Clinical implementation of a digital tomosynthesis-based seed reconstruction algorithm for intraoperative postimplant dose evaluation in low dose rate prostate brachytherapy

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(Received 24 February 2009; revised 24 August 2009; accepted for publication 19 September 2009; published 14 October 2009)

Purpose: The low dose rate brachytherapy procedure would benefit from an intraoperative postimplant dosimetry verification technique to identify possible suboptimal dose coverage and suggest a potential reimplantation. The main objective of this project is to develop an efficient, operator-free, intraoperative seed detection technique using the imaging modalities available in a low dose rate brachytherapy treatment room.

Methods: This intraoperative detection allows a complete dosimetry calculation that can be performed right after an I-125 prostate seed implantation, while the patient is still under anesthesia. To accomplish this, a digital tomosynthesis-based algorithm was developed. This automatic filtered reconstruction of the 3D volume requires seven projections acquired over a total angle of 60° with an isocentric imaging system.

Results: A phantom study was performed to validate the technique that was used in a retrospective clinical study involving 23 patients. In the patient study, the automatic tomosynthesis-based reconstruction yielded seed detection rates of 96.7% and 2.6% false positives. The seed localization error obtained with a phantom study is 0.4 ± 0.4 mm. The average time needed for reconstruction is below 1 min. The reconstruction algorithm also provides the seed orientation with an uncertainty of 10° ± 8°. The seed detection algorithm presented here is reliable and was efficiently used in the clinic.

Conclusions: When combined with an appropriate coregistration technique to identify the organs in the seed coordinate system, this algorithm will offer new possibilities for a next generation of clinical brachytherapy systems. © 2009 American Association of Physicists in Medicine. [DOI: 10.1118/1.3245888]

Key words: low dose rate brachytherapy, postimplant dosimetry, seed reconstruction, digital tomosynthesis
I. INTRODUCTION

Recent advances in imaging, delivery technology, and treatment planning led to a renewed interest in permanent seed implants for prostate brachytherapy. Since the early 1990s, the number of prostate cancer cases treated with low dose rate brachytherapy has increased very rapidly.1-3 Nowadays, it is estimated that 30%–40% of all eligible patients with prostate cancer receive low dose rate brachytherapy as part of their treatment in the United States.4

The implantation procedure involves transrectal ultrasound guidance and transperineal seed insertion to the prostate. However, the actual positions where the seeds are deposited are inevitably different from the planned positions.5-7 The main factors explaining this discrepancy are implantation of needles leading to prostate motion during the treatment, seed displacement along the channel created by the needles, uncertainty due to the manual placement of needles, modification of the shape and size of the gland due to edema, and seed migration inside or even outside the prostate. The combined effects of these factors have a major impact on the dosimetry.8 With a low energy isotope such as I-125, the dose distribution is highly dependent on the precise location of the seeds in relation to the target.

The difference between the planned implant and the real implanted seed distributions raises the need for a postimplant dosimetric verification. The American Brachytherapy Society recommends a CT-based dose evaluation at a consistent postoperative interval.9 There is no consensus on the optimal time interval between the implantation and the postimplant dose evaluation, but the 1 month interval applied at Centre hospitalier de l’Université de Montréal (CHUM) gives the most reproducible dosimetric results.10 The use of CT to obtain precise dosimetric information is questionable because of the difficulty in properly delineating the prostate.11 With increasing evidence of treatment effectiveness being correlated with postimplant dosimetry,12,13 it is clearly desirable to assess intraoperatively the quality of the implant and to correct the suboptimal results, if needed. To accomplish this, one needs to reconstruct the 3D position of each seed and coregister with the organ contours.

Such an intraoperative dosimetric study has to be done with minimum additional time to the procedure and with the imaging modalities commonly available in the brachytherapy operating room (OR). Unless the scanner is in the brachytherapy suite, this excludes the use of a CT scan, adequate to image the seeds, or the use of magnetic resonance imaging (MRI), the gold standard to delineate the prostate. Both of these imaging modalities have limited availability and would require the patient to be moved from the OR to the imaging room and then possibly back to the OR. In addition, both CT and MRI have some issues related to seed detection in clinical settings. CT has problems detecting automatically small seeds because of the large slice thickness, which can result in localization errors. In MRI, seeds are imaged as low signal regions that can be difficult to distinguish from other low intensity structures such as vessels or calcifications.14,15

Transrectal ultrasound (TRUS) imaging, used to guide the implant procedure, would be an obvious technique to identify the seed positions. However, the poor imaging contrast of seeds is very limiting and only a subset of the implanted seeds can be identified.16,17 Furthermore, spacers or calcifications can be misinterpreted as radioactive sources. On the other hand, plane radiography, commonly available in the treatment room, provides very good seed visibility. Plane radiography can take the form of radiographic film, fluoroscopy, or digital radiograph. Several methods have been developed to locate the 3D seed positions from two or more x-ray projections acquired isocentrically from different orientations. Most of them rely on a two-step process: (1) Localizing the seed positions on each radiograph and (2) matching each seed from one projection to the others. When the seeds are localized and matched, reconstructing the 3D positions is trivial.

The early attempts toward seed reconstruction were performed with the use of two films,18 but this technique raised the problem of matching ambiguity. In fact, when two seeds and two x-ray source positions are located on the same plane, there are two sets of possibly valid reconstructed 3D positions. The use of a third or a fourth projection strongly reduces the risk of false positive detections, but the drawback is the mathematical complexity of the matching process. Several methods have been developed to solve this problem,19-23 but they are limited by the requirement that all seeds must be accurately identified in each of the 2D projection data. Although certain methods can handle incomplete seed identification on the projections,23-26 some seeds can still be missed if they are not detected on a minimum of two projections.

The localization of the seeds on the radiograph, either manually or automatically, can be a difficult task due to the presence of overlapping seeds.25 Automatic seed identification techniques can handle seed localization in small clusters of two or three overlapping seeds29 but fail to correctly distinguish seeds in large clusters. In some patient implant projections at CHUM, there can be over ten seeds overlapping in a single cluster.

In this paper, an in-house digital tomosynthesis (DTS)-based seed position reconstruction method is presented. A first application of the method was tested with a validation study on a prostate phantom. Once the technique was validated, it was used for 23 patients for a preliminary study. The results are presented for both applications, i.e., the validation test and the clinical study.

II. MATERIAL AND METHODS

To get around the problem related to seed identification and matching, a DTS-based method was developed. This method does not require exact seed segmentation on 2D projections. DTS refers to a limited angle 3D image reconstruction using a small number of projections of an object using conventional x-ray systems. Some reconstruction algorithms based on DTS have been applied to seed detection,30,31 but results were based either on simulations or phantom study. Consequently, these methods did not take into account issues...
related to clinical implants such as seed clustering or internal motion of the prostate. Our DTS method can reconstruct the 3D seed-only volume of a patient implant, i.e., a volume including nothing but the seeds, from a limited set of projections. Hence, the seed positions can be extracted from that reconstructed volume. DTS seed reconstruction offers several advantages over the three-film approach:

1. DTS reconstruction does not require exact segmentation and localization of the seeds in the projections, which eliminates the need for manual correction on the projections.
2. Using several projections eliminates matching ambiguities.
3. Computational complexity is greatly reduced and is independent of the number of implanted seeds, thus the reconstruction can be done very quickly.

The low dose rate brachytherapy suite at the Hôpital Notre-Dame du CHUM is equipped with an isocentric imager, the Simulix Evolution™ (Nucletron, Veenendaal, The Netherlands). This latest generation simulator incorporates a flat panel detector and the option of cone beam CT. Its 41 ×1024 amorphous silicon detector with a 1024 ×1024 pixel matrix provides a resolution of 0.4 mm/pixel. This relatively high spatial resolution combined with good seed contrast makes it a very good device to image brachytherapy seeds. This device was used for all imaging phases of the project.

II.A. Validation test with phantom

A tissue-equivalent prostate phantom (model 053, Computerized Imaging Reference Systems, Norfolk, VA) was used to validate the DTS-based seed detection algorithm. The phantom includes several organs: Prostate, seminal vesicles, rectal wall, and urethra. The phantom is embedded in a 11.5×7.0×9.5 cm³ clear acrylic box and the different organs are made of water-equivalent gel, Blue Zerdine™ and ZerdineTM. The phantom was implanted with 45 nonradioactive seeds (4.5 mm long×0.4 mm radius, Nucletron dummy seeds) under TRUS guidance for needle placement through a brachytherapy template. The planned seed positions were generated by the SPOT PRO™ treatment planning system (Nucletron) to reproduce a typical clinical treatment plan.

To evaluate the positioning uncertainty, the implanted phantom was imaged under a CT scan with slices of 0.4 mm to reach the best achievable resolution. The seed centroids were extracted from the CT volume with the SPOT PRO™ seed localization utility. To coregister the CT-based seed positions and the DTS-based seed positions, five fiducial markers, visible on CT and on the simulator images, were placed on the surface of the phantom.

II.B. Patient study

The clinical procedure is performed at the CHUM. The entire operation, from anesthesia to the end of the implantation, takes an average of 90–120 min. During the implantation, the patient is under anesthesia in lithotomy position. The implanted iodine seed model is the selectSeedTM (Nucletron, The Netherlands). With a half-life of 59.4 days, approximately 90% of the dose is delivered over the first 6 month interval. The whole clinical procedure is performed using the Nucletron FIRST system.

The phantom study is a first step toward the validation of the algorithm. However, the procedure needs to be robust in a clinical setting involving patient data. The main pitfall of the phantom study is that it neglects the prostate internal motion, which is usually quite small but not always negligible. Thus, the DTS algorithm was used in a clinical setting after validation tests and the quality of the automated reconstruction output was evaluated for 23 patients implanted at the CHUM. The average number of implanted loose seeds was 51 per patient (36–69).

II.C. DTS-based reconstruction algorithm

The coordinate system is presented in Fig. 1. The center of the global coordinate system (x,y,z) is the isocenter of the simulator and the center of the projection coordinates (u,v) is the center of the detector. The source-to-axis distance is fixed at 100 cm, while the source-to-detector distance is variable. Right after the implantation, the patient lies in the x-y plane with his head pointing toward the y axis (see Fig. 1). The patient is imaged in this setup, while he is still under anesthesia, right after the prostate implantation. The DTS-based reconstruction algorithm requires seven planar images acquired automatically at selected gantry angles: −30°, −20°, −10°, 0°, 10°, 20°, and 30°. To avoid localization imprecision caused by small parallaxes in 3D seed reconstruction, the gantry angles between each projection are chosen as large as possible.32 On the other hand, the choice of gantry angle is limited by the body anatomy because lateral images suffer from poor seed contrast due to bony structures and patient thickness. The best quality images are obtained with gantry angle between −35° and 35°.29 In tomosynthesis, the reconstruction quality is generally better when a larger number of images is used. However, seven images are sufficient to provide reasonable reconstruction quality with-
out adding too much time to the procedure and unnecessary radiation dose to the patient. The image acquisition step is completed in an average of 5 min.

**II.C.1. 2D image processing**

All digital image processing steps were coded in MATLAB® (version 7.4.2, MathWorks, Inc., Natick, MA) using functions included in the image processing toolbox. The first step toward seed position reconstruction is to process each projection to automatically generate seed-only images. The different steps for the 2D processing are presented in Figs. 2(a)–2(d). A typical raw image of a patient provided by the Simulix imager is presented in Fig. 2(a).

A simple thresholding of the cropped image is not sufficient to properly segment the seeds because some bone regions can have either smaller or larger intensity than the seeds. Thus, some preliminary steps are implemented to attenuate the background and therefore to increase seed contrast. To limit the influence of the structure thicknesses on the resulting signal intensity, the value of each pixel is converted into a logarithmic fashion so that the resulting intensity represents a simple linear sum of attenuation coefficients of the seeds and the body for all pixels. An example of a normalized image is presented in Fig. 2(b).

Before proceeding to the automatic thresholding of the normalized image, the background of the radiograph needs to be as uniform as possible. However, the nonuniformity of patient thickness and the presence of bony structures lead to a nonuniform background, which is problematic for appropriate seed extraction. To solve this problem, morphological closing is used to attenuate the background on the image. A Wiener-filtering step is also applied to the image. The goal of the 2D Wiener filter is to filter out noise corrupting the signal. This filter is based on a statistical approach using the information given in the neighborhood of each pixel. The result of this background removal step is presented in Fig. 2(c).

The intensity of the seed and of the background can vary significantly from one patient to another and from different projection angles. Thus, the intensity level of the threshold cannot be a fixed value to separate the seeds from other objects. A manual selection of this threshold is undesirable because the seed reconstruction process needs to be as automated as possible. This problem can be solved using the Otsu algorithm, which uses the information in the histogram to separate the pixels into two different classes: Background and foreground (seeds). The optimal threshold will separate the pixels into two classes so that the combined within-class variance is minimized. This algorithm assumes a uniform illumination, which emphasizes the importance of removing the background. Figure 2(d) presents the result of the seed binarization where the selected threshold clearly segments the seeds and rejects the background. A simple connected-component analysis is performed on the binary image to remove very small structures and a geometrical filter is applied to the image so that more importance is given to pixels that are located at the center of the segmented areas relative to the peripheral pixels.

**II.C.2. 3D reconstruction**

Tomosynthesis can be defined as the creation of the 3D image of an object by digital processing of multiple x-ray projections acquired over a limited angle of view. The main input to our DTS-based 3D reconstruction algorithm is seven filtered seed-only images acquired at seven different angles. The objective is to first reconstruct a seed-only volume, i.e., a binary volume including exclusively brachytherapy seeds. Then, the seed positions are localized with a 3D connected-component analysis.

The seed-only volume is obtained by a combination of backprojection and binarization. To correctly reconstruct and detect objects as small as brachytherapy seeds, the volume is reconstructed with a resolution of $0.25 \times 0.25 \times 0.25$ mm$^3$. The resolution of the flat panel detector is 0.4 mm and the magnification factor of the seeds is approximately 3/2, depending on the specific detector position. For each voxel located at $(x, y, z)$, the corresponding coordinates $(u, v)$ can be found by projecting the 3D point on the 2D detector from the x-ray source point of view. Likewise, the 3D seed-only volume is obtained by a superposition of the back-projection of the seven seed-only planar images. Figure 3(a) shows one axial slice of the reconstructed volume for a patient implant. In this figure, seeds can be located in the regions of high intensity. The seed regions can simply be extracted with the application of a threshold to generate a seed-only binary volume. An example of such a volume is presented in Fig. 3(b).

From the tomosynthesis reconstruction properties, the resolution is much better in the $x$-$y$ plane than in the vertical dimension ($z$) because of the limited image acquisition.
angle.\textsuperscript{32} When some implanted seeds are very near in the $x$-$y$ plane or relatively close in the $z$ direction, they aggregate in large clusters of connected voxels into the seed-only volume. This clustering effect is very likely when using loose seeds. From the analysis of ten patient implants, we evaluated that approximately 40\% of the seeds were included in such an aggregate composed of two (28\%), three (10\%), or four (2\%) seeds. To determine the exact position of each seed, a 3D connected-component analysis is then performed. The main challenge is to identify the seed centroids in the clusters of connected voxels including more than one seed. To achieve this, a statistical classifier based on the cluster’s geometrical properties is generated to determine the number of seeds in each cluster. The number of implanted seeds is used as an upper limit to the total number of detected seeds, but not as an aim since the number of seeds in the prostate may be inferior to the number of implanted seeds. In fact, an important issue in seed motion inside the prostate is seed migration to the lung through embolization.\textsuperscript{37-39}

Clusters of connected voxels are defined with 26-connectivity, i.e., any two neighboring binarized voxels are considered as part of the same cluster. A first analysis is performed to discard all the clusters with a volume smaller than 30\% of a regular seed volume, which are considered as reconstruction artifacts. Then, each remaining cluster is characterized based on its geometrical characteristics. An ellipsoid fitting is performed on each cluster\textsuperscript{40} to extract the length of the major axis $a$, intermediate axis $b$ and minor axis $c$, and the orientation of the major axis. A statistical classifier based on the following identification function $ID$,

$$ID = \frac{a}{\langle a \rangle} + \frac{b}{\langle b \rangle} + \frac{c}{\langle c \rangle} + \frac{\text{volume}}{\langle \text{volume} \rangle},$$

where $\langle a \rangle$, $\langle b \rangle$, $\langle c \rangle$, and $\langle \text{volume} \rangle$ are the average geometrical properties for a single seed, is used to evaluate the number of seeds per cluster. Obviously, the larger the value of the ID function, the larger the number of seeds in the cluster. To correlate the ID values with the number of seeds per cluster, 177 clusters in 12 patients were analyzed.

The next step is to localize the centroid of each seed in each cluster. This is done differently, depending on the number of seeds in the analyzed cluster. For clusters including only one seed, the seed centroid is simply the center of mass of the cluster of connected voxels. For clusters including two seeds, the two seeds are positioned along the major axis, one located at $-2a/3$ and the other at $2a/3$ from the cluster centroid. For clusters including more than two seeds, the grid of connected voxels is resampled on a $3 \times 3 \times 3$ grid and the seed centroids are defined as the center of the resampled voxels with the highest intensity. When a cluster has more than one seed, the seed positioning is done fairly approximately. According to our data, this approximate seed placement has a significant influence on the distribution of hot spots but has a limited impact on the presence of cold spots. Since the final aim of intraoperative dosimetry is to localize cold spots, those approximations are reasonable as confirmed by the following phantom validation and patient studies.

A graphical user interface (GUI) has been developed with MATLAB\textsuperscript{TM} to provide visual feedback of all the steps leading to intraoperative dosimetry evaluation. The GUI is composed of three modules corresponding to the three main steps of the postimplant intraoperative dosimetry assessment: Input information and image processing, seed positioning display and correction, and intraoperative dosimetry information. All potential reconstruction errors can be easily corrected manually using this user-friendly GUI. The GUI also allows the user to extract the seed orientation.

III. RESULTS

III.A. Validation test with phantom

The phantom study is the best way to test the result of the DTS-based algorithm since the calculated seed position can be compared to highly precise reference seed positions. The phantom study shows very good agreement between the tomosynthesis-based seed positions and the CT reference. From a one to one correspondence between the two sets of positions, the average localization error was evaluated at $0.4 \pm 0.4$ mm, which is of the same magnitude as the inherent reference positioning uncertainty. The localization error is reported in the histogram of Fig. 4 where one can see that 96\% of the reconstructed seed positions are within 1 mm from the CT standard position. To evaluate the dosimetric impact of the positioning uncertainty, the dosimetry calculation generated with CT seed positions is compared to the dosimetry evaluation generated with DTS-based seed positions on the user-defined prostate volume. From the results of
The quality of the automated reconstruction output was evaluated for 23 patients implanted at the Hôpital Notre-Dame du CHUM. An example of reconstructed seed positions projected on the simulator images is presented in Figs. 5(a) and 5(b) where two projections are shown (respectively, \( \theta = -30^\circ \) and \( \theta = 30^\circ \)) along with the automatically identified seed positions (white crosses). This is a consequence of the lower resolution in the \( z \) direction, which is perceivable in oblique radiograph as Figs. 5(a) and 5(b).

From the analysis of the 23 patients, the automatic seed reconstruction algorithm has shown to accurately retrieve 96.7 \( \pm \) 2.2\% of the implanted seeds. Thus, 3.3 \( \pm \) 2.2\% of the implanted seeds are undetected, while 2.6 \( \pm \) 2.1\% of the total number of seeds are falsely detected (false positive). Most of the reconstruction flaws come from errors of the statistical classifier that over- or underestimates the number of seeds in the individual clusters. The seed reconstruction errors generally happen in regions of high seed density. Indeed, these high seed density regions are subject to shadowing artifacts, especially in the anterior-posterior direction because of the limited tomosynthesis angle of acquisition. These artifacts can either result in distorted seed geometry or large clusters of connected seeds.

All the reconstruction errors can be corrected manually using the GUI. Figure 6(a) presents the worst case for which four seed regions, circled on the figure, were wrongly managed by the algorithm and corrected manually [see Fig. 6(b)]. Since the method would be much faster and more effective without the need for human intervention, the dosimetry effect of the reconstruction errors was assessed for all patients. To do so, the reconstruction errors were manually corrected using the GUI tools. The dosimetry of the automatic and corrected reconstructions was compared.

For this test, prostate contours were taken from the planning TRUS and coregistered with the reconstructed seed positions using planned seed positions as reference points. This approximate prostate contour is not optimal and we are working on a better coregistration method to get images of organ contours postoperatively. For the purpose of the cur-

![Fig. 4. Histogram of seed position errors for the phantom study.](image)

![Fig. 5. Example of image projections with automatically detected seed positions (white crosses).](image)

### TABLE I. Influence on dosimetry of the seed positioning uncertainty for the phantom study.

<table>
<thead>
<tr>
<th></th>
<th>( D_{90} ) (Gy)</th>
<th>( D_{90} ) (Gy)</th>
<th>( D_{100} ) (Gy)</th>
<th>( V_{80} ) (%)</th>
<th>( D_{90} ) (Gy)</th>
<th>( V_{100} ) (%)</th>
<th>( V_{150} ) (%)</th>
<th>( V_{200} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT-based</td>
<td>151.5</td>
<td>118.9</td>
<td>61.6</td>
<td>91.1</td>
<td>86.8</td>
<td>82.6</td>
<td>48.8</td>
<td>21.9</td>
</tr>
<tr>
<td>DTS-based</td>
<td>151.6</td>
<td>119.5</td>
<td>61.9</td>
<td>91.2</td>
<td>86.9</td>
<td>82.5</td>
<td>48.8</td>
<td>22.3</td>
</tr>
<tr>
<td>Rel. difference (%)</td>
<td>0.1</td>
<td>0.5</td>
<td>0.4</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>
rent test, however, this registration technique was considered adequate. The results, summarized in Table II in terms of the relative mean difference and standard deviation, show little difference for the two main parameters $D_{90}$ and $V_{100}$. For the worst of the patients analyzed [see Fig. 6(a)], the differences in $D_{90}$ and $V_{100}$ are, respectively, 3% and 1.4%. The dosimetry parameters that are the most influenced by the reconstruction flaws are the $V_{150}$ and $V_{200}$, which correspond to the volume of the prostate receiving very high dose. The reconstruction errors mostly influence the hot spot distribution, while it has little impact on the presence of cold spots and on the average dose distribution. The analysis of the isodoses for several patient implants presents significant deviations between the automatic and the corrected dose distribution mostly for 200+ Gy isodose lines.

The availability of the precise reconstructed seed positions can be used to generate and display the isodose distributions in axial plane or in a 3D view. Even if the DTS-based seed positions are not yet coregistered with the prostate and OAR contours, the dose coverage can still be evaluated in a qualitative manner. Based on the seed positioning, the dose coverage of the apex, midgland, and base can be displayed and inadequate dose coverage—such as gaps, islands, or holes—can be identified. Figures 7(a) and 7(b) present a patient case where a suboptimal coverage is apparent even in the absence of the anatomical information. Indeed, the upper part of the midgland region in Fig. 7(b) is clearly underdosed, as shown by the 100% isodose gap (light line). In addition, cold spots can be suspected in the upper-center and lower-center parts of the base [Fig. 7(a)]. However, the prostate contours would be necessary, in this case, to draw a clear conclusion. Despite the fact that the clinical team can have an approximate idea of the quality of the implant solely based on the seed positioning, the availability of the prostate boundary is crucial to accurately compute relevant dosimetry parameters. The development and validation of a coregistration technique between seed positions and prostate contour—the next logical step in this project—is already underway.

### III.C. Computation time

To implement an intraoperative seed detection method in the clinic, the computation time needs to be as short as possible. The DTS-based algorithm has the advantage over the three-film technique that it is less computationally intensive. In the three-film method, the computation time increases very steeply with the number of implanted seeds, while for the DTS-based method, the computation time is simply proportional to the size of the reconstructed volume. The original version of the algorithm, entirely coded in MATLAB, was relatively slow taking approximately 4 min on a 1.8 GHz Pentium dual PC to reconstruct and display the seed positions from the preprocessed images. Two sections of the MAT-

![Fig. 6. Example of manually corrected errors on an axial plane. (a) Original automatically reconstructed seed positions with the four falsely managed seed regions. (b) Manually corrected seed positions.](image)

![Fig. 7. Example of a dose distribution based on postimplant reconstructed seed positions. (a) Base of the prostate. (b) Middle of the prostate.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$D_{80}$</th>
<th>$D_{90}$</th>
<th>$D_{100}$</th>
<th>$V_{80}$</th>
<th>$D_{90}$</th>
<th>$V_{100}$</th>
<th>$V_{150}$</th>
<th>$V_{200}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rel. difference (%)</td>
<td>1.4 ± 1.1</td>
<td>1.8 ± 0.7</td>
<td>1.8 ± 1.1</td>
<td>0.5 ± 0.3</td>
<td>0.6 ± 0.3</td>
<td>0.8 ± 0.4</td>
<td>3.5 ± 3.8</td>
<td>4.2 ± 5.0</td>
</tr>
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Furthermore, the average impact of the seed detection errors could achieve this rate for 21 out of the 23 clinical cases.

There is a real need for standardization of the postimplant procedure. The postimplant dosimetry analysis provides very useful information to identify possible suboptimal dose coverage, to help the physician improving his implant technique, and to correlate the clinical outcomes with the quality of the implant. A quick intraoperative dose evaluation can be used to reimplant additional seeds if isodose holes or islands are located within the seed cluster.

Based on simulation studies, it has been shown that 95% or more seeds need to be localized in order to obtain a $D_{90}$ within 5% of the real value. Our seed detection method could achieve this rate for 21 out of the 23 clinical cases. Furthermore, the average impact of the seed detection errors on $D_{90}$ and $V_{100}$ were shown to be, respectively, 2% and 1%. These results demonstrate that our automatic seed reconstruction method is suitable for accurate dose evaluation.

Precautions need to be taken concerning internal prostate motion during the 5 min imaging sequence. Small prostate motion can affect the accuracy of the DTS-based volume reconstruction. However, our algorithm has shown clinically that it could handle normal prostate motion and correctly retrieve the seed positions. On the other hand, large prostate motion cannot be handled properly by our reconstruction method. One of the patients was discarded from our clinical study because of abnormal prostate motion during the imaging sequence. Prostate motion raises the need for an automated image acquisition system which could bring down the imaging sequence from a few minutes to a few seconds.

Neglecting edema can be a severe pitfall in the analysis of the postimplant intraoperative dosimetric results because it occurs during the course of the operation. The magnitude of the edema can be predicted on day 0, but its duration is impossible to estimate. One of the main challenges to evaluate the quality of an implant in low dose rate prostate brachytherapy is that the dose is inherently deposited dynamically over time. All the methods to assess the dosimetry only provide a snapshot of the dose coverage at a specific moment in time. However, the implant is not static over time because the prostate size and shape change over the course of the treatment, and the seeds can migrate through soft tissues or through the vascular system. Consequently, a significant uncertainty in postimplant dose evaluation comes from the generalization of an isolated observation over the entire life of the implant. Thus, to achieve a very accurate dosimetry analysis, several postimplant dosimetry evaluations would have to be performed over the life of the implant. However, such a longitudinal study would require a low cost, low dose, and quick dosimetry analysis procedure, which is not available practically at the present time. Nonetheless, the TRUS-based treatment planning, the DTS-based intraoperative analysis and the CT-based day 30 dosimetry provide information to investigate the evolution of the dosimetry coverage. This three-step dose coverage analysis reports the progression from the planning, the achieved dosimetry right after the implant to the dose coverage 1 month after the implant. The analysis is complex because the dose evaluations are based on different imaging modalities, which complicates the comparison. Furthermore, prostate brachytherapy is very operator dependent so caution is needed when attempting to generalize the results obtained at one specific institution.

Although a coregistration technique is still to be validated, preliminary results were obtained for complete organ dosimetry. The organ contours were obtained from the planning stage and coregistered with the seed positions calculated at postimplant. We have not been able to establish any correlation between the day 0 postimplant DTS-based dosimetry and the day 30 CT-based dosimetry. These preliminary results will need a confirmation once a coregistration technique is established. This result would be consistent with other reports (see, for example, Ref. 50) in literature, claiming that there is no correlation between intraoperative preimplant dosimetry and day 30 dosimetry. However, this is a controversial issue since other studies indicate the opposite direction. Differences in patient selection, planning technique, contouring method, and implant procedure can lead to different outcomes from one institution to another.

V. CONCLUSION

The classical procedure used in low dose rate prostate brachytherapy would benefit from an intraoperative postimplant dosimetry verification technique to identify possible suboptimal dose coverage of the target. Several clinical factors influence the quality of an implant and many cases would benefit from the implantation of remedial seeds to correct for coverage flaws. Furthermore, an inexperienced brachytherapy team would benefit from direct intraoperative dosimetric feedback to bypass the learning curve associated with the procedure. In addition, the intraoperative dosimetry information would facilitate future correlation studies between dosimetry parameters and clinical outcomes.

The main objective of this project was to develop an efficient, operator-free, intraoperative seed detection technique using the imaging modalities commonly available in a
brachytherapy treatment room. The phantom study demonstrated that the reconstruction accuracy of the seed position is submillimetric and the patient study yielded a seed detection rate of 96.7%, which results in dosimetric parameters very close to reality. Most of the detection errors come from the analysis of the clusters including several seeds. The reconstruction algorithm also provides the seed orientation with an uncertainty of $10^\circ \pm 8^\circ$. The results show that the localization accuracy provides adequate dosimetry information. In addition, the algorithm determines the seed positions in an average of 36 s, independent of the number of seeds.

Enhancements in intraoperative dose evaluation will ultimately set new standards in the quality of prostate brachytherapy. The next generation of clinical brachytherapy systems will probably include postimplant intraoperative dosimetric capabilities. Combining an accurate and reliable postimplant intraoperative dose assessment with new dosimetry standards, new brachytherapy techniques should achieve better dose distributions and result in better clinical outcomes.

ACKNOWLEDGMENTS

One of the authors (M. Brunet-Benkhoucha) was supported by the Québec MSSS scholarship. NSERC is also acknowledged for financial support.

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