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Robotic Ultrasound and Needle Guidance for Prostate Cancer Management: Review of the Contemporary Literature

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Abstract

Purpose of review—To present recent advances in needle guidance and robotic ultrasound technology which are used for prostate cancer diagnosis and management.

Recent findings—Prostate biopsy technology has remained relatively unchanged. Improved needle localization and precision would allow for better management of this common disease. Robotic ultrasound and needle guidance is one strategy to improve needle localization and diagnostic accuracy of PCa. This review focuses on recent advances in robotic ultrasound and needle guidance technologies and their potential impact on prostate cancer diagnosis and management

Summary—The use of robotic ultrasound and robotic-assisted needle guidance has the potential to improve prostate cancer diagnosis and management.

Keywords

prostate; prostatic neoplasms; biopsy; ultrasonography; robotics

Introduction

Prostate cancer is the most common non-dermatologic malignancy is US men. Over 1 million transrectal ultrasound (TRUS) guided biopsies are performed annually in the United States with an estimated cost burden of over $2 billion[1, 2]. Although transrectal ultrasound (TRUS)-guided prostate biopsy is the most commonly performed procedure to diagnose prostate cancer, it has significant shortcomings. Primarily, biopsy cores are often clustered, instead of the intended biopsy schema, resulting in suboptimal sampling of the whole prostate gland [3–6]. Secondly, standard, freehand TRUS biopsy technique does not allow precise localization of a lesion or re-sampling of an area of interest. Since the quality of biopsy core sampling and the biopsy core distribution are associated to cancer detection rate

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[7–10], improved sampling technique should enhance prostate cancer detection and, ultimately, its management.

One strategy to overcome these limitations of the standard TRUS biopsy is to supplement a current TRUS biopsy platform with a steady and reproducible motion device, such as a robot, and 3-dimensional (3D) reconstruction software. Similarly, a robotic ultrasound application can provide image stability and guidance during common prostate cancer treatment options such as brachytherapy and radical prostatectomy. This article reviews the contemporary literature on the robotic application for the diagnosis and management of prostate cancer.

Non-robotic 3-Dimensional TRUS-guided Prostate Biopsy

In a typical freehand prostate biopsy, the TRUS probe is operated manually and the positional information required for 3D computation is lost. A recent study demonstrated that even experienced urologists under sample large regions of the prostate and do not follow the intended biopsy schema when equipped with traditional, freehand TRUS biopsy technology [6]. To overcome the limitations of the standard biopsy technique, two commercial systems are currently available that allow 3D schemata for prostate biopsies.

The TargetScan system (Envisioneering Medical Technologies, MO, USA) is a system that was originally developed for brachytherapy, and has been adapted for office-based template-guided prostate biopsies. The system is comprised of a TRUS probe and transducer and software to aid in 3D mapping of the prostate. The system's conformational software creates a 3D model of the prostate and a resultant biopsy schema. The software saves each biopsy coordinate [11]. In a multi-center review, the technology had a 36% cancer detection rate in 140 biopsied patients with 52% accuracy of predicting pathology after radical prostatectomy[12]. One detriment of the system, however, is that the 3D image and biopsy template does not change with patient position and prostate deformation. Patient movement may cause errors between the planned template and the executed biopsy. Although the technology can theoretically be used in an awake patient with local anesthesia, the inability to adjust to a moving patient makes general anesthesia the necessity [13]. The system has been primarily designed for prostate brachytherapy. Since it uses lateral-fire ultrasound probes, the prostate may only be accessible using a bendable needle that is inserted parallel to the TRUS probe, but exits at 45 degrees. This compromises targeting accuracy and causes frequent aborted procedures due to the needle jamming. [14]

The Artemis system (Eigen Inc., CA, USA) is the other prostate biopsy system using 3D technology. This system provides real-time 3D images and ultrasound probe localization. It is comprised of a mechanical arm with four degrees of freedom (4-DoF) which controls an end-fire 2D ultrasound probe. The system creates a 3D picture of the prostate by obtaining sequential axial images and can facilitate MRI/TRUS guided biopsies[15]. Three-dimensional images are stored and can facilitate repeat biopsies. A review of the Artemis system by Natarajan, et al demonstrated that in a digital model, one could re-biopsy within 1.2 mm of a previous biopsy[16]. However, this finding needs to be confirmed in a pure tissue model as patient movement, prostate deformation, and needle deformation may not be accurately reflected in a mathematical model. In addition, the probe movement in the Artemis system is controlled manually, reducing its ability to scan the prostate for imaging. In addition, an operator has to manually set and maintain the trajectory of the needle during biopsy. Although both TargetScan and Artemis systems offer clear advantages compared to freehand TRUS-guided prostate biopsy, they also have distinct limitations as listed above. As a result, these systems have not become widely used in clinical practice.

Several MRI-TRUS fusion (registration) methods are currently investigated [17–21]. Pre-acquired MRI is registered to 3D TRUS, typically acquired with special 3D probes. The biopsy procedure is conducted as usual based on the ultrasound, but with the aid of the fused MRI. The main technical limitation is that targeting accuracy is gauged based on the outdated MRI. Temporal differences, patient repositioning form the MRI supine to the TRUS decubitus position, different prostate compressions with the transrectal coil in the MRI and the TRUS probe [22], all these contribute to differences between the shapes of the prostate acquired with MRI and TRUS. These make the accuracy of fusion difficult to quantify especially after the initial alignment [23]. Consequently, biopsy targeting accuracy relative to the MRI is uncertain, even though it appears to be correct in TRUS and fusion. Several clinical trials are in progress to investigate the efficacy of these methods. Direct MRI-guided prostate targeting methods that typically involve the use of robotic devices are also explored [24–26]. Compared to pre-acquired images, direct image-guidance (DIGI) eliminates image-fusion errors, provides interventional PCa imaging feedback, and may reduce prostate motion and deformation errors [27].

Robot-Assisted Prostate Biopsy

All aforementioned 3-D TRUS-guided biopsy systems include image-guidance, but the TRUS probe is still handled by hand. There are several potential advantages of using a robot to handle the probe: (1) scanning motion can render uniformly distributed 2-D image slices for 3-D reconstruction; (2) the needle guide can be automatically aligned on target and locked in place for biopsy; and (3) prostate deformations due to the interaction with the probe can be minimized since the same motion can be used for both scanning and aligning the probe for biopsy. In a recent simulation study, Han et al demonstrated that TRUS probe-holding robot-assisted prostate biopsies had greater accuracy and precision, and improved cancer detection rates compared to freehand, TRUS-guided biopsies by urologists [6, 28]. For example, the robot's mean targeting error was 1.0 mm compared to 9.0 mm for the urologists. More importantly, robotic prostate biopsy was associated with a higher significant cancer detection rate of 43% compared to 36% in freehand prostate biopsy by urologists ($p < 0.0001$).

Although most urologists today perform transrectal prostate biopsies, some argue that transperineal biopsies are preferable as they can be performed sterilely with decreased risk for procedure-related sepsis. However, most of these systems require a perineal brachytherapy template and general anesthesia for a patient. Robotic systems for transperineal biopsies have been developed which incorporate 3D mapping with a needle system which only requires one or two perineal needle insertion sites[29, 30]. Long et al reported their robotic transperineal biopsy experience, where the system could respond to intra-procedural prostate motion[31]. Limitations to this transperineal approach were that anterior zone sampling may be challenging in a patient with an enlarged prostate and the fixed needle insertion may cause needle insertion into the urethra, dorsal vein complex, or neurovascular bundles[32].

Robot-Assisted Brachytherapy

Most transperineal prostate biopsy templates were initially developed for brachytherapy, which requires ultrasound imaging and accurate seed implantation in a 3D conformational space. Inaccurate needle placement during brachytherapy can lead to insufficient radiation dosing or radiation-induced side effects to the rectum, urethra and bladder. Most current brachytherapy systems require manual placement of the TRUS probe and brachytherapy needles. However, robots can provide stable image acquisition, tracking, orientation, and needle placement, and allow more accurately and precisely placed brachytherapy probes[33, 34]. Robotic brachytherapy platforms may provide additional benefits: robotically guided needles can be placed with increased velocity when compared to manually placed needles, which potentially translates to decreased prostate motion [35]. The technology may further allow for decreased needle deflection and tissue deformation [36], potentially decreased radiation exposure to operating personnel, decreased procedure times and therefore the potential for less intra-procedural edema [37, 38].

Wei et al developed a robot-assisted brachytherapy system which combined the robot for stabilization and accuracy with a 3D image coordination system, allowing for consistent and precise needle insertion[33]. They found that the fiducial registration error (FRE) and target registration error (TRE) were improved with the use of the robot. Fichtinger et al demonstrated that a robotic assisted brachytherapy platform with computed tomographic (CT) is feasible, but that accuracy greatly depended on tissue displacement and needle deflection [37, 38].

Three-Dimensional Imaging and Motion Control

In order for 3-D imaging systems to be useful for active surveillance protocols, brachytherapy, or focal therapy for prostate cancer, accurate calibration and rendering of 2D to 3D images, real-time imaging and minimizing errors for patient motion and prostate deformation are critical. The availability of 3D images is a major advance in prostate imaging. The 3D images are typically created from combining real-time 2D images and real-time tracking systems [32], and special ultrasound calibration methods have been developed [39]. Various tracking systems are currently available, which include real-time 3D TRUS probes, optical sensors, magnetic sensors and mechanical arms which allow tracking of the 2D images[13]. De Silva, et al recently reported a 2D to 3D registration technique which helped to compensate for prostate motion [40]. The future development in this imaging technology will be essential for further improving robotic-assisted prostate biopsy accuracy and precision.

Robotic Ultrasound use in Laparoscopic/Robotic Prostatectomy

In addition to improving the accuracy of prostate biopsy and brachytherapy fiducial placement, robotic systems have been applied to laparoscopic technology for better visualization and dissection. During radical prostatectomy, preservation of the neurovascular bundles is paramount for post-operative recovery of continence and potency. These bundles can be difficult to visualize intra-operatively. TRUS technology with Doppler ultrasound can improve the localization of these bundles and therefore can potentially improve the dissection and preservation.

TRUS imaging was first used with laparoscopy. Ukimara et al initially reported using freehand TRUS imaging to visualize the prostate during laparoscopic radical prostatectomy (LRP) without robotic assistance[41]. Next, van der Poel et al used freehand TRUS for the bladder neck dissection in daVinci (Intuitive Surgical, Sunnyvale, CA) robotic assisted laparoscopic prostatectomy (RALP) and demonstrated that intraoperative TRUS resulted in fewer basal positive margins during a surgeon's initial experience with RALP [42].

Other groups developed a robotic instrument to hold and manipulate the TRUS probe during RALP. For example, Han et al used the TRUS Robot [28], a novel robotic device to hold and manipulate the TRUS probe, in combination with 3-D reconstruction software and the daVinci surgical robot to provide intraoperative guidance to identify and preserve the neurovascular bundles (NVBs) [43]. The TRUS Robot is comprised of a robotic orientation remote center of motion (RCM) module, which is attached to an ultrasound probe and an arm that attaches to the operating table. The TRUS Robot is controlled remotely by the surgeon and has 4-DoF (Figure 1).

Subsequently, Long et al reported their experience in using the robotic TRUS to navigate and visualize the NVB release, bladder neck and apical dissection. One downside to this approach was that it displaced the rectum anteriorly, making the posterior dissection more challenging in a patient with a large prostate [44]. Hung et al also found that they could use the TRUS to help identify the neurovascular bundles and the borders of prostate lesions. They used the robotic technology to maximally preserve the nerves given the extent of the prostatic lesion [45].

Conclusions

Robotic prostate biopsy and needle localization is an emerging technology, which has the potential to positively affect prostate cancer diagnosis and management. Significant advances have been made which allow for more precise and accurate localization of the target. Further advances are required to bring this technology available for daily clinical use.

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Key Points

- Robotic transrectal ultrasound is an emerging technology to improve prostate biopsy schema and needle localization.
- TRUS robots have been applied to 12-core trans-rectal biopsy techniques, perineal biopsies, brachytherapy, and laparoscopic and robotic assisted prostatectomy procedures.
- Further advances are required before the technology can be adopted for daily clinical use.

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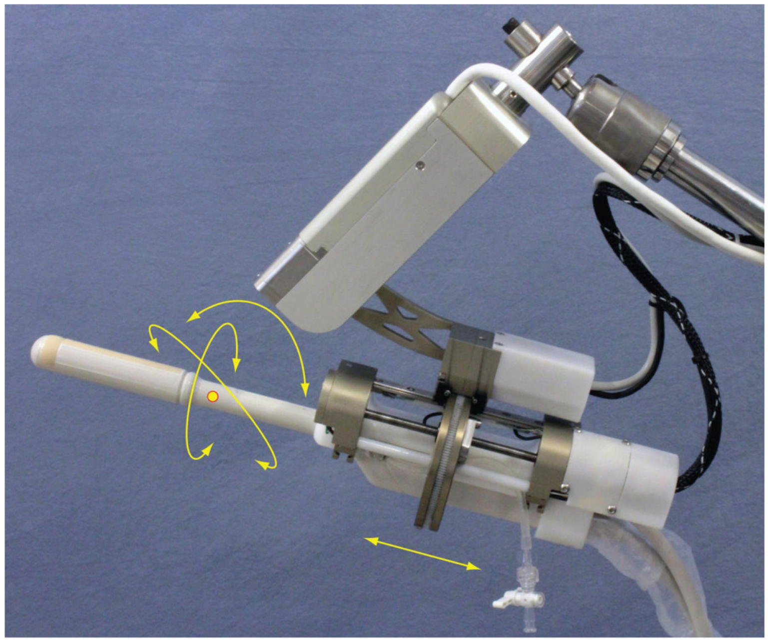

Figure 1.

TRUS Robot developed at the Urology Robotics Lab, Johns Hopkins University

It measures position without the need for a separate tracker. After setting up the probe, the authors obtained 2-D images of each patient's prostate with corresponding location coordinates. The images obtained had minimal prostate displacement and deformation given that the TRUS probe was rotated around its axis. The authors demonstrated the TRUS Robot can safely obtain accurate 3-D images of the prostate gland and NVBs with minimal set-up time. The setup of the tandem robot approach (T-RALP), a photo showing the TRUS-Robot before docking the daVinci robot, and a 3D reconstruction of the prostate structures based on the TRUS are shown in Figure legends

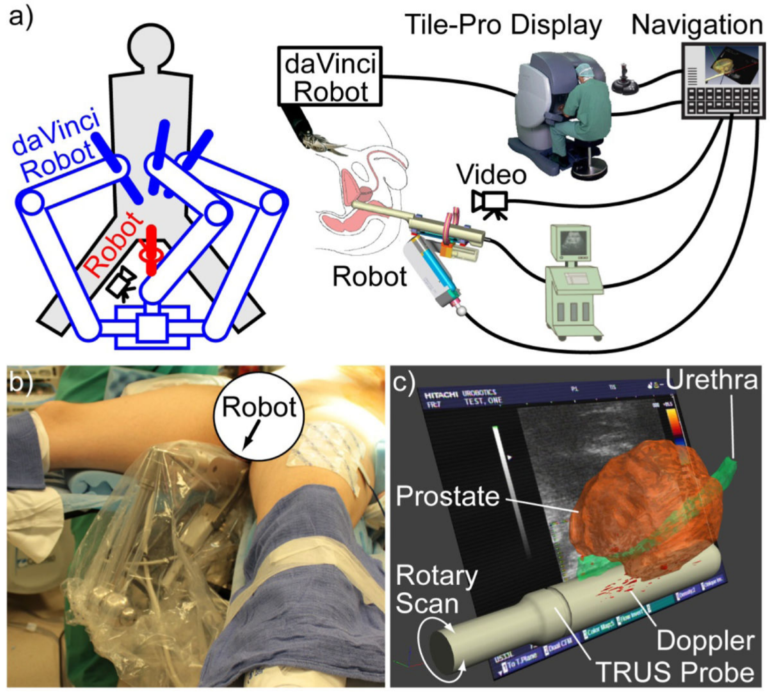

Figure 2.

Tandem Robot Assisted Laparoscopic Prostatectomy (T-RALP): a) intraoperative setup, b) TRUS-Robot, c) 3D reconstruction based on TRUS images (offline segmentation).