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Real-time electromagnetic tracking–based treatment platform for high-dose-rate prostate brachytherapy: Clinical workflows and end-to-end validation

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ABSTRACT

PURPOSE: New technologies were integrated into a novel treatment platform combining electromagnetically (EM) tracked catheters, a 3D ultrasound (3DUS) imaging device, and a new treatment planning system to provide a real-time prostate high-dose-rate (HDR) brachytherapy treatment system. This work defines workflows for offline CT and online 3DUS planning scenarios and preclinical end-to-end validation of the platform.

METHODS AND MATERIALS: The platform is composed of an EM-tracked stylet, a EM-tracked 3DUS probe, and an EM-tracked template guide, all used with the NDI Aurora field generator (NDI, Ontario, Canada). The treatment planning system performs continuous position and angular readings from all three EM sensors into a streamlined environment that allows for (1) contouring; (2) planning; (3) catheter insertion guidance and reconstruction; (4) QA of catheter path and tip position; and (5) exporting to an afterloader. Data were gathered on the times required for the various key steps of the 3DUS-based workflow.

RESULTS: The complete 3DUS-based workflow on 16-catheter implant phantoms took approximately 15 min. This time is expected to increase for actual patients. Plan generation is fast (7.6 ± 2.5s) and the initial catheter reconstruction with updated dose distribution is obtained at no (time) cost as part of the insertion process. Subsequent catheter reconstruction takes on average 10.5 ± 3.1s per catheter, representing less than 3 min for a 16-catheter implant.

CONCLUSIONS: This preclinical study suggests that EM technology could help to significantly streamline real-time US-based high-dose-rate prostate brachytherapy.

Keywords: Brachytherapy; Prostate; HDR; Electromagnetic tracking; EMT; RF tracking; IGABT

Introduction

Interstitial prostate high-dose-rate (HDR) brachytherapy has proven to be an exceptional modality to treat prostate cancer either as a boost for intermediate or high-risk localized cancers or as monotherapy for low-risk patients (1, 2). Combining the r^{-2} dose fall-off with inverse planning (3, 4) allows single fraction of very doses of 15 (boost) or even 19 (monotherapy) Gy to be delivered safely. Because of the fine control over dose distribution achievable in such procedures, various new approaches have been proposed to further increase the therapeutic ratio by reducing organs at risk (OARs) toxicity; groups have explored new implantation patterns (5, 6), decreasing the number of necessary catheters (7), moving to half gland and focal therapy (8). To move the field in this direction, increases in the ability to deliver catheters on target with high accuracy and reproducibility within a clinically

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relevant procedure time is required. Similarly, treatment planning systems (TPSs) should be able to provide a brachytherapy team with on-the-fly feedback related to changes in the volumes of interest, implant geometry, and dose distribution. Ultrasound-based image-guided adaptive brachytherapy (IGABT) provides part of the solution (9−11) but catheter reconstruction either from CT, US, or MRI—and in particular catheter tip localization—remains a time-consuming and error-prone process; any error introduced at that stage of the treatment will have a direct systematic effect on the dose distribution (12).

Electromagnetic tracking (EMT) technology has seen a rapid increase in use in the medical fields over the last decade (13). At its most basic, the technology consists of an electromagnetic field generator, a sensor, and a signal processing unit. The unit is able to pinpoint the location of sensor in the active volume of the field generator using the signal induced in the sensor by the EM field (14). The sensitive region of table-top sensors for medical use is approximately one cubic meter in front of and centered on the field generator. Though, in practice, usable field sizes (±1 mm positional uncertainty) are less than about $30 \times 30 \times 30$ cm^3 (15).

A $30 \times 30 \times 30$ cm^3 field size is sufficient for using an EMT system with a standard setup for transrectal ultrasound (TRUS) brachytherapy of the prostate. For HDR brachytherapy, several authors have shown the feasibility of in vivo catheter reconstruction using either DC (16) or AC version of EMT (17−19), where the latter seems to perform better in an operating room setting (17).

In this work, we present a new standalone interstitial prostate HDR IGABT system in which catheters, catheter template guide, and the TRUS probe are simultaneously tracked in a common reference frame using EM technology. It is posit that the new information provided by EMT technology will streamline US-based IGABT and allow for true-dynamic dose optimization. This work defines workflows for offline CT planning and online 3DUS planning scenarios and presents a preclinical end-to-end validation of the platform.

Methods and materials

The platform

As depicted in Fig. 1, the platform is composed of an EM-tracked stylet (Philips Electronics Ltd Toronto, Canada) in which a 6 degrees of freedom sensor is used with the NDI V3 Aurora field generator (NDI, Ontario, Canada). The system provides real-time (40 Hz) x, y, and z coordinates as well as pitch, yaw, and roll information of the stylet tip. Retraction of the stylet after insertion provides reconstruction of each catheter, including the catheter's tip position, which is registered in real-time by the TPS. In practice, the data are noisy and sampling will depend on

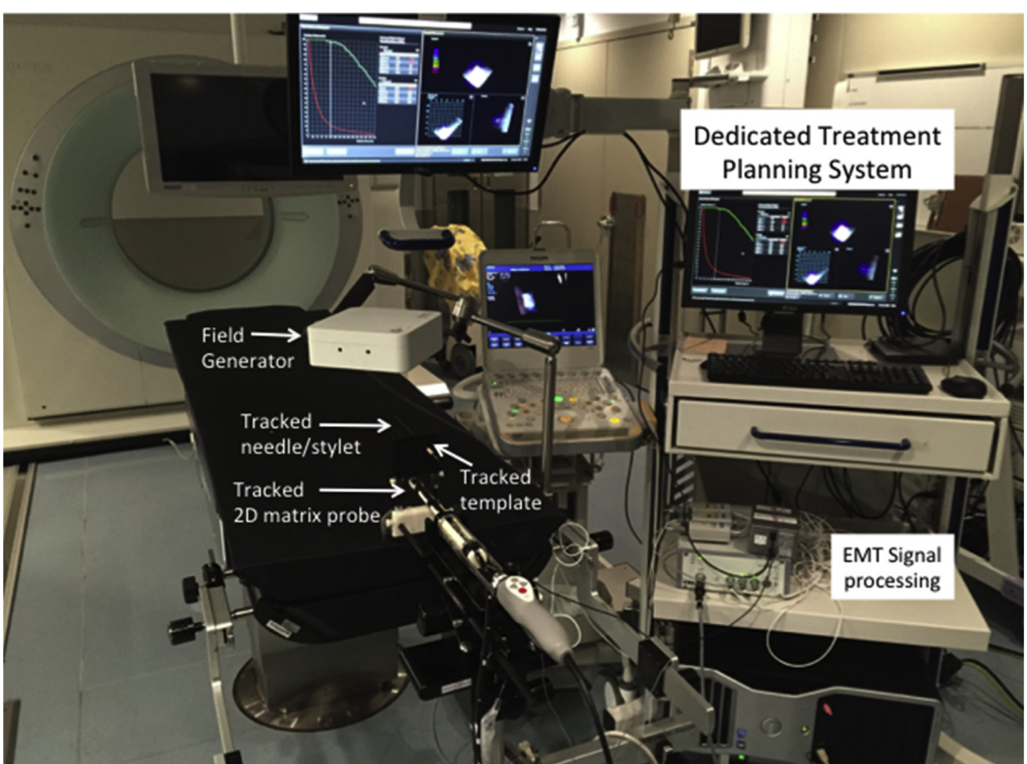

Fig. 1. Components of the proposed new system deployed in a shielded brachytherapy-dedicated operating room. Key components such as the field generator, EM-tracked stylet, EMT signal processing unit, and treatment planning systems are shown. EMT = electromagnetic tracking.