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Electromagnetic tracking for catheter reconstruction in ultrasound-guided high-dose-rate brachytherapy of the prostate

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ABSTRACT

PURPOSE: The accurate delivery of high-dose-rate brachytherapy is dependent on the correct identification of the position and shape of the treatment catheters. In many brachytherapy clinics, transrectal ultrasound (TRUS) imaging is used to identify the catheters. However, manual catheter identification on TRUS images can be time consuming, subjective, and operator dependent because of calcifications and distal shadowing artifacts. We report the use of electromagnetic (EM) tracking technology to map the position and shape of catheters inserted in a tissue-mimicking phantom.

METHODS AND MATERIALS: The accuracy of the EM system was comprehensively quantified using a three-axis robotic system. In addition, EM tracks acquired from catheters in a phantom were compared with catheter positions determined from TRUS and CT images to compare EM system performance to standard clinical imaging modalities. The tracking experiments were performed in a controlled laboratory environment and also in a typical brachytherapy operating room to test for potential EM distortions.

RESULTS: The robotic validation of the EM system yielded a mean accuracy of <0.5 mm for a clinically acceptable field of view in a nondistorting environment. The EM-tracked catheter representations were found to have an accuracy of <1 mm when compared with TRUS- and CT-identified positions, both in the laboratory environment and in the brachytherapy operating room. The achievable accuracy depends to a large extent on the calibration of the TRUS probe, geometry of the tracked devices relative to the EM field generator, and locations of surrounding clinical equipment. To address the issue of variable accuracy, a robust calibration algorithm has been developed and integrated into the workflow. The proposed mapping technique was also found to improve the workflow efficiency of catheter identification.

CONCLUSIONS: The high baseline accuracy of the EM system, the consistent agreement between EM-tracked, TRUS- and CT-identified catheters, and the improved workflow efficiency illustrate the potential value of using EM tracking for catheter mapping in high-dose-rate brachytherapy.

Keywords: High-dose-rate brachytherapy; Electromagnetic tracking; Treatment planning; Catheter mapping

Introduction

Because of the ablative doses encountered in high-dose-rate (HDR) brachytherapy and to minimize the dose to nearby organs at risk, it is necessary to be able to generate and deliver dosimetric distributions with sharp gradients (1–4). To this end, accurate placement and localization of the catheters is critical.

In prostate HDR brachytherapy, transrectal ultrasound (TRUS) image guidance is used for transperineal insertion of 10–20 catheters, often in a generic template-based pattern. The ability to visualize the catheters simultaneously

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with the prostate, rectal wall, and urethra in real time makes TRUS the preferred modality for image guidance during catheter insertion (5). After insertion, CT, MRI, or TRUS imaging may be used to localize the catheters and contour the prostate, urethra, bladder, and rectum (6–9). Next, an anatomy-based inverse planning algorithm uses the catheter positions and the organ contours to optimize the dwell positions and dwell times of radioactive sources in the catheters (10). Therefore, it is vital to be able to accurately implant the catheters relative to the patient's anatomy and then digitize this geometry in the treatment planning system. CT provides good quality visualization of the catheters with high geometric fidelity (5). However, the use of CT for catheter localization and organ contouring has the disadvantages of having to transport the patient to the CT scanner (5, 7), the associated possibility of catheter displacement (11), and the subjectivity of prostate visualization on CT (12). The use of MRI for prostate HDR treatment planning has the benefit of exquisite soft tissue definition and the ability to visualize voids for the implanted catheters. However, patient transfer issues similar to that of CT treatment planning and limited access to this high value resource make MR approaches difficult to implement. Manual catheter identification on TRUS images can be subjective, challenging, and operator dependent because of problems of calcifications and distal shadowing artifacts. Figure 1 illustrates a typical ultrasound (US) B-mode axial image of the prostate, with multiple catheters implanted. Having many catheters in a small volume increases the level of difficulty in accurately identifying the catheters in axial and sagittal TRUS images.

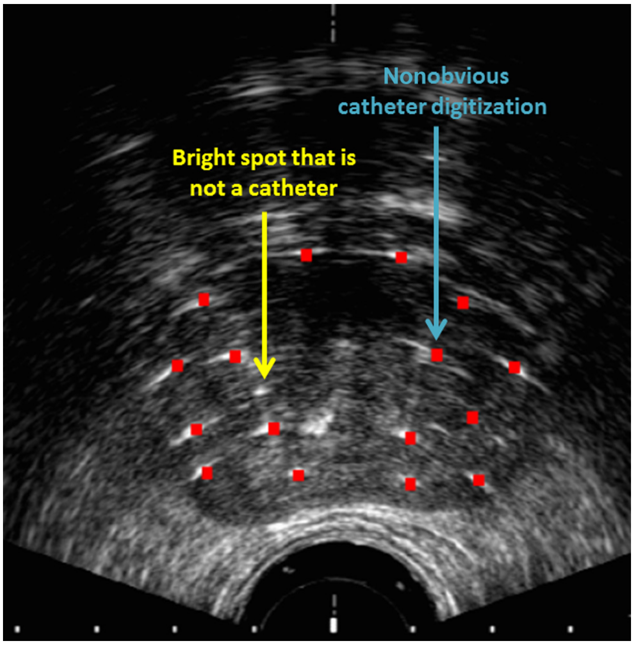

Fig. 1. Axial transrectal ultrasound image of the prostate, with catheters in place (illustrated by the dots). The bright spots represent the proximal edge of the catheters. Note the difficulty in identifying some of the catheters.

Typically in clinical practice, the operator scrolls through several US slices in the three-dimensional (3D) data set and sometimes adjusts the TRUS probe in the live two-dimensional (2D) mode to get a more complete picture of the catheter locations, which can be a time-consuming process. To improve efficiency and reduce potential interoperator variability in catheter identification, we propose an electromagnetic (EM) tracking solution that has the ability to provide enhanced intraoperative image guidance and accurately map the 3D locations of the catheters while also improving workflow efficiency in HDR prostate brachytherapy.

EM tracking technology works on the principle of an electric field being induced in response to a time-varying magnetic field (Faraday's law). A field generator (FG) produces a weak magnetic field that is calibrated so that the position and orientation of an EM sensor/tool in its field can be determined by analyzing the amplitude of the weak electric current that is generated in the tool. EM technology has previously been used in procedures such as interventional radiology, biopsy guidance, radiofrequency ablation, and external-beam radiation therapy (13–17). The performance accuracy of EM tracking in an HDR operating room (OR) was reported by Zhou *et al.* (18) in a recent publication. In this article, we describe an EM system customized for use in HDR brachytherapy procedures, including a novel framework for registration with TRUS imaging. The accuracy of the EM system was tested using a three-axis robotic system. We also report feasibility results on the use of EM tracking for mapping the 3D positions of catheters in a prostate phantom, concurrent with TRUS imaging. A framework for registering EM catheter positions to the TRUS image and generating a calibration that is robust against environmental distortions has also been developed. The EM-reported catheter positions were validated against manually identified catheter positions on TRUS and CT images. The experiments were performed in an ideal laboratory environment and in a brachytherapy OR, the latter to test the potential impact of the presence of clinical equipment around the treatment table on the EM measurements.

Methods and materials

The EM system

The Aurora EM system (Northern Digital, Inc., Waterloo, ON, Canada) was used in these experiments. The system consists of an FG, which generates a 50 × 50 × 50 cm^3 tracking field, within which up to four separate EM sensors can be tracked simultaneously. In our experiments, we used three EM sensors: a flexible tracked guidewire to map the catheters, a customized EM sensor pair to track the TRUS probe, and a reference sensor to aid in combined EM–TRUS data acquisition. The details of the use of these sensors are described later.