Having in a single fraction the displacements of the pubis symphisis and the prostate in relation to the external system, the prostate position in relation to the pubis symphysis can be calculated in this fraction. For patient number n, fraction m, and direction k we have:

$$\left(\Delta sb_{n,m}\right)_k = \left(s_{n,m}\right)_k - \left(b_{n,m}\right)_k$$

Using this data collected in the first three sessions, the average position of the prostate in relation to the pubis symphysis is calculated:

$$\left\langle \left(\Delta sb_{n}\right)_k \right\rangle_{mean} = \frac{1}{3}\sum_{m=1}^{3}\left[\left(s_{n,m}\right)_k - \left(b_{j,m}\right)_k\right]$$

This vector, describing the average position of the prostate in relation to the pubis symphysis, is part of the input data for the adaptive protocol.