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Three-dimensional transrectal ultrasound guided high-dose-rate prostate brachytherapy: A comparison of needle segmentation accuracy with two-dimensional image guidance

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ABSTRACT

PURPOSE: Conventional transrectal ultrasound guided high-dose-rate prostate brachytherapy (HDR-BT) uses an axially acquired image set for organ segmentation and 2D sagittal images for needle segmentation. Sagittally reconstructed 3D (SR3D) transrectal ultrasound enables both organ and needle segmentation and has the potential to reduce organ-needle alignment uncertainty. This study compares the accuracy of needle tip localization between the conventional 2D sagittally assisted axially reconstructed (SAAR) and SR3D approaches.

METHODS AND MATERIALS: Twelve patients underwent SAAR-guided HDR-BT, during which SR3D images were acquired for subsequent segmentation and analysis. A total of 183 needles were investigated. Needle end-length measurements were taken, providing a gold standard for insertion depths. Dosimetric impact of insertion depth errors (IDEs) on clinical treatment plans was assessed.

RESULTS: SR3D guidance provided statistically significantly smaller IDEs than SAAR guidance with a mean ± SD of -0.6 ± 3.2 mm and 2.8 ± 3.2 mm, respectively ($p < 0.001$). Shadow artifacts were found to obstruct the view of some needle tips in SR3D images either partially (12%) or fully (10%); however, SR3D IDEs had a statistically significantly smaller impact on prostate V_{100}% than SAAR IDEs with mean ± SD decreases of -1.2 ± 1.3% and -6.5 ± 6.7%, respectively ($p < 0.05$).

CONCLUSIONS: SR3D-guided HDR-BT eliminates a source of systematic uncertainty from the SAAR-guided approach, providing decreased IDEs for most needles, leading to a significant decrease in dosimetric uncertainty. Although imaging artifacts can limit the accuracy of tip localization in a subset of needles, we identified a method to mitigate these artifacts for clinical implementation.

Keywords: Prostate cancer; High-dose-rate brachytherapy; 3D ultrasound; Transrectal ultrasound

Introduction

High-dose-rate brachytherapy (HDR-BT) has been shown to be an effective method of dose escalation when used in combination with external beam radiation therapy (EBRT) for the treatment of intermediate- to high-risk prostate cancer (1–4). Clinical trials have shown an improvement in biochemical disease–free survival using HDR-BT dose-escalated EBRT vs. EBRT alone (5, 6). Furthermore, with the recent report of positive results from the ASCENDE-RT randomized trial (7), there will likely be an increase in the number of intermediate-

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and high-risk prostate cancer patients who will undergo brachytherapy.

Although it is well known that HDR-BT techniques offer improved conformity and normal tissue sparing (8, 9), this presupposes that the needles used to guide the high-activity gamma source have been segmented accurately on imaging, with one study finding that the source must be localized to within 3 mm for acceptable dosimetric uncertainty (10). Because of the high spatial accuracy and high needle-to-tissue contrast in CT imaging, image-guided HDR-BT was originally performed using CT scans acquired after transrectal ultrasound (TRUS)−guided needle insertion (11). Unfortunately, patient repositioning and swelling that occurs during patient setup for CT imaging has been found to cause shifts in needle positions as evidenced by studies reporting mean [range] shifts of 11.5 [0 to 42] mm (12), 10 (5 to 23) mm (13), and 5.4 [−4 to 18] mm (14) between treatment fractions. For patients undergoing single fraction CT-guided HDR-BT, mean shifts of 11 mm have been found between the planning CT and time of treatment delivery, with 10% of needles shifting inferiorly by more than 20 mm (15).

In an effort to eliminate the need to reposition patients during treatment, intraoperative TRUS imaging has been proposed for needle and organ segmentation. By using a tracked probe stepper and compatible segmentation software, TRUS images may be used for needle insertion guidance and segmentation while the patient remains in the operating room. The prostate and nearby organs may be localized by stepping the probe in the superior/inferior direction to create a stack of axial images for segmentation; however, limited image sampling in the needle insertion direction (typically 1−5 mm) introduces uncertainty in needle tip positions (16−18). Siebert *et al.* (16) investigated the ability to identify needle tips in water phantoms and found that submillimeter accuracy was achievable when using the sagittal crystal of a biplane TRUS probe.

With these imaging characteristics in mind, HDR-BT workflows have been proposed that involve segmenting the prostate and nearby organs using an image volume reconstructed from axial images, segmenting needle tips using live 2D sagittal images, and combining the views by manually aligning the axial organ segmentations on a midgland sagittal image, using anatomic landmarks such as the bladder as indicated in Fig. 1. Schmid *et al.* (17) investigated the accuracy of this 2D sagittally assisted axially reconstructed (SAAR) approach in phantoms by comparing TRUS- and CT-based segmentations, finding tip localization accuracy within 1.9 mm is achievable in phantoms with up to 18 needles. Batchelar *et al.* (18) investigated the accuracy of the TRUS-based approach *in vivo* by comparing SAAR-guided needle segmentations with in-room cone-beam CT-based needle segmentations from 37 HDR-BT procedures. Relative needle segmentation error was measured by selecting a posterior needle tip on both the SAAR-guided segmentation and the cone-beam CT-based segmentation and aligning the remaining needle

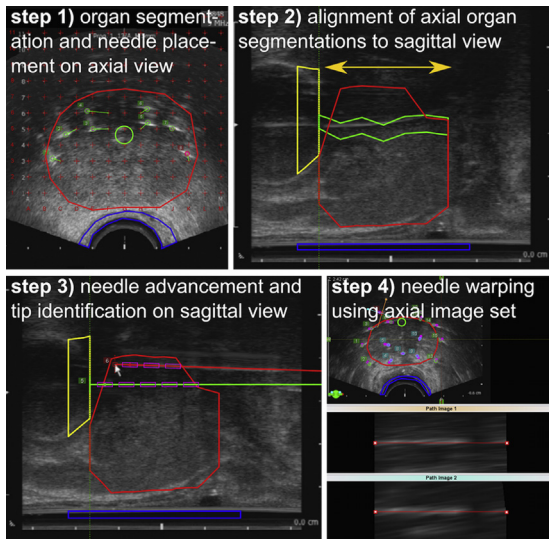

Fig. 1. Screenshots taken from Vitesse treatment planning software during SAAR-guided HDR-BT needle insertion. Major steps of the imaging and segmentation procedure are highlighted, and details are provided in Appendix 1. Among the differences between the SAAR and SR3D-guided segmentation techniques described in this study, the SR3D-guided technique would eliminate the need for the axial-to-sagittal segmentation alignment indicated in Step 2. SAAR = sagittally assisted axially reconstructed; HDR-BT = high-dose-rate brachytherapy; SR3D = sagittally reconstructed 3D.

segmentations using this corresponding point. Results indicated relative tip localization error was less than 3 mm in 97% of all needles when using the SAAR technique. Although the relative needle tip localization accuracy for TRUS-guided HDR-BT is promising, potential systematic shifts in tip positions introduced during the axial-to-sagittal image registration step have not been fully investigated and may contribute to absolute needle tip localization uncertainty.

Our laboratory has previously developed TRUS imaging techniques that allow the reconstruction of a 3D image using the sagittal crystal of a biplane probe by rotating the probe using a motor and simultaneously capturing images (19). This method of acquiring sagittally reconstructed 3D (SR3D) images maintains high spatial resolution in the needle insertion direction while providing a complete 3D image for prostate and organ segmentation, thereby eliminating the need to move the probe in the superior/inferior direction for sagittal and axial imaging and eliminating the axial-to-sagittal segmentation alignment step (20). Variants of this SR3D image reconstruction technique have also been made commercially available, including the Twister image acquisition feature available in Variseed 8.0 (Varian Medical Systems Inc., Palo Alto, CA). Our laboratory has also developed a compact mechatronic device designed for SR3D image-guided transperineal needle insertions that enables superior/inferior probe position tracking relative to an external frame of reference (21). Through calibration, the position of each image relative to the insertion template is determined. Tracking this