Dose uncertainty due to computed tomography (CT) slice thickness in CT-based high dose rate brachytherapy of the prostate cancer

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(Received 12 February 2004; revised 24 June 2004; accepted for publication 2 July 2004; published 24 August 2004)

In computed tomography (CT)-based high dose rate (HDR) brachytherapy, the uncertainty in the localization of the longitudinal catheter-tip positions due to the discrete CT slice thickness, results in a delivered dose uncertainty. Catheter coordinates were extracted from five patients treated for prostate cancer, and three simulation scenarios were followed to mimic the longitudinal imprecision of the catheter tips, hence the dwell positions. All catheters were displaced (1) forward, (2) backward, or (3) randomly distributed within the space defined by one CT slice thickness, for thicknesses ranging from 2 to 5 mm. Average and standard deviation values of the relative dose variations are reported for the various catheter displacement scenarios. Also, the dose points were grouped according to their relative position in the prostate, inner, peripheral and outer area of prostate and base, median and apex zones, in order to estimate the spatial sensitivity of the dose errors. For scenarios (1) and (2), the dose uncertainties due to the finite slice thickness increase linearly with the slice spacing, from 3% to 8% for the slice thickness values ranging from 2 to 5 mm, respectively. The more realistic scenario (3) yields average errors ranging from 0.7% to 1.7%. The apex and the base show larger dose errors and variability of dose errors than the median of the prostate. No statistical difference was observed among different transversal sections of the prostate. A CT slice thickness of 3 mm appears to be a good compromise showing an acceptable average dose uncertainty of 1%, without unduly increasing the number of slices. © 2004 American Association of Physicists in Medicine. [DOI: 10.1118/1.1785454]

Key words: high dose rate brachytherapy, computed tomography, prostate cancer, dose uncertainty, dose calculation, thickness of CT slice

I. INTRODUCTION

High dose rate (HDR) brachytherapy is a highly accurate and flexible method of delivering radiation dose into the target volume since computerized remote afterloader controls the dose delivery according to the treatment planning using an optimal source dwell time distribution. The passage from conventional radiographic film-based to image-based HDR brachytherapy for prostate cancer has significantly improved the ability to define the targets and organs at risk (OARs) by providing three-dimensional (3D) anatomical information from computed tomography (CT) or magnetic resonance imaging (MRI). Better quality images are obtained, more details of the anatomy can be seen, sharper organ boundaries can be delimited, and suspected gross tumor can be validated using functional imaging with magnetic resonance spectroscopy imaging (MRSI). To fully benefit from these new pieces of information, HDR brachytherapy planning systems are now image-based and inverse planning routines have been developed producing anatomically conformal dose distribution with better sparing of normal tissue.

However, uncertainties inherent to the use of the new imaging modalities may impact on the dose distribution. The transversal coordinates of the catheters can be determined with a high accuracy in CT-based treatment planning. Due to the discrete nature of the spiral CT scan, each slice being reconstructed within the slice thickness by interpolation, the tip of the catheters cannot be identified at a specific slice precisely. The conceivable range of ambiguity in the definition of catheter-tips on a CT slice is from negative to positive CT slice thickness relative to the CT slice of interest. Since all axial coordinates of the source dwell positions are determined by the localization of the tip of each catheter, the longitudinal coordinates of possible dwell positions for the radioactive source have a maximum uncertainty equivalent to the CT slice spacing in the forward (cranial) and backward (caudal) directions. The consecutive dwell positions are usually 2.5 or 5 mm apart, while typical CT slice thickness varies from 2 to 5 mm. For the spiral CT modality [SOMATOM Emotion, SIEMENS] used at our clinic, the reconstruction with a given thickness is carried out after obtaining continuous 3D data according to the organ of interest. Also, 3 mm slice spacing CT with 3 mm collimation and reconstruction thickness, 6 mm/rotation bed speed, and one second gantry rotation period, is preferred for the anatomy delimiting pelvic scan. However, in the CT-based HDR brachytherapy, the choice of the proper
thickness of CT is open to question because the slice thickness is the same order of magnitude as the spacing of the consecutive dwell positions of the sources.

We have investigated the dose variations generated from the uncertainty in the determination of catheter tip positions due to finite slice thickness of CT in the CT-based HDR brachytherapy for the prostate cancer. In this paper, we present the results obtained with a simulation model designed to mimic dose uncertainties in catheter positions obtained from 5 clinical cases.

II. METHODS AND MATERIALS

The study was performed using the data collected from five consecutive patients (later referred to as patients A to E) treated with HDR brachytherapy. For each patient, the catheter positions were extracted from the median slice of the prostate from the CT scan acquired immediately after catheter insertion. The longitudinal length of all catheters and prostates were assumed 4.5 cm. A few hundred dose points were distributed throughout the prostate as well as outside the gland.

The variations of dose to the dose points were calculated from different scenarios simulating longitudinal catheter position uncertainty due to finite CT slice thickness. The number of catheters used varied from 16 to 18. The step size between each source position was set to 5 mm. Dose calculations were done on the 380 dose points generated inside and around the prostate. 10, 25, 50, 75, 90 percentiles of the relative dose variations were calculated. Additionally the dose error dependency was investigated as a function of the distance to a dose point from catheters and of its relative location to the prostate (base, mid, and apex of prostate) along the cranio-caudal direction of catheters. For two out of five prostates, 380 dose points were classified into three sections (central, peripheral, and outer area of prostate) in order to estimate the dose uncertainty for different prostate areas.

Since the end-point of this study was mainly to assess the relative dose variation due to longitudinal catheter position uncertainty, few assumptions were possible to simplify the work. First, the catheters were assumed to be parallel to the z-axis, i.e., cranio-caudal direction, perpendicular to the XY (transversal)-plane with the coordinates determined on the median plane of prostate using a CT-based planning system [Nucletron Brachytherapy Planning System™, PLATO 14.2]. Second, each catheter was assigned ten possible source positions, covering the entire gland from base to apex and a constant dwell time was used for all positions.

A. Dose points

In order to evaluate the dose distribution around the catheters, 380 dose points were generated throughout each prostate volume of the five patients. The points were spread within and outside the prostate to be representative of the different anatomical areas, namely bladder, rectum, urethra, and prostate, and prostate. Twenty dose points on the first transversal plane at Z=0 cm were generated and repeated up to the last (19th) plane at Z=4.5 cm with a 2.5 mm increment. Hence, each group of 19 dose points along the longitudinal direction of a catheter had identical X and Y coordinates with different Z coordinates. Furthermore, to investigate the sensitivity of dose uncertainty effect on the position in the prostate in the transversal plane, these 380 dose points were categorized...
B. Dose calculation

The commercial HDR brachytherapy planning system uses the known dose points and source dwell position coordinates to calculate the dose contribution from a source dwell position \(j\) to a given dose calculation point \(i\). Eq. (1) used for dose calculation is very similar to the point source approximation of TG43 formalism,\(^{18}\) with the exception of the angular dependent anisotropic function.

\[
D_{ij} = S_k \Lambda \Phi_{an}(\theta, r_{ij}) g(r_{ij}) \frac{r_i^2}{r_{ij}^2}, \tag{1}
\]

where \(S_k\) is the air kerma rate, \(\Lambda\) is the dose rate constant defined at the reference point \(r_o\), \(\Phi_{an}(\theta, r_{ij})\) is the anisotropy function, \(g(r_{ij})\) is the radial dose function, \(r_{ij}\) is the distance between the source dwell position \(j\) and the dose calculation point \(i\), \(r_o\) is the reference distance of 1 cm for the definition of dose rate constant, \(\theta\) is the angle with respect to the long axis of the source, the same angle definition as in TG43,\(^{18}\) and \(t_j\) is the source dwell time spent at position \(j\).

C. Catheter displacement simulation

For each catheter configuration corresponding to each of the five patients, three catheter displacement scenarios were simulated: (1)—all catheter tips were displaced forward (cranial direction), (2)—backward (caudal direction), and (3)—all catheters were randomly shifted. The three scenarios are illustrated in Fig. 2. For all scenarios, displacements of 2, 3,
prostate median and from $Z_0$ to 1.25 cm for the apex, from $Z_1$ to 3 cm for the base, median, and prostate. In addition, the dose points were categorized into nine groups (a to i) on the basis of the distance from dose point to the closest catheter: 2 mm $\leq a < 3$ mm, 3 mm $\leq b < 4$ mm, 4 mm $\leq c < 5$ mm, 5 mm $\leq d < 6$ mm, 6 mm $\leq e < 7$ mm, 7 mm $\leq f < 8$ mm, 8 mm $\leq g < 9$ mm, 9 mm $\leq h < 10$ mm, and i $\geq 10$ mm. Finally, for patient A and D, 380 dose points were classified into three regions on the transversal plane as shown in Fig. 1: Outside, peripheral and central prostate.

D. Relative dose error

The relative dose error expressed in percent at a given dose point was calculated using Eq. (2), for each catheter displacement scenarios.

$$\text{Error(\%)} = \frac{|D_{\text{after}} - D_{\text{before}}|}{D_{\text{before}}} \times 100$$

$$= \frac{|(D'_{\text{after}} \times t) - (D'_{\text{before}} \times t)|}{D'_{\text{before}} \times t} \times 100$$

$$= \frac{|D'_{\text{after}} - D'_{\text{before}}|}{D'_{\text{before}}} \times 100,$$

where $D_{\text{before}}$ is the dose before displacement, $D_{\text{after}}$ is the dose after displacement, $D'_{\text{before}}$ is the dose rate before displacement, $D'_{\text{after}}$ is the dose rate after displacement, and $t$ is the constant dwell time for all available source positions.

The dose at the dose points were further categorized to study the spatial dependency of the dose uncertainty caused by catheter displacement. First, the dose values from the dose points were gathered in three groups (base, median, and apex) according to their cranio-caudal coordinate: From $Z = 0$ to 1.25 cm for the apex, from $Z = 1.5$ to 3 cm for the prostate median and from $Z = 3.25$ to 4.5 cm for the base of prostate. In addition, the dose points were categorized to the worst case for the positioning of catheter tips where all catheter tips would be misidentified in the same direction. The third scenario describes a more realistic situation, where each tip of catheters was randomly shifted over the range of negative (caudal direction) to positive (cranial direction) CT slice thickness relative to a reference CT slice. The third scenario was repeated a 1000 times and the average displacement value for each catheter was computed.

III. RESULTS

In Fig. 3, the relative dose errors for each catheter displacement scenarios (forward, backward, and random shifts) are presented as a function of the CT slice thickness, equivalent to the tip position uncertainty. Each parallel bar indicates 10, 25, 50, 75, and 90 percentiles from the lowest to the highest. The mean (standard deviation) for dose error in a random shifting simulation performed one thousand times are 0.7% (0.7%) for 2 mm CT scan, 1.1% (1.1%) for 3 mm CT scan, 1.4% (1.4%) for 4 mm CT scan, and 1.7% (1.6%) for 5 mm CT scan, respectively. Incidentally, extreme simulations such as backward and forward shifting have almost fivefold larger errors than the random shifting for any thickness scan. Based on the numerical values, we can assert that the wider thickness of the CT modality results in the larger dose error and variability of dose uncertainty. The dose error and variability of dose uncertainty increase linearly, not exponentially, as the thickness of CT scan increases.
variability of dose errors than the middle of the prostate. Because of the symmetry, the base and apex of prostate have the same dose error. The mean (standard deviation) of the dose error for the 3 mm scan is 1.4% (1.1%) at the apex, 1.4% (1.1%) at the base, and 0.5% (0.6%) in the middle portion of the prostate. Figure 5 displays that there is little difference in dose error on the transversal regions of prostate. The mean (standard deviation) of the dose errors for the 3 mm scan is 1.0% (0.9%) for the central zone, 1.2% (1.1%) for the peripheral zone, and 0.9% (0.8%) for the outside zone of prostate. Figure 6 shows the impact on the dose error of the nearest distance from catheters to a dose point. For the 3 mm CT scan case, the dose points within 5–10 mm from sources (from group d to h), have a similar average dose error of about 0.9%, even if the distance increases. Farther beyond 10 mm, the dose error is negligible with an average of 0.6% or so. For the dose points within 2 to 5 mm of a source, however, the dose error decreases approximately according to the inverse square law as the distance increases from an average 4.4% for group a, via 2.1% for group b, to 1.1% for group e.

### IV. DISCUSSION AND CONCLUSION

The catheter coordinates were extracted from five patients treated for prostate cancer, and three simulation scenarios were followed to mimic the longitudinal imprecision of the catheter tips, hence the dwell positions, either with all catheters displaced forward, backward or randomly distributed within the space defined by one CT slice thickness, for thicknesses ranging from 2 to 5 mm. It was found that the relative dose error due to the inaccuracy of determining the catheter tip position from a CT scan increases with the CT slice thickness. For 3 mm CT scan, the average dose error in the worst case was 5%, while the average dose error in a realistic simulation was 1% with a 90 percentile value below 3.

As for all patient calculations, little difference on dose errors was observed between a single random shifting and a thousand times repeated random shifting case since the number of catheters used for each patient, 16 or 18, is large enough to demonstrate the random characteristic of random numbers. Single random shifting simulation has slightly smaller dose error and more variability of dose error as seen in Fig. 3. Moreover, for the two extreme simulations such as all forward or backward displacement, the statistical values are the same since the magnitude of shifting is equal even if the directions of displacement are opposite to each other.

Although the average dose error for the current 3 mm CT scan is around 1%, more attention should be paid to the apex and base than the middle of prostate according to findings shown in Fig. 4. However, the dose error 90 percentiles for both ends are still below 3%.

The dose error showed no variation for any transversal region of prostate. The difference among the regional dose uncertainties depends on which domain includes the dose calculation point sensitive to dose uncertainty. For patient A, the dose point (3 mm nearest distance from a source) identified as solid arrow in Fig. 1(a) and the dose point (3.3 mm nearest distance from a source) pointed out by dot arrow in Fig. 1(a) produce significant dose error degrading the global dose error statistically. Accordingly, we can anticipate larger errors in the central and peripheral zones than outside of the prostate. For patient D, the dose point (3 mm nearest distance from a source) indicated by a solid arrow in Fig. 1(b) dominates the dose error statistics. Thus the dose error in the peripheral zone of prostate is greater than that in the other zones. The dose uncertainty dependence upon the proximal distance from catheters to a dose point directly follows the feature of inverse square law in brachytherapy dose calcula-
tion, in particular, up to 5 mm of the shortest distance from a source as shown in Fig. 6.

There is a trade-off between the treatment planning time and the number of CT slices employed in HDR brachytherapy treatment planning. If we make use of the fine thickness CT scan in order to minimize the dose error induced by uncertainty of CT reconstruction, additional time and effort from a radiation oncologist who contours the target volume of tumor are needed to do the treatment planning. For instance, the change from 3 mm-CT scan to 2 mm-CT scan for the longitudinal 3 cm prostate organ theoretically increases the number of CT slices by 50%, from 10 slices to 15 slices, making an improvement of only 0.4% average dose error reduction from 1.1% to 0.7% in realistic simulation case. Instead of the film based HDR brachytherapy, the dose uncertainty on account of finite thickness of CT slice can be compensated with the introduction of better anatomical definition of OARs along with target volume obtained from CT information into CT-based inverse HDR planning.3–6

In summary, a CT slice thickness of 3 mm appears to be a good compromise showing an acceptable average dose uncertainty of 1%, without unduly increasing the number of slices.

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