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Accuracy and variability of high-dose-rate prostate brachytherapy needle tip localization using live two-dimensional and sagittally reconstructed three-dimensional ultrasound

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ABSTRACT

PURPOSE: To measure the accuracy and variability of manual high-dose-rate (HDR) prostate brachytherapy (BT) needle tip localization using sagittally reconstructed three-dimensional (3D) transrectal ultrasound (TRUS) augmented with live two-dimensional (2D) sagittal TRUS.

METHODS AND MATERIALS: Ten prostate cancer patients underwent HDR-BT during which the sagittally assisted sagittally reconstructed (SASR) segmentation technique was completed in parallel with commercially available sagittally assisted axially reconstructed (SAAR) TRUS for comparison. The SASR technique makes use of live 2D ultrasound intraoperatively and allows needle tip updates using the final 3D image in the absence of image artifacts. These updates were repeated offline twice by two separate users. Needle end-length measurements were used to calculate insertion depth errors (IDEs) for each technique.

RESULTS: Images of 147 needles were analyzed. For the SASR technique, both users were confident in tip positions on the final 3D image within 3 mm for 52% of needles, so these tip positions were updated. For the remaining 48% of needles, the tip positions from the live 2D images were used. This SASR technique enabled the localization of all needles with IDEs within ±3 mm for 84% of needles and IDE range of [−6.2 mm, 5.9 mm], compared with 57% and [−8.1 mm, 7.7 mm] when using the commercially available SAAR technique.

CONCLUSIONS: The SASR technique mitigates the impact of 3D TRUS image artifacts on HDR-BT needle tip localization by incorporating live 2D sagittal TRUS intraoperatively and provides a statistically significant reduction in IDE variance compared with the routine SAAR technique.

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

Introduction

High-dose-rate prostate brachytherapy (HDR-BT) is used routinely as a boost to external beam radiation therapy (1–4) and increasingly as a monotherapy (5–7). Evidence suggests that it is possible to deliver dose distributions using HDR-BT with decreased dose to normal tissue (8) and decreased dosimetric uncertainty (9) than low-dose-rate prostate brachytherapy, but achieving these treatment plan

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characteristics is critically dependent on accurately localizing HDR-BT needles relative to anatomy (10–12). Image guidance for HDR-BT has been implemented using CT (13), MRI (14, 15), and transrectal ultrasound (TRUS) (16, 17). Patient repositioning for imaging, as required for conventional CT and MRI-guided workflows, has been shown to cause caudal needle shifts before treatment (18). In-bore treatments have been proposed, but lowering patients' legs to fit in the bore may compromise access to the perineum and increase pubic arch interference (19). TRUS-guided HDR-BT workflows allow needle insertion, imaging, and treatment to be completed in existing brachytherapy bunkers without the need to reposition the patient (16, 17). TRUS guidance has demonstrated comparable needle tip localization accuracy (16) and treatment plan dosimetry to CT guidance (20); however, conventional multistep TRUS-guided procedures create the potential for needle tip localization errors for some patients.

TRUS-guided HDR-BT makes use of live 2D sagittal images to localize needle tips at the time of insertion (10). Accurate organ dose calculation requires reconstruction of a 3D image, which is typically performed by acquiring multiple axial images while stepping the probe in the superior/inferior direction (16). An alternative TRUS-guided approach was proposed making use of sagittally reconstructed 3D ultrasound (SR3D), which is produced by rotating the probe using a motor while simultaneously capturing a fan of sagittal images that are reconstructed into a 3D image with submillimeter resolution in the needle insertion direction (21, 22), eliminating the need to combine axial and sagittal views. Custom hardware and software solutions have been presented for SR3D reconstruction (22), and vendors including Varian Medical Systems (Palo Alto, CA) and Elekta (Stolkholm SE) have introduced technologies with similar SR3D reconstruction capabilities. It was demonstrated that HDR-BT needles could be segmented using SR3D images with insertion depth errors (IDEs) $\leq$5 mm for 93% of needles, versus 76% when using the sagittally assisted axially reconstructed (SAAR) technique (23). Unfortunately, shadow artifacts were found to introduce uncertainty in needle tip locations when using a single post-insertion SR3D image, leading to IDEs $>$10 mm in 3% of needles and completely obstructing the view of an additional 3% of needles, impacting 4 of 12 patients in the study (23). Although these artifacts impacted a relatively small number of needles, the potential for large errors limited the utility of single post-insertion SR3D images for localizing all HDR-BT needles.

The clinical SAAR approach is not as susceptible to these image artifacts due to the incorporation of live 2D sagittal imaging to localize needle tips at the time of insertion. The live 2D technique enables the identification of needle tips as the needles are inserted from the prostate anterior-to-posterior, effectively eliminating the impact of shadow artifacts caused by posterior needles on tip localization (16). The SAAR-guided technique incorporating live 2D tip identification was found to lead to larger IDEs than the SR3D approach for most needles; however, these errors were attributed to superior/inferior probe motion required for axially reconstructed 3D (AR3D) ultrasound introducing uncertainty in tip positions relative to organs (23).

Based on the characteristics of SR3D images and live 2D sagittal images, we have investigated a sagittally assisted sagittally reconstructed (SASR) needle segmentation workflow designed to eliminate uncertainty created by probe movement when switching between axial and sagittal transducers required for the conventional SAAR technique and to mitigate the impact of shadow artifacts created by posterior needles in SR3D images. The purpose of this study is to measure the accuracy and variability of manual HDR-BT needle tip localization using the SASR technique and to compare it with the conventional SAAR technique geometrically using calibrated needle end-length measurements (23, 24) as the gold standard.

Methods and materials

Intraoperative imaging and segmentation

Ten prostate cancer patients underwent TRUS-guided HDR-BT using a Profocus 2202 ultrasound machine and 8848 biplanar probe (BK Medical, Boston, MA) operating at 9 MHz. The probe was supported by a custom compact mechatronic device enabling SR3D image acquisition (22), and the ultrasound machine video output was captured by two systems simultaneously: (*1*) a computer running Vitesse 2.5 (Varian Medial Systems, Palo Alto, CA) for conventional SAAR-guided segmentation by one user and (*2*) a computer running custom software for parallel SASR-guided segmentation by an additional user.

The SASR and SAAR techniques both involve acquiring a 3D image before needle insertion for organ segmentation. Needles are then inserted to the prostate mid-gland using a live 2D axial view, and each needle is advanced to the prostate–bladder interface using live 2D sagittal images. This advancement is performed from prostate anterior-to-posterior to mitigate the impact of shadow artifacts, and needle tip positions are localized at the time of advancement on the live 2D view using both Vitesse and our custom software. Following advancement of all needles, they are locked into place, and two final 3D images are acquired: (*1*) an SR3D image spanning 140° at 0.5° angular intervals for the SASR technique and (*2*) an AR3D image at 5 mm intervals for the SAAR technique. Example 3D images are provided in Fig. 1. These images are used to adjust needle segmentations to account for potential out-of-plane trajectories and tip motion during the insertion and to adjust organ segmentations to account for anatomical motion and deformation.