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Validation of MRI to TRUS registration for high-dose-rate prostate brachytherapy

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ABSTRACT

PURPOSE: The objective of this study was to develop and validate an open-source module for MRI to transrectal ultrasound (TRUS) registration to support tumor-targeted prostate brachytherapy.
METHODS AND MATERIALS: In this study, 15 patients with prostate cancer lesions visible on multiparametric MRI were selected for the validation. T2-weighted images with 1-mm isotropic voxel size and diffusion weighted images were acquired on a 1.5T Siemens imager. Three-dimensional (3D) TRUS images with 0.5-mm slice thickness were acquired. The investigated registration module was incorporated in the open-source 3D Slicer platform, which can compute rigid and deformable transformations. An extension of 3D Slicer, SlicerRT, allows import of and export to DICOM-RT formats. For validation, similarity indices, prostate volumes, and centroid positions were determined in addition to registration errors for common 3D points identified by an experienced radiation oncologist.
RESULTS: The average time to compute the registration was 35 ± 3 s. For the rigid and deformable registration, respectively, Dice similarity coefficients were 0.87 ± 0.05 and 0.93 ± 0.01 while the 95% Hausdorff distances were 4.2 ± 1.0 and 2.2 ± 0.3 mm. MRI volumes obtained after the rigid and deformable registration were not statistically different ($p > 0.05$) from reference TRUS volumes. For the rigid and deformable registration, respectively, 3D distance errors between reference and registered centroid positions were 2.1 ± 1.0 and 0.4 ± 0.1 mm while registration errors between common points were 3.5 ± 3.2 and 2.3 ± 1.1 mm. Deformable registration was found significantly better ($p < 0.05$) than rigid registration for all parameters.
CONCLUSIONS: An open-source MRI to TRUS registration platform was validated for integration in the brachytherapy workflow.

Keywords: HDR brachytherapy; Registration; MRI; Ultrasound; Prostate; Open source

Introduction

Long-term disease control for prostate cancer patients can be achieved using high-dose-rate (HDR) brachytherapy (1, 2) with conventional techniques treating the whole gland (3). However, such an approach may limit the efficacy of radiotherapy as escalation of dose will be limited by the tolerance of adjacent organs at risk (4). Pathology studies suggest that in many cases, a dominant cancer focus may exist within the gland and could be at the epicenter of recurrence after treatment (5, 6). Strategies to identify and intensify treatment to dominant intraprostatic lesions (GTV) are therefore needed, and MRI demonstrates high performance in addressing this need (7, 8). Multiparametric MRI (9, 10) has been integrated in the clinic to identify the GTV in order to boost or target intraprostatic lesions (11, 12). Several

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recent studies were performed to investigate the feasibility of dose escalation and focal brachytherapy using multiparametric MRI to define GTVs (13−17).

However, a significant number of programs are using transrectal ultrasound (TRUS) as their treatment planning modality due to its low cost, easy accessibility, and real-time capability. The current clinical procedures, based on ultrasound images, cannot identify the position of the GTV (18). Therefore, a spatial registration is needed between MRI and TRUS images to accurately locate the GTV. Adequate registration between MRI and TRUS would allow dose escalation or focal brachytherapy using an ultrasound technique. On the other hand, most rigid registration algorithms rely on similar prostate shape (19), which is often inadequate. In fact, the prostate shape is often different between TRUS and MRI images; a transrectal probe is used to obtain TRUS images while MRI images are usually obtained several days before TRUS images, with or without an endorectal coil. In brachytherapy, there is currently no commercially available MRI to TRUS deformable registration algorithm to correct for this difference in prostate shape.

Several commercial MRI to TRUS registration systems are available for biopsy patients (20); however, they were not adapted to prostate brachytherapy, and they have several issues. In fact, most commercial MRI-TRUS fusion products implement linear registration only (20). In addition, they are typically used as a black box and do not allow the export of the registration results (19). MIM Software Inc has developed the predictive fusion technology (21), named bkFusion (22), to reslice MRI images into the ultrasound by placing the virtual position of the ultrasound probe into the MRI. It has the advantage of being integrated in the bk3000 ultrasound system. However, it relies on the supposition that the ultrasound probe is actually where it was virtually inserted and that there is no deformation induced by the probe. MRI can be segmented in advance of the brachytherapy procedure; therefore, a registration algorithm based on the contours would be a feasible approach. RaySearch Laboratories offers a contour-based deformable registration algorithm MORFEUS (23); however, accessibility to the system is limited, and there is no publication that specifically validates the algorithm for MRI to TRUS prostate registration to date.

The goal of the study was to develop and validate an open-source module for MRI to TRUS registration to support tumor-targeted prostate brachytherapy. The module was implemented in the three-dimensional (3D) Slicer medical image visualization and analysis software platform (24).

Methods and materials

Clinical data

Fifteen patients who underwent HDR brachytherapy with confirmed prostate cancer and lesions visible on MRI were selected for the validation. This study was approved by the local Institutional Review Board. T2-weighted 3D variable-flip-angle Turbo Spin Echo images with 1-mm isotropic voxel, apparent diffusion coefficient maps (b-value = 50, 500, and 1000 s/mm^2), and extrapolated diffusion weighted images with b-value = 1400 s/mm^2 were acquired on a 1.5 T Siemens Aera Magnetom (Siemens Healthineers, Erlangen, Germany), using surface coils, for prostate and GTV contouring. Three-dimensional TRUS images, with 0.5-mm thick slices, were obtained with Oncentra Prostate (OcP) system v4.2 (Elekta Brachytherapy, Veenendaal, The Netherlands) using BK Flex Focus 400 and the transrectal probe 8848 (BK Ultrasound, Peabody, MA). MRI contouring was performed at least 1 day before the procedure on the Varian Eclipse planning station (Varian Medical Systems, Palo Alto, CA), whereas TRUS contours, before catheter placement, were obtained on OcP during the HDR brachytherapy procedure.

Registration

The registration software tool is available as a module of the open-source 3D Slicer platform (24). Figure 1 shows the MRI-TRUS registration module within the 3D Slicer environment, for version 4.7.0-2017-03-13. The user needs to install the extension Segment Registration through the 3D Slicer extension manager, and the module name is "Prostate MRI-US Contour Propagation" in 3D Slicer. The SlicerProstate and SlicerRT (25) extensions are used by the new modules for the data management and registration steps. The validated BRAINSFit algorithm was used for the registration (26). The proposed module is also based on a validated registration method based on distance maps (19). Before the registration step, in the contour propagation module, 3D TRUS volumes were resampled to the resolution of T2-weighted MRI volumes (1 mm). Briefly, the rigid registration method uses an iterative closest point method on the prostate surface meshes (27) to align both prostate contours. Consequently, the centroids of the reference and moving images should closely match in the same coordinate space. The deformable registration (19) is performed after the initial rigid registration. First, an affine registration is performed. Second, a B-spline regularization is executed to elastically align the binary 3D label maps (19). The proposed module, combined with SlicerRT, allows DICOM-RT structures to be imported. Furthermore, the module permits the conversion of planar contours, generated by the treatment planning system, to label maps. A label map volume can be defined as a 3D image where each voxel is a number indicating the type of tissue at that location. This representation allows the efficient handling of the different representations of the segmentation. In addition, contours obtained from rigid and deformable transformations can be exported in RT structures, which are compatible with a treatment planning system. The transformed contour (denoted here as either rigid and deform) is converted to the original 3D TRUS resolution.