Prototype Design and Phantom Evaluation of a Device for Co-registered MRI/TRUS Imaging of the Prostate

Andriy Fedorov[1(✉)], Sang-Eun Song[1], Tina Kapur[1], Robert Owen[2], Emily Neubauer Sugar[3], Paul Nguyen[3], William M. Wells III[1], and Clare M. Tempany[1]

[1] Department of Radiology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115, USA
fedorov@bwh.harvard.edu
[2] BK Medical, Peabody, MA 01960, USA
[3] Department of Radiation Oncology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115, USA

Abstract. Magnetic Resonance Imaging (MRI) and transrectal Ultrasound (TRUS) are both used in imaging interventions in men suspected of having and with prostate cancer for diagnosis as well as treatment. Due to the widespread availability and ease of use of TRUS, it is widely acknowledged that availability of spatially registered MRI/TRUS data could provide the optimal combination for characterization of prostate tissue and interventional guidance. To provide such spatially aligned data, we propose a device to support co-registered acquisition of MRI and TRUS data while maintaining a stable configuration (shape) of the prostate. We present the design and evaluation of a custom sleeve that can be introduced transrectally, and can accommodate both TRUS and endorectal MRI probes. Our experiments on a phantom have demonstrated that imaging with this sleeve did not compromise differentiation of internal structures and did not affect the quality of the MR acquisition. Reduction of the signal and contrast were however observed and quantified in the TRUS data. Further evaluation and modification of the device necessary for possible patient studies are discussed.

Keywords: Prostate cancer · Image-guided interventions · Magnetic resonance imaging · Transrectal ultrasound · Image registration · Tissue characterization · Phantom evaluation

1 Introduction

Prostate cancer (PCa) is the most common non-cutaneous malignancy in men in the USA [1]. Imaging has a unique role in the clinical management of this disease. Transrectal ultrasound (TRUS) is the most commonly used method for image guided biopsy of the prostate gland; it is widely used for collection of core biopsy

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samples in sextant approaches, and for guiding treatment procedures. The use of TRUS has expanded beyond routine clinical B-mode acquisitions to guide treatment, to research in US elastography and analysis of radiofrequency (RF) signal for tissue characterization [2]. Meanwhile, Magnetic Resonance Imaging (MRI) is most commonly used for detection, localization and staging of PCa [3, 4]. The complementary utility of these two imaging approaches is recognized and has motivated the development of systems that augment intra-procedural TRUS for real-time imaging of the gland with pre-procedural MRI clearly showing the confirmed or suspected cancer regions. In practice, development of such systems is challenging due to lack of spatial alignment between the MR and US modalities. To alleviate this problem, we report our initial experience in the development of a device to reduce deformation of the prostate by providing a fixed physical setup during the acquisition of MRI and TRUS data.

One of the challenges in supporting joint MRI/US visualization is the difference in the spatial configuration, i.e. shape, of the prostate between the TRUS and MRI imaging sessions. Each imaging modality is associated with its own unique deformation of the gland tissues. As a result, some form of registration between the MRI and TRUS imaging is typically required to provide meaningful joint visualization. Due to the significant differences between the MRI and TRUS images, practical registration approaches are often augmented by the use of various forms of tracking and segmentation of the prostate gland to simplify the registration problem. Early approaches to MRI/TRUS registration were based on rigid alignment using anatomical landmarks [5]. More commonly, the registration is based on aligning boundaries of the prostate segmented in MRI and TRUS. Several surface-based registration approaches have been proposed [6,7]. Hu et al. developed a model-to-image registration method that relies on biomechanical simulation to estimate the most likely deformation in the planning stage of the procedure [8]. Over the last years, several systems have become available commercially to support MRI/TRUS image fusion [9]. Most of these commercial systems rely on the segmentation of the prostate gland to provide non-rigid deformation between MRI and TRUS. While there is strong evidence that MRI/TRUS fusion improves accuracy of biopsy guidance for PCa detection, the targeting accuracy of the fusion systems is difficult to assess. Commonly used error quantification approaches only utilize manually identified corresponding features that are consistent in MRI and TRUS. Due to the differences between the MR and US modalities, localization of the corresponding features is challenging and time-consuming, limiting the applicability of the approach.

In this article we propose an alternative to commonly used registration of images obtained from MRI and TRUS. Our method relies on a custom device that can maintain the spatial arrangement of the prostate between the MRI and TRUS imaging sessions. As an expected result, deformable registration of the two imaging modalities can be eliminated, thus, a rigid coordinate system transformation between the two images collected by the respective modalities should be sufficient for spatial alignment. Such a device can facilitate intra-procedural

tracking of the target, providing valuable data for joint characterization of the MRI/TRUS and for validation of image-based deformable registration.

The goals of this paper are twofold. First, we present the technical considerations and the initial design of a device to maintain consistent spatial arrangement of the prostate gland. Second, we report a phantom study that we performed, using this device, to establish the feasibility of MRI and TRUS imaging, and to evaluate the quality of the collected images.

2 Methods

Our initial design of the Adjustable Sleeve Template Assembly (ASTA) device was conceived to support consistent spatial arrangement of the prostate and interchangeable MRI/TRUS imaging during two targeted transperineal interventions – template-based biopsy, and implantation of low-dose radioactive seeds in prostate brachytherapy. To achieve this goal, the complete ASTA device would include (1) a sleeve, constructed to be MR safe and US-transparent, to interchangeably accommodate both the MRI endorectal coil and the TRUS probe, (2) the biopsy/brachytherapy grid template rigidly attached to the sleeve, and (3) a calibration device, such as Z-frame [10]. Consistent position of the ASTA would be maintained by semi-rigid mechanical coupling to the procedure table. In this article, we focus on the development of the sleeve component of ASTA, and evaluation of the image quality when such a sleeve is used.

Design of the ASTA Sleeve. Our design was intended to accommodate two imaging probes interchangeably: a rigid transrectal MR coil (Hologic Endo MRI Coil, Hologic Inc, Bedford, MA), measuring 25 mm at its widest cross-section, and a transrectal ultrasound probe (BK 8848, BK Medical, Peabody, MA) measuring 20 mm at its widest cross-section. A sleeve was fabricated from polymethylpentene (TPX), a material with acoustic impedance similar to tissue [11]. Sleeve thickness was set to 1.8 mm, resulting in sleeve outer diameter of 29 mm (25.4 mm inside diameter to accommodate the coil). To account for the differences in the outer diameter between the MR coil and US transducer, a saline-filled endocavity balloon (Civco Medical Solutions, Kalona, IA) was used during TRUS imaging through the sleeve. As an FDA-approved clinical device, the endocavity balloon serves a dual purpose: it improves acoustic coupling between the tissue and the transducer surface, and, when necessary, pushes the prostate gland to match the coverage field of the brachytherapy template. In our scenario, the balloon was used to ensure acoustic coupling between the transducer and the sleeve. The components involved in the experimental setup are shown in Fig. 1.

Image Acquisition. Ultrasound imaging Our experiments for evaluating the feasibility imaging, and the quality of resulting images, utilized a standard multimodality prostate phantom (model 053-MM, CIRS, Norfolk, VA). The phantom is constructed with different types of materials to emulate imaging contrast between anatomical structures, including the prostate gland, urethra and lesions. TRUS imaging was performed using the BK ProFocus system and the transverse array of

Fig. 1. Components used in the experimental setup. From top to bottom shown are (1) a syringe connected with the endocavity balloon (Civco); (2) rigid transrectal MRI coil (Hologic); (3) transrectal ultrasound probe (BK Medical); (4) custom fabricated TPX sleeve.

the 8848 transrectal probe with the endocavity balloon mounted according to the manufacturer instructions. The experiments were performed with and without the sleeve to compare image quality. Each of the experiments was repeated 10 times, with the transducer reinserted during each experiment to evaluate the repeatability of the measurements. Ultrasound gel (Aquasonic, Parker Labs, Farfield, NJ) was used to enhance acoustic coupling of the surfaces. Identical acquisition settings were used for the imaging experiments with and without the sleeve (gain 80 %, dynamic range 79 dB, frequency 12 MHz, depth 5.4 cm, identical range and depth of the focal interval). Image collection was facilitated by the open source Public Library for UltraSound research (PLUS)[1] [12].

MR Imaging. MR imaging experiments were conducted in a 3 Tesla scanner (Siemens Magnetom Verio, Erlangen, Germany). Imaging was performed using the commercially available tabletop attachment (Hologic Inc, Bedford, MA) to the scanner table. Two pelvic array coils were placed above and below the phantom, and the rigid endorectal coil was placed in the phantom rectum. Imaging was performed using multi-slice Turbo Spin Echo T2-weighted sequence (TR/TE = 2700 ms/106 ms; acquisition matrix = 280×280; flip angle = 48°; field of view = $200 \times 200\,\text{mm}^2$; slice thickness = 3 mm; receiver bandwidth = 252 Hz/pixel; imaging time: 1 min). MR imaging was repeated 5 times both with and without ASTA sleeve, with the endorectal coil reinserted for each imaging session.

Image Quality Assessment. Images of the phantom corresponding to approximately the same transverse plane were assessed. A consistent transverse location was selected such that the slice covered the widest cross-section of the specific lesion implanted in the phantom. To quantitatively measure the degradation in image quality caused by the ASTA sleeve, we used two measures:

1. Average signal value in the regions of interest (TRUS only). For US images, signal intensity relates to the energy of the returning ultrasound waves. There-

[1] Public Library for UltraSound research (PLUS), http://plustoolkit.org.

fore, reduction in grayscale values is a measure of signal loss due to the introduction of extra layers between the scanned object and transducer surface.

2. Pairwise contrast to noise (CNR) measure:

$$CNR = \frac{2(\mu_1 - \mu_2)^2}{(\sigma_1^2 + \sigma_2^2)}, \tag{1}$$

where μ_1 and μ_2 are the mean intensity values, and σ_1 and σ_2 are standard deviation values for the two regions. CNR was measured pairwise between the prostate, urethra and lesion in the phantom.

3 Results

Using visual examination of the acquired images, we confirmed that MRI and TRUS imaging through the ASTA sleeve was feasible. Acoustic coupling during US imaging was established in all experiments and no gross artifacts were observed. Image contrast was sufficient to differentiate all the phantom structures considered in the evaluation (prostate, urethra and lesions regions). Representative images are shown in Fig. 2. US images collected through the balloon/sleeve assembly had noticeably reduced signal, were noisier and had reduced sharpness of the boundary between the distinctive phantom structures, based on visual inspection, as can be observed in Fig. 2 (top row). A bright double halo surrounding the region corresponding to the probe location was apparent in the MR images, however no noticeable degradation of the MR image quality was observed by introducing the sleeve.

The results of the quantitative assessment of the collected data are summarized in Fig. 3 and Table 1. Measurements of the signal strength agreed with

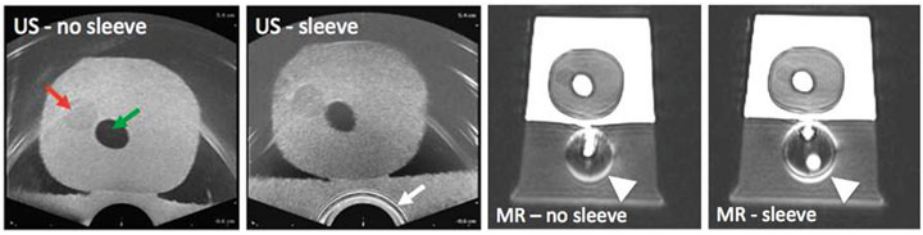

Fig. 2. Representative US and MR images of the multimodality prostate phantom. The slice shown corresponds to approximately the same transverse position relative to the phantom geometry. CNR measurements were performed pairwise between the lesion (red arrow), urethra (green arrow) and prostate regions (structure enclosing lesion and urethra). Strong reflection artifact near the surface of the TRUS probe (white arrow) corresponds to the saline-filled endocavity balloon, TPX sleeve and the layers of gel that were used to ensure acoustic coupling between the surfaces. Single and double bright circles observed in MRI (white arrowhead) are due to the signal from the acoustic gel surrounding the coil and the sleeve (Color figure online).

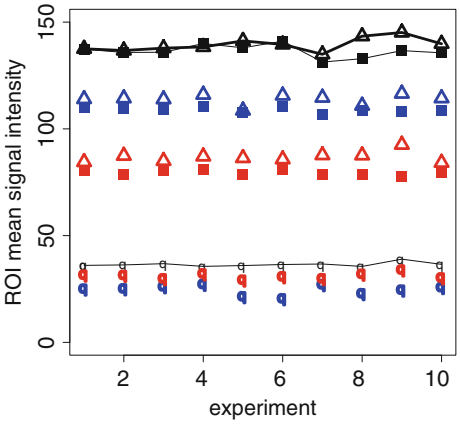

Fig. 3. Average signal measured from the regions of interest defined in lesion (square marker), prostate (triangle) and urethra (circle) areas. Colors correspond to the images acquires using transducer without introducing any additional layers (black), using endocavity balloon alone (blue), and together with the TPX sleeve (red). Reduction of signal introduced by addition of extra layers is apparent (Color figure online).

Table 1. Quantitative assessment of the US and MR image contrast between the lesion (region 1), urethra (2) and prostate (3) phantom tissue types. Mean and standard deviation reported for the pairwise combinations of the considered regions.

Modality	Summary statistics	CNR, no sleeve 1–2	1–3	2–3	CNR, sleeve 1–2	1–3	2–3
US	mean	144	0.2	182	47	0.5	71
US	STD	29	0.4	40	9	0.3	10
MR	mean	952	0.7	1004	804	1.8	826
MR	STD	397	0.5	420	215	2.8	217

the visual assessment of US images, as we observed reduction of the signal that was reproducible across the experiments. Averaged over 10 experiments, the mean grayscale values measured in the TRUS images were (for the three regions of interest considered) 136, 37 and 139 when the transducer was used without extra attachments, 109, 25 and 114 units when endocavity balloon was used, and 75, 36 and 87 units when we added the TPX sleeve. Differences between the signal values for the MR images were minimal. CNR measurements showed reduction of CNR when balloon/TPX sleeve were introduced.

4 Discussion and Conclusions

In this study we introduced a prototype of a simple sleeve-based device to facilitate co-registered acquisition of endorectal MRI/TRUS imaging of the prostate. The motivation for this device is to maintain the prostate in a consistent position

and shape so that there is minimal or no effect on the prostate configuration due to removal or introduction of imaging probes. Our study focused on the preliminary evaluation of technical feasibility of the prototype and assessment of the image quality. We confirmed experimentally that imaging of the phantom with the sleeve assembly was feasible using both MR and US, does not introduce severe artifacts, and does not compromise the ability of the operator to differentiate the structures of interest in the phantom. This was confirmed even for the lesion structure of the phantom, which has rather low contrast relative to its surrounding.

Our experimental evaluation also showed that introduction of the extra layers, even when those layers are fabricated from materials with acoustic properties similar to tissue, resulted in reduction of signal strength and contrast in the US images. Such signal loss is not only due to the presence of the extra TPX/saline layers, but also due to the intermediate layers of gel used for acoustic coupling. There are several observations related to this reduction of signal and image contrast. First, we note that the loss of signal strength due to the presence of a TPX sleeve appears to be comparable with that caused by the saline-filled endocavity balloon (as can be seen in Fig. 3), an FDA-approved product for our clinical scenario. This leads us to conjecture that the signal loss we are introducing with the TPX is comparable to what is considered acceptable clinically. Second, we used identical setup and image acquisition parameters for the experiments with and without the sleeve. An increase in the TRUS gain settings in the experiments that used the sleeve can potentially improve CNR. Finally, we note that while the phantom experiments reported in this study allow us to understand and quantify some of the technical issues related to image acquisition, further investigations are needed in order to understand the applicability of the device in the patient studies.

There are several specific clinical usage scenarios where a sleeve-based device such as the one presented can be used. For example, an MRI scan with the device in place can be obtained at the beginning of a procedure, followed by an US scan. After that the device can be removed, and targets identified in MRI can be tracked by registration between the initial, possibly 3D reconstructed, US, with the intra-procedural US data. Alternatively, volumetric TRUS study can be performed immediately after the MRI scan at the time of the diagnostic exam, in advance of the intervention. As a second example, RF TRUS data that is acquired in near-perfect alignment with mpMRI can be used for characterization of the prostate tissue. To implement such scenarios, further engineering efforts are underway. For instance, ASTA design must be able to maintain the sleeve at a fixed position while imaging probes are exchanged. A multi-modality operating room, such as AMIGO at BWH[2], would be ideal for evaluation of the setup, as the patient lithotomy position needs to be maintained while the patient is moved out of the scanner bore.

[2] The Advanced Multimodality Image-Guided Operating (AMIGO) Suite, Brigham and Women's Hospital, Boston, USA, http://www.ncigt.org/pages/AMIGO.

The design evaluated in this study represents only one of the prototypes we have considered. Alternative designs that do not introduce extra layers between the ultrasound transducer and the tissue have been tested and will be included in future evaluations. The US imaging experiments were performed utilizing only the transverse array of the probe. Additional experiments may be performed to evaluate the feasibility of the sagittal array scanning and the quality of the 3D reconstructed TRUS volumes.

In conclusion, we have presented initial results in developing and evaluating a device for co-registered MR/TRUS prostate imaging. The images of the phantom obtained while using the sleeve have reasonable quality. Further evaluation and modification of the device are planned prior to clinical use. ASTA can provide MR/US data with minimal misalignment and it can be valuable for improved understanding of prostate tissue characterization, development of joint MR/US appearance models of prostate, and improved accuracy of image-guided prostate interventions.

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