A Dynamic Dosimetry System for Prostate Brachytherapy

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Abstract

The lack of dynamic dosimetry tools for permanent prostate brachytherapy causes otherwise avoidable problems in prostate cancer patient care. The goal of this work is to satisfy this need in a readily adoptable manner. Using the ubiquitous ultrasound scanner and mobile non-isocentric C-arm, we show that dynamic dosimetry is now possible with only the addition of an arbitrarily configured marker-based fiducial. Not only is the system easily configured from accessible hardware, but it is also simple and convenient, requiring little training from technicians. Furthermore, the proposed system is built upon robust algorithms of seed segmentation, fiducial detection, seed reconstruction, and image registration. All individual steps of the pipeline have been thoroughly tested, and the system as a whole has been validated on a study of 25 patients. The system has shown excellent results of accurately computing dose, and does so with minimal manual intervention, therefore showing promise for widespread adoption of dynamic dosimetry.

Keywords

prostate brachytherapy; dynamic dosimetry; mobile non-isocentric C-arm; transrectal ultrasound

1 INTRODUCTION

Prostate cancer is the second deadliest killer among cancers affecting men in the United States [1]. As such, efforts are continually made to improve prostate cancer patient care and treatment. One such treatment is permanent prostate brachytherapy, a one-time minimally invasive outpatient surgery involving the permanent implantation of dozens of grain-sized radioactive sources known as seeds into the prostate. The goal of the procedure is to strategically place a cloud of seeds to maximize radioactive coverage of the prostate while minimizing toxicity to adjacent organs. Over the years, brachytherapy has become popular among patients due to its reputation for excellent outcome and general convenience.

While normally a straightforward procedure, problems may occur, such as gross misplacement of seeds, or minor inaccuracies that leave a region of the prostate underexposed (i.e. a "cold spot"). In such cases, the patient may need to return for additional therapy, complicating matters for both the patient and surgeon. These problems can be avoided with a dynamic dosimetry system that during the operation would accurately locate seeds already implanted and guide the surgeon to place seeds yet to be implanted [2]. Several research groups have sought to produce such a system, but arguably the most

promising one yet was published by Jain et al. [3] involving the combined use of a clinical ultrasound scanner and a non-isocentric mobile C-arm, two imaging devices that are ubiquitous in operating rooms across clinics.

The prototype dynamic dosimetry system presented by Jain et al. is sufficient but limited. The main premise of the system is to register a three-dimensional (3D) fluoroscopic reconstruction of seeds to a corresponding 3D transrectal ultrasound (TRUS) prostate volume in order to locate implanted seeds and compute dose (see Figure 1). A key component is the Fluoroscope TRACKing fiducial (FTRAC) [4], a compact fiducial composed of several radio-opaque features such as points, lines, and ellipses, which enables image-based C-arm tracking for fluoroscopy reconstruction and a predefined mechanical transformation between the fiducial and ultrasound volume for fluoroscopy-to-ultrasound registration. Although the FTRAC has its strength in accurate C-arm pose tracking, it also has significant weaknesses, especially in restrictive X-ray acquisition and cumbersome X-ray segmentation. The FTRAC restricts X-ray acquisition because the FTRAC and seeds must not overlap but still be present in the same field of view. This is a challenging task since the C-arm is typically confined between the raised legs of the patient in the surgically convenient lithotomy position. The FTRAC also complicates segmentation with its multiple features. Although automatic segmentation algorithms exist, no algorithm is fail-proof and manual segmentation of points, lines and ellipses is both tedious and time-consuming.

In this paper, we present an alternative ultrasound-fluoroscopic system for dynamic dosimetry in permanent prostate brachytherapy. Workflow has become streamlined so that it is easy for technicians to use and learn. Recently developed algorithms have also eliminated the need for the FTRAC. With advances made in seed segmentation, fiducial detection, seed reconstruction, and fluoroscopy-ultrasound registration, we now present a system for dynamic dosimetry that is more robust and easier to use than ever before.

2 METHODS

Our proposed dynamic dosimetry system follows a similar premise to the system proposed by Jain et al. (see Figure 1). Three or more different two-dimensional (2D) fluoroscopic images are taken of the seeds and fiducial, generally within a 20° cone of the anterior-posterior axis of the patient lying on the table. TRUS images are also taken to acquire the prostate volume. Both image sets are processed and registered to compute dose.

Our proposed system requires three pieces of hardware. Two of them are imaging devices, specifically the ultrasound scanner and the non-isocentric mobile C-arm, both of which are assumed to be calibrated prior to the operation. The third piece of hardware is a simple fiducial composed of nine seed-like point markers attached to a cylindrical radiolucent rod (see Figure 2). This simple fiducial has many advantages. While fiducials based on lines or conics would significantly degrade segmentation with overlap of seeds, the technician now gains the much needed freedom with this alternative fiducial to operate the C-arm in the confined space of the operating room. Moreover, the seed-like markers allow these fiducial points to be treated and reconstructed as implanted seeds, thus simplifying workflow. The configuration of the nine markers on the cylindrical rod is arbitrary; the only requirement in our experience is that at least four markers should be placed in a 3D configuration for more accurate pose tracking. Such a liberty in the configuration of the fiducial therefore makes it extremely inexpensive to manufacture, especially when compared to other common tracking systems. This fiducial does not provide poses as accurate as the FTRAC [4] since it does not incorporate lines or ellipses (our point-based fiducial has up to 3 mm in translation and 2° in rotation inaccuracies), but it is sufficiently accurate for the purposes of our later-described seed reconstruction algorithm. There is also no predefined mechanical registration between

the fiducial and the ultrasound coordinate system, but registration is handled later by image processing.

In software, there are four main image processing steps: 1) seed segmentation, 2) fiducial detection and pose estimation, 3) seed reconstruction, and 4) seed-to-volume registration. We describe each step in detail.

The first step in the image processing pipeline is seed segmentation, which has the purpose of locating seeds in the X-ray images in preparation for seed reconstruction. It therefore takes as input each distortion-corrected X-ray image (the particular distortion correction algorithm we use is outlined in [5]) and outputs the 2D coordinates of each seed in the image. Since our fiducial is made of seed-like point markers, this algorithm consequently outputs the coordinates of both seeds and fiducial markers without differentiating the two types. The algorithm we currently use is based off the seed segmentation algorithm published by Kuo et al. [6]. Briefly stated, the algorithm performs on the X-ray image a morphological operation known as top-hat by reconstruction to improve contrast between the seeds and the background of the patient's anatomy. The resulting image is thresholded and each connected component region is then analyzed to distinguish any seeds that are closely overlapping. Although the algorithm recovers overlapping seeds reasonably well, there is also no need to perfectly recover all overlapping seeds since the reconstruction algorithm further along the pipeline also recovers seeds that appear "hidden".

The next step is X-ray fiducial detection for the purpose of pose estimation that is required for the later step of reconstruction. The objective is therefore to detect which coordinates in the previous seed segmentation belong to the fiducial, and to estimate the pose corresponding to such a projection. This step therefore takes as input the coordinates and outputs the ones belonging to the fiducial as well as the corresponding pose. We also assume the 3D model of the fiducial is known and there is some general knowledge of the pose (in our case, the fiducial is oriented approximately foot-to-head and pose is roughly along the anterior-posterior axis), both of which are reasonable to know in a clinical setting. The fact that the fiducial model is one of the inputs also allows this algorithm to work for fiducials of arbitrary seed configuration. Fiducial detection then follows in several steps. First, a 2D projection of the 3D model is calculated according to the rough initial pose. A sub-function then finds a best fit for this template projection among the segmented seeds (see Figure 3). This is done by taking the two furthest points in the projected template (see Figure 3a) and registering them in 2D to all possible pairs of segmented seeds (see Figure 3b). Once registered, the registered template is then compared to the segmented coordinates to find closest matches (see Figure 3c). The registration that matches with least error (e.g., mean Euclidean distance; see Figure 3d) therefore corresponds to the best template fit and is consequently a likely detection of the fiducial seeds. This best match may not necessarily be the correct detection, however, because the initial pose used to calculate the initial template is incorrect albeit roughly accurate. Nonetheless, this can be resolved by a final step of iterating between pose estimation and this sub-function of template matching. Pose is estimated once a template is matched; likewise, a new and more accurate template is regenerated once pose is estimated. Such iterations continue until convergence. On patient images, the algorithm almost always converges within three iterations.

Once poses are estimated, the third step of X-ray seed reconstruction continues the pipeline by computing a 3D cloud of seeds from the few different X-ray projection images. This algorithm therefore takes as input the seed coordinates and poses of all X-ray images; it then outputs the 3D seed coordinates with respect to the fiducial coordinate system. The algorithm we use for this system is known as Automatic Pose Correction REduced Dimensionality Matching Algorithm for Prostate brachytherapy Seed reconstruction (APC-

REDMAPS) published by Lee et al. [7]. It is an extremely robust reconstruction algorithm that is insensitive to pose inaccuracies yet handles overlapping, or "hidden", seeds. It optimally solves the extended assignment problem to match segmented seeds among multiple X-ray projections, but also does so quickly by exploiting the cost metric to reduce the immense dimensionality of solving such a problem. Once the seeds are reasonably matched, the reconstruction is improved by using the matches to correct the initial poses. The corrected poses then are reused to improve matching. Iterations therefore occur between matching and pose correction to make the reconstruction algorithm more robust and less sensitive to pose inaccuracies.

Finally, the last step in the pipeline is fluoroscopy seeds to ultrasound volume registration. The idea is to take the computed 3D seed coordinates from X-ray and position them properly in the ultrasound volume. Once completed, dosimetry computation and plan re-optimization becomes a straightforward task. Our algorithm thus takes as input the 3D reconstructed seed coordinates and the acquired ultrasound volume, and outputs a new set of seed coordinates that are registered to the ultrasound coordinate system. It may also take as input the prostate contour as delineated by the surgeon during the operation or a manually selected rectangular region of interest if the prostate contour is unavailable. Our algorithm for this task is the one published by Dehghan et al. [8]. Briefly stated, it performs morphological preprocessing of the ultrasound volume to identify some bright seed regions within the ultrasound region of interest. It then Gaussian blurs these identified regions to speed optimization convergence between the overlap of the X-ray seed cloud with the ultrasound volume. The registration result is found once optimization is completed. In addition, we have noticed that the most crucial deformation of the prostate in the ultrasound caused by TRUS probe pressure occurs along the anterior-posterior direction. We account for this deformation by including scale along this direction as a parameter in the optimization, therefore making this particular algorithm in fact an affine registration method.

Putting it all together, we have a complete dynamic dosimetry system which locates seeds already implanted and produces dosimetry results to guide seeds yet to be implanted. This desired result is produced by acquiring a TRUS volume of the prostate and taking three fluoroscopic images of the fiducial and seeds.

3 RESULTS

The system has been evaluated on 25 patients under approval of the Institutional Review Board at the Johns Hopkins Hospital using a GE OEC 9800 C-arm and BK Medical Pro Focus ultrasound scanner. Each step in the pipeline has been tested and evaluated. As reported in [6], seed segmentation gives a 98.9% detection rate but a 2.6% false positive rate. Given corrected segmentation, the next step of fiducial detection achieves a 100% detection rate for all 150 images (6 images/patient × 25 patients). APC-REDMAPS produces seed reconstructions with a 99.4% matching rate, solution optimality of 99.8%, and an average reconstruction accuracy of 0.5 mm [7]. Finally, affine image registration results in a mean seed-to-seed registration error of 1.5 mm [8]. All of these values are within clinically acceptable limits.

Figure 4 walks through images of each step on a sample patient data set. First, an undistorted image is inputted into the system (see Figure 4a). Next, the seed segmentation algorithm is run on the input image so that both seeds and fiducial points are segmented and possible overlapping seeds are identified (see Figure 4b). Although seed segmentation is accurate, occasionally there may be false positives (two near the bottom of Figure 4b marked by white dotted squares). Since no algorithm is fail-proof, our software also allows for quick manual correction of errors. After correction (if needed), the fiducial points are

detected from among the segmentation to estimate poses (see Figure 4c). Both seed segmentation and fiducial detection are repeated for at least two other fluoroscopy images before the next step of seed reconstruction takes place (see Figure 4d). The reconstructed seed cloud is then registered to the ultrasound volume to produce our final registration of ultrasound and fluoroscopy (see Figures 4e and 4f).

The system as a whole also has the capability of detecting cold spots as shown in Figure 5. This highlights the utility of the system, as cold spots can then be addressed immediately in the operating room rather than requiring the patient to return for additional therapy after being discharged.

4 CONCLUSION

In this paper, we present an intraoperative image-guidance system for prostate brachytherapy dynamic dosimetry. With the help of a point-based fiducial and a few robust image processing algorithms, dose is accurately and quickly computed with unprecedented convenience. The system therefore ultimately leads to saved time and money while improving the surgical outcome for prostate cancer patients.

Acknowledgments

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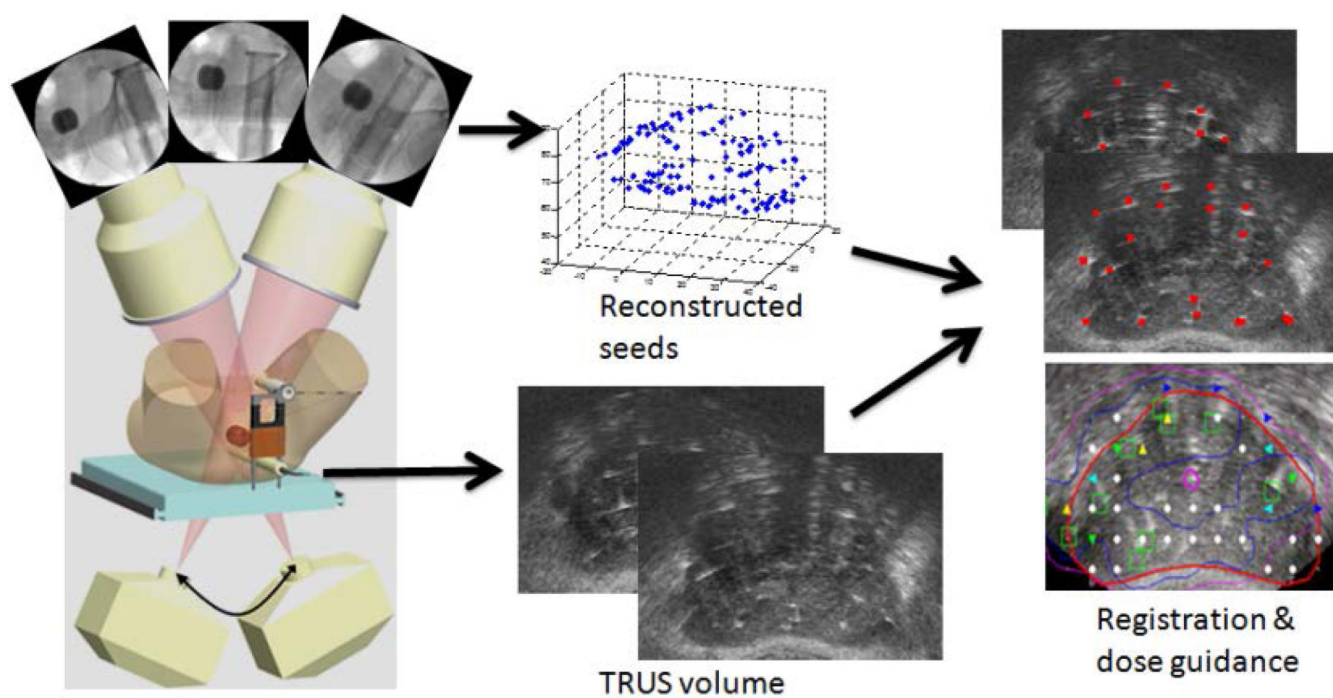
Figure 1.
Workflow of ultrasound-fluoroscopic dynamic dosimetry system
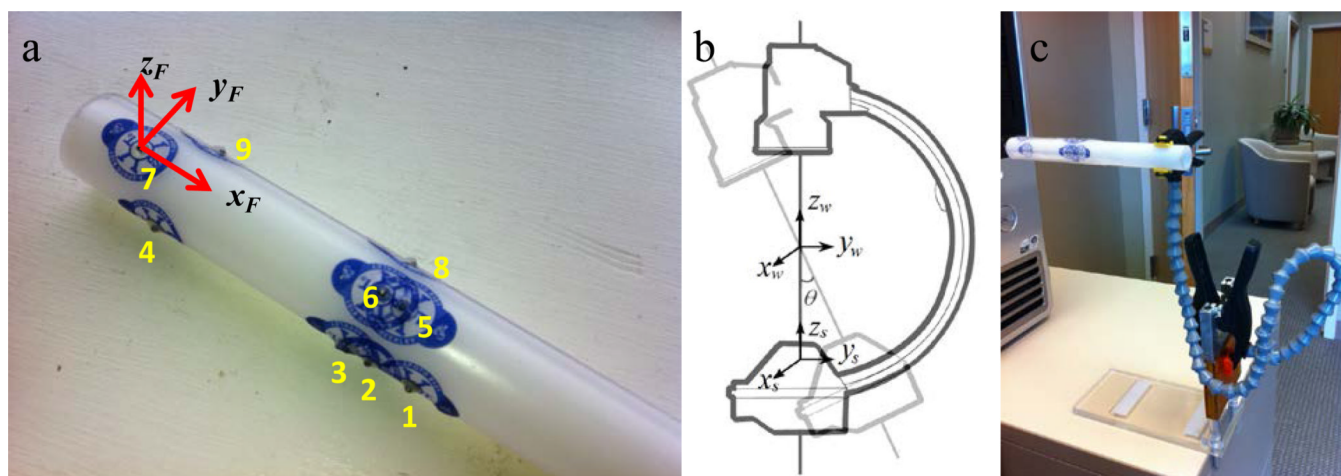
Figure 2.
Illustrations of simple cylindrical point-based fiducial. (a) Photograph of fiducial with markers numbered and coordinate system defined. (b) Diagram of C-arm; fiducial coordinate system F should be roughly aligned with world coordinate system W. (c) Photograph of fiducial attached to needle-guiding template via a flexible arm.
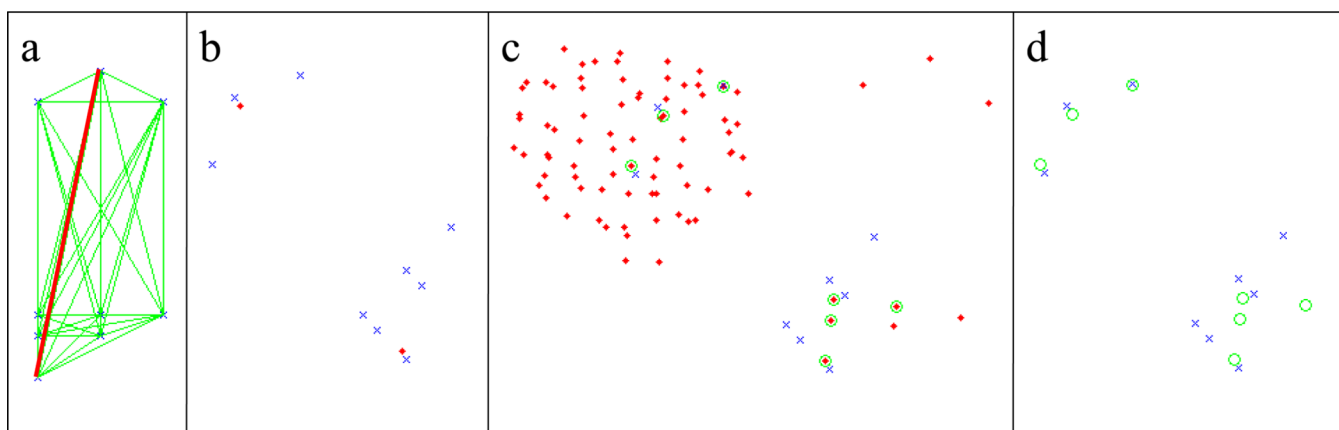
Figure 3.
Illustration of steps for template matching sub-function in fiducial detection. Red dots are the segmented coordinates (both seeds and fiducial), blue crosses represent the projected fiducial template, and green circles are the closest segmented coordinates. (a) Find the two furthest points in template; (b) register these template points to a pair of segmented coordinates; (c) find the closest segmented coordinates to the registered template, (d) calculate the error using these closest coordinates; the error for this case is high.
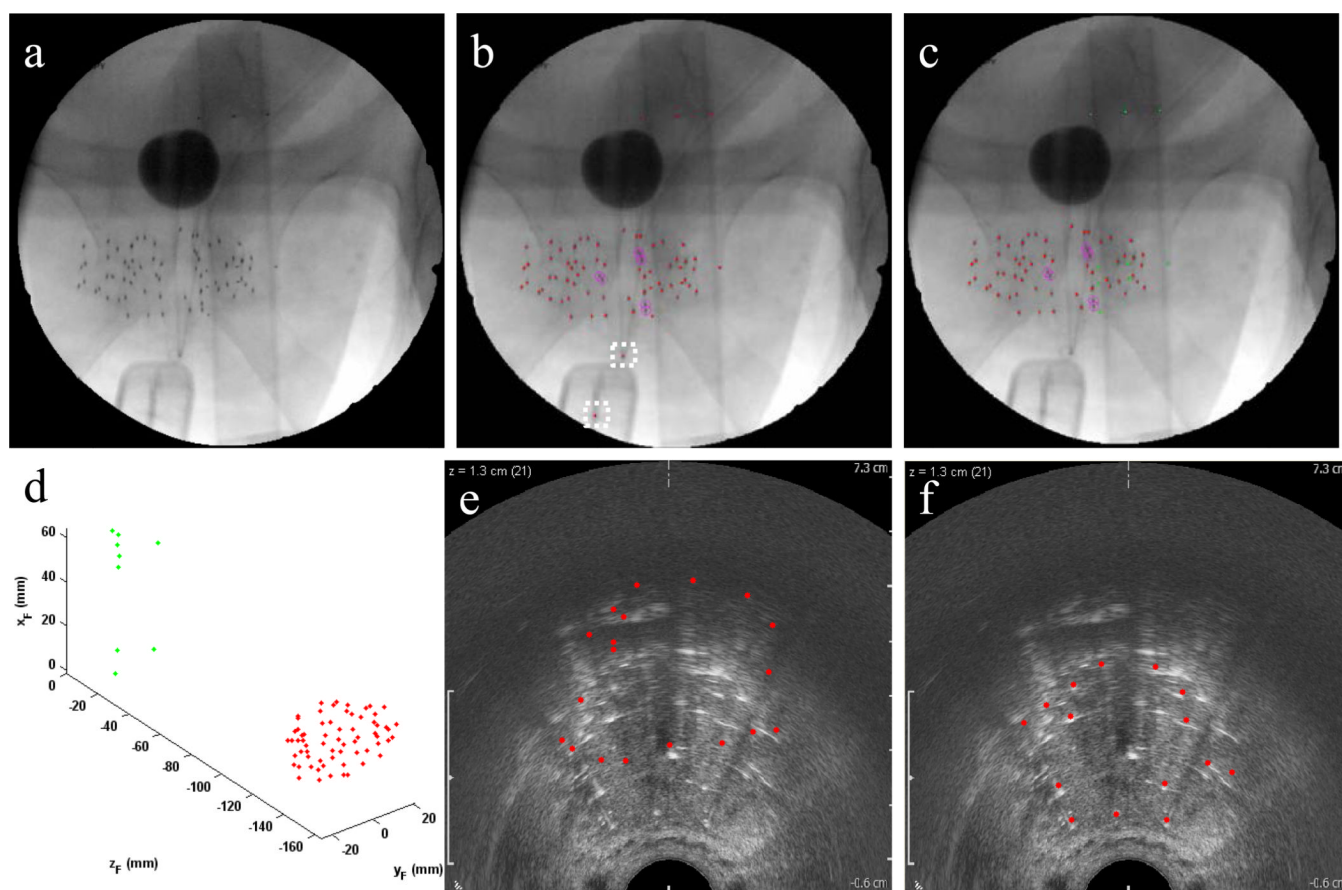
Figure 4.
Images along the image processing pipeline. (a) Undistorted fluoroscopy image. (b) Image after seed segmentation with segmented points as red dots and suspected overlapping seeds in magenta circles. (c) Image after fiducial segmentation with fiducial points now as green dots. (d) 3D reconstruction of points with seeds as red dots and fiducial as green dots. (e) Slice of ultrasound volume before registration with reconstructed seeds as red dots; (f) Slice of final result with seeds registered to the ultrasound volume.
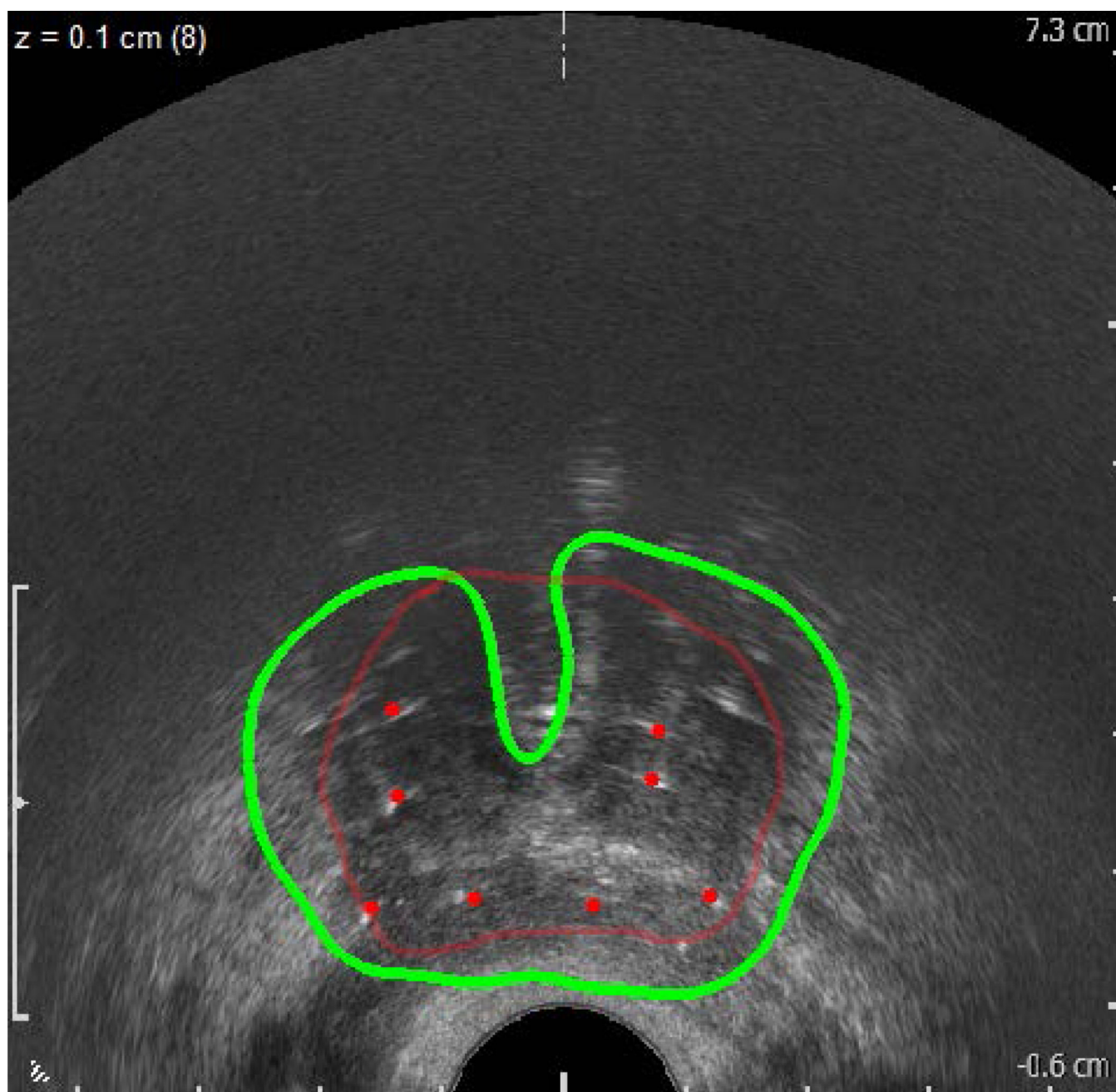
Figure 5.
Intraoperative dosimetry result showing cold spot. TRUS image is overlaid with the registered seed reconstruction (red dots), prostate contour (red line) and the 100% isodose level (green line).