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A 3D Neurovascular Bundles Segmentation Method based on MR-TRUS Deformable Registration

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Abstract

In this paper, we propose a 3D neurovascular bundles (NVB) segmentation method for ultrasound (US) image by integrating MR and transrectal ultrasound (TRUS) images through MR-TRUS deformable registration. First, 3D NVB was contoured by a physician in MR images, and the 3D MR-defined NVB was then transformed into US images using a MR-TRUS registration method, which models the prostate tissue as an elastic material, and jointly estimates the boundary deformation and the volumetric deformations under the elastic constraint. This technique was validated with a clinical study of 6 patients undergoing radiation therapy (RT) treatment for prostate cancer. The accuracy of our approach was assessed through the locations of landmarks, as well as previous ultrasound Doppler images of patients. MR-TRUS registration was successfully performed for all patients. The mean displacement of the landmarks between the post-registration MR and TRUS images was less than 2 mm, and the average NVB volume Dice Overlap Coefficient was over 89%. This NVB segmentation technique could be a useful tool as we try to spare the NVB in prostate RT, monitor NVB response to RT, and potentially improve post-RT potency outcomes.

Keywords

Neurovascular bundles (NVB); segmentation; MRI-US registration; erectile dysfunction

1. INTRODUCTION

In the United States, 2.36 million men have survived prostate cancer, and are currently living with cancer-affected life years [1–3]. Erectile dysfunction (ED), the loss of sexual potency, is the most common and debilitating side effect after radiotherapy (RT) for prostate cancer. The mechanism behind radiotherapy-related ED is not fully understood and one hypothesis is that neurovascular bundle (NVB) injury is correlated with the radiation-associated ED [4–11]. The NVB are difficult to see on the CT or US B-mode images that physicians often rely

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on to plan radiation treatment. Thus, high dose of radiation is frequently delivered to the NVB. There is a critical clinical need to localize the NVB in prostate RT treatment planning [12, 13].

We propose to integrate MR into transrectal ultrasound (TRUS) images through MR-TRUS registration for accurate segmentation of 3D NVB in TRUS. The proposed method uses a deformable MRI-TRUS registration based on a patient-specific biomechanical model to transform the 3D MR-defined NVB into TRUS images to accurately localize and segment NVB in TRUS images. This technology was tested in a pilot study of 7 prostate-cancer patients. To the best of our knowledge, we are the first to utilize MR images to accurately define the NVBs to improve NVB localization in prostate radiation therapy based on MR-TRUS deformable registration.

2. METHODS

As shown in Figure 1, our segmentation approach involves 5 major steps: 1) MR diagnostics prostate images are captured before the RT procedure; 2) Patient receives 2 3D TRUS ultrasound scans and ultrasound Doppler scans; 3) Physician contours NVB volumes using MR images; 4) MR-TRUS image registration is performed using a patient-specific biomechanical model; and 5) MR-based NVB volumes are integrated into 3D TRUS images for treatment planning.

2.1 MR image acquisition

In this pilot study, all patients had previous diagnostic MR scans of the prostate. As compared with CT, MRI has a high soft tissue contrast and is the best imaging modality for 3D visualization of the NVB. Hence, in this study, we used NVB contours from the MR images as the gold standard to segment NVB in the TRUS images. All patients were scanned in the head first, feet-down supine position with a body coil using a Philips MRI with a 2 mm slice thickness. All NVBs were manually segmented from the T2-weighted MR images.

2.2 3D TRUS image acquisition

The 3D TRUS images were captured with a clinical ultrasound scanner (HI VISION Avius, Hitachi Medical Group, Japan) and a transrectal 7.5 MHz prostate biplane probe (UST-672–5/7.5). During the data acquisition, the transrectal probe was held with a mechanical SurePoint stepper (Bard Medical, Inc., GA) to allow for a manual stepwise movement along the longitudinal axis. The patient was scanned in the lithotomy position, and a series of parallel axial (transverse) scans were captured, from the apex to the base with a 1 or 2 mm step size, to cover the entire prostate gland and NVBs plus the 5–10 mm anterior and posterior margins. In addition, power Doppler images were captured at 5 mm step size through the entire prostate regions.

2.3 NVB segmentation in MR image

A radiation oncologist manually contoured the prostate, and the right and left NVB volumes using MR prostate images. For a typical prostate of 50 mm, with 2 mm slide thickness, approximately 25 TRUS slides needed to be contoured and it took 10 to 20 minutes to

contour the prostate and NVB volumes. Even though this was time consuming, manual contours would provide the most accurate prostate and NVB volumes.

2.4 MR-TRUS fusion

The key part of our proposed segmentation method was MR-TRUS registration. This paper used a new MR-TRUS registration method that combined a subject-specific biomechanical model with B-spline-based transformation [13]. As shown in Figure 2, the MR-TRUS registration method consisted of three major components. First, we calculated a 3D patient-specific prostate-gland strain map from two 3D TRUS scans under different probe-induced pressures, which was similar to ultrasound elastography. We used surface registration between the MR and TRUS prostate surfaces to capture the prostate transformation based on the B-spline model by minimizing the Euclidean distance between the normalized attribute vectors of surface landmarks of MR and TRUS prostate surfaces [14]. Finally, we combined the prior prostate-gland strain map into the surface-based transformation to constrain/guide the volumetric deformation of the prostate gland in the MR-TRUS registration [2]. The proposed registration method took into account the wide variations among patients and within each prostate gland – normal prostatic tissue, cysts, cancers and calcifications that all have different elastic properties. This registration based on the inhomogeneous elasticity model could improve the prostate tissue deformation by providing a physical regularization of the deformation map.

2.5 Integration of MR-based NVB into 3D TRUS mages

This registration method used one-modality image registration between two 3D TRUS images to provide prior tissue deformation guidance for two-modality image registration between MR and TRUS to improve the accuracy of MR-TRUS registration. The NVB are composed of numerous nerve fibers superimposed on a scaffold of veins, arteries, and variable amounts of adipose tissue surrounding almost the entire lateral and posterior surfaces of the prostate. The accurate prostate tissue deformation provides the basis for an accurate TRUS segmentation of the NVB surrounding the prostate surface. After the MR-TRUS deformable registration the MR-defined NVB can be transferred into the TRUS image using the transformation obtained from this registration to achieve the 3D NVB segmentation in TRUS images.

2.6 Reliability evaluation of the segmentation algorithm

The NVB segmentation results were compared with the Doppler-defined NVB regions. A common evaluation measure for a segmentation method is the Dice overlap ratio. The Dice overlap ratio [15] is defined as follows:

$$Dice(Vol_1, Vol_2) = \frac{2|Vol_1 \cap Vol_2|}{|Vol_1| + |Vol_2|}$$

where Vol_1 represents the voxels of the NVB segmented by the automated algorithm in TRUS and Vol_2 represents the voxels of the corresponding ultrasound Doppler-defined NVB in TRUS images.

3. RESULTS

In order to validate the proposed registration method, we conducted a clinical study with 7 prostate cancer patients. All patients' TRUS data were acquired using a Hitachi ultrasound machine and a 7.5MHz bi-plane probe. Each 3D B-mode TRUS data set consisted of $1024 \times 768 \times 75$ voxels and the voxel size was $0.10 \times 0.10 \times 1.00 \text{ mm}^3$. The ultrasound Doppler images were captured from the prostate base to apex at a 5-mm step. All MR images were acquired using a Philips 1.5T MR scanner and a pelvic phase-array coil. The 3D MRI data consisted of $320 \times 320 \times 92$ voxels, and the voxel size was $0.63 \times 0.63 \times 2.00 \text{ mm}^3$. All prostate glands were contoured in T2-weighted MR and TRUS images by an experienced physician. For each patient, three to six landmarks were identified in post-registration MR and TRUS images to facilitate quantitative comparison. In addition, we used the patients' ultrasound Doppler images to further validate our MR-based NVB segmentation.

We successfully performed the segmentation method for all enrolled 6 prostate-cancer patients. Figure 3 shows the NVB in MR images for a 65-year old prostate-cancer patient. Figure 4 demonstrates the ultrasound Doppler validation of our segmentation method. In Figure 4(b) the red and blue regions are blood signals in Doppler images and the region within the yellow contour is the MR-defined NVB. The segmented NVB matches with the Doppler signal very well. In addition, though MR-TRUS registration, 3D visualization and blood flow information of the NVB are also obtained. The mean displacement of the landmarks between the post-registration MR and TRUS images was $1.87 \pm 0.37 \text{ mm}$, which demonstrated the precision of the registration based on the biomechanical model. Figure 5 shows the left and right NVB volume overlap between the segmented NVB and ultrasound-Doppler-defined NVB for each patient. Overall, the average NVB volume Dice Overlap coefficient was $89.5 \pm 3.5\%$, which demonstrated the accuracy of the proposed registration-based segmentation method.

4. DISCUSSION AND CONCLUSION

Currently, MRI is the most reliable imaging modality for 3D visualization of the NVB, while Doppler ultrasound can provide blood flow information of the NVB [16]. We have developed a novel approach to improve 3D NVB segmentation through MR-TRUS deformable registration for prostate RT, demonstrated its clinical feasibility, and validated its accuracy with ultrasound Doppler data. Our method combines its anatomical structures in MR images and its functional information in ultrasound Doppler imaging [17]. Our method not only provides the 3D visualization of the NVB, but also provides its functional and dynamic property (blood flow) [13]. This tool could be useful as we try to protect the NVB in prostate RT, monitor NBV response to RT, and potentially improve post-RT potency outcomes.

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Figure 1.
Flow chart of integrating MR-based 3D NVB into TRUS.

Figure 2.
Flow chart of the MR-TRUS registration

Figure 3.
The NVB in MR image in axial (a), coronal (b) and sagittal (c) planes.

Figure 4. Ultrasound Doppler validation of our technology. 3D NVB in TRUS after MR-TRUS registration (a) and ultrasound Doppler image (b). Though MR-US registration, 3D visualization and blood flow information of the NVB are obtained.

Figure 5.
The left and right NVB volume overlap of each patient.