CLINICAL ACCURACY OF ROBOT-ASSISTED PROSTATE BIOPSY IN CLOSED MRI SCANNER

Helen Xu[1], Andras Lasso[1], Siddharth Vikal[1], Peter Guion[2],
Axel Krieger[3], Aradhana Kaushal[2], Louis L. Whitcomb[4], Gabor Fichtinger[1,4]

[1]Queen's University, Kingston, Canada; [2]National Institutes of Health, Bethesda, USA; [3]Sentinelle Medical Inc., Toronto, Canada; [4]Johns Hopkins University, Baltimore, USA

Contact: gabor@cs.queens.ca

INTRODUCTION

Prostate cancer, affecting one in every six men, remains the number one cancer-related death in men [1]. In the pursuit of more accurate biopsy, Krieger and Susil [2,3] developed robotic assistance under MR image guidance. To date, their system has been used in 200+ biopsies at the U.S. National Cancer Institute. A limited validation study was presented earlier [4]. Here we report a more comprehensive retrospective evaluation of the Krieger-Susil biopsy system. We analyze a larger set of patient data in an improved validation workflow and produce a formal statistical analysis and draw strong conclusions.

MATERIALS AND METHODS

Imaging: The patient was placed in the scanner prone, and 2D high-resolution T2 axial volume of the prostate was acquired. The clinician picked biopsy targets in scanner coordinates. The robot was then used to guide a biopsy needle through the rectum into the target sites within the prostate to collect tissue samples. After the needle was in place, 2D axial volume was taken to confirm needle placement. We used these pre- and post-needle insertion volumes in our validation.

Registration: Developing a registration algorithm for patient data collected over five years, by many clinicians, with a variety of scanners, imaging protocol, image resolution, field strength, frequency etc. was a challenge. Prostate motion upon needle insertion can be complex as it dislocates differently from surrounding structures, varying from patient to patient. Our goal was to find a method that captures most of the prostate motion for the majority of patients. The pre- and post-needle insertions images were examined. We found that while the ensemble of organs moved deformably, each major relevant structures (prostate, rectum, pubic bone) shows little deformation, just recently corroborated by Karnik et al. concluded that the results from rigid and non-rigid registration were not statistically significantly different ($p>0.05$) in transrectal prostate biopsies [5].

We devised a two-step 3D/3D rigid registration scheme using mutual information (MI) to capture this motion. We used the Insight Toolkit to register the pre- and post-needle insertion volumes. First, we apply global registration over the rectum, prostate and pubic bone, to capture gross prostate motion in coherence with robot and patient. Next, we capture residual decoupled prostate motion by further registering the global image with the original fixed image using only the prostate as the region of interest. In doing so, motion in the superior and inferior direction is penalized because the first step should already have corrected for it.

Registration validation: The prostate seldom shows apparent anatomical features in MRI and it can move independently of bony structures, rendering landmark based registration accuracy evaluation inapplicable. Instead, we segmented the prostate, rectum and pubic bone in both the fixed and moving image volumes. Each component organ was registered by aligning surfaces. Finally, the results of surface based prostate registration were compared with the results of MI registration. The transformations of bone and rectum indicated the amount of patient motion during procedure. At least one biopsy for each patient was validated using this method. In addition, all registrations that contained a translation of more than 10 mm were individually validated. Fig. 1 shows the overlay of a segmented model before and after the automatic MI-based registration.

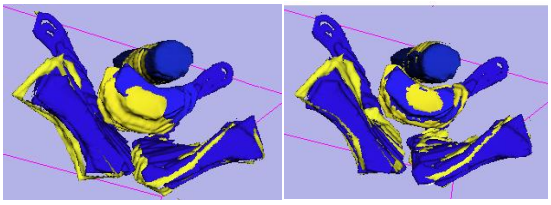

Fig. 1. 3D overlays of segmented rectum, prostate, and pubic bone from before (left) and after (right) MI-based registration

Biopsy Accuracy: We define target displacement as the distance between the original and transformed target (Fig. 2). The transformed target was obtained by using the transformations from the MI-based registrations to the original target. In order to determine whether this motion is related to the needle insertion direction, the displacement was decomposed into two vectors: one parallel and one orthogonal to the needle. A Wilcoxon Signed Rank Test was used to see if prostate motion in the needle direction was significantly larger than the orthogonal one. We define needle placement error as the distance from the original target to the biopsy needle trajectory line (Fig. 2). This is how much the robot missed the intended target in scanner coordinates. The needle trajectory was obtained from rectifying the track in the post-insertion volume. Biopsy error was defined as the distance from the transformed target to the needle trajectory line (Fig. 2), which represents the distance between the planned and actual biopsy locations. This

measurement is relevant for assessing accuracy. Since the tissue biopsy core is over 1.5 cm long, insertion depth is of a lesser issue.

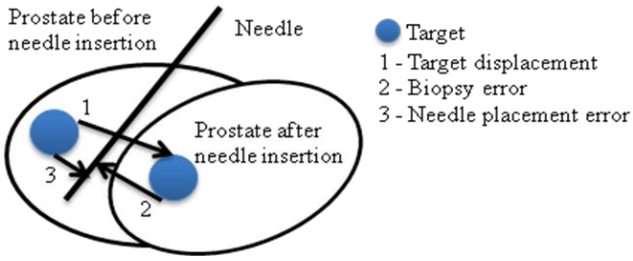

Fig. 2. Illustration of prostate motion during needle insertion and biopsy error calculations

RESULTS AND DISCUSSION

Registration accuracy: A total of 82 biopsies from 21 patients were evaluated, one half requiring manual validation. Organ segmentation error was about 2 mm. The results from manual registration were used for the ones that were off by 3 mm or more. The inaccuracy was mainly due to poor image quality and patient motion; 11 biopsies contained patient motion over 5 mm. After adjustment, all registrations were accurate to 2 mm. **Biopsy accuracy:** Table 1 summarizes the mean, range, and standard deviation for the target displacement, needle placement error, and biopsy error (Fig. 2) of all biopsies and of 11 biopsies which had more than 5 mm patient movement. Lilliefors tests have shown that only the needle placement error has a normal distribution (significance: α=0.05, p-value=0.06).

Table 1. Data statistics for biopsy accuracy (mm)

	Target disp.		Needle pl.	Biopsy error	
Mean	5.9	7.2*	2.3	4	4.8*
Range	1-13.4	3.7-11.2*	0.1-6.5	0.5-14.1	1.4-8.8*
STD	3.5	2.9*	1.3	2.1	2.3*

* Biopsies for patient motion larger than 5 mm only

Target displacement: Target displacement parallel and orthogonal to the needle direction was also calculated. For the parallel component, 46% of the biopsies moved towards the needle insertion direction (average distance: 5.7 mm) and 54% went in the opposite direction (average distance: 2.9 mm). The average was 4.2 mm in the parallel and 3.4 mm in the orthogonal direction. Results from the Wilcoxon Signed Rank Test showed that parallel motion was not significantly greater than the orthogonal one (level of significance: α=0.05, p-value: 0.36). For the group of patient motion larger than 5 mm, the average parallel and orthogonal motion was 3.9 mm and 5.3 mm respectively. To analyze the displacement that was not in the needle direction, the orthogonal component was further broken down into movement in scanner coordinates. 73% of the biopsies showed a target movement either towards the superior-posterior (SP) or inferior-anterior (IA) direction. However, the correlation coefficient between SI and AP was only 0.56. During MI-based automatic registration validation, the segmented rectum and pubic bone were registered separately. Their motions were different from the motion of the prostate, while bone motion was more similar to prostate motion than to rectum motion.

The mean needle placement error (Table 1) is less than both the slice thickness (3 mm) and clinically significant size of cancer (approx. 4 mm), confirming that the robot is sufficiently accurate if patient motion is curtailed. In reality, patient motion and prostate dislocation cause the target to move, as evident by the 5.9 mm mean average target displacement from 82 biopsies studied. It results in an average biopsy error of 4 mm, which is on verge of clinical acceptability.

DISCUSSION

In the 11 biopsies when patient motion was above 5 mm, we studied the impact of patient motion on biopsy error, revealing that better patient fixation may yield only slight decrease in biopsy error of about one 1 mm. The biopsy needle is inserted into the prostate in a mainly superior-anterior direction. It is would be reasonable to assume that the target moves in a direction similar to the needle path. But as statistical tests show no significant difference between target displacement parallel and orthogonal to the needle direction, it means that about half of the displacements were in the needle direction. The other half could be due to patient motion during the procedure, in addition to the impact of needle insertion. Separate registration of the rectum and bone indicates that the prostate can move independently of these two structures. The robot in the rectum limits its ability to move, explaining the observation that prostate moves more with the bone than with the rectum.

In conclusion, even taking into account imperfections of the registration scheme (assuming local rigidity of organs, course out plane resolution, segmentation error), these results clearly and forcefully suggest that motion compensation is necessary before committing the biopsy needle to action.

REFERENCES

[1] Jemal, et al., "Cancer statistics, 2009," *CA Cancer J Clin.*, vol. 59, no. 4, pp. 225-249, May 2009.

[2] Krieger, et al., "Design of novel MRI compatible manipulator for image guided prostate interventions," *IEEE Trans. Biomed. Eng.*, 52(2), pp. 295-304, 2008.

[3] R.C. Susil, et al., "Transrectal prostate biopsy and fiducial marker placement in a standard 1.5T magnetic resonance imaging scanner," *J Urol.*, vol. 175, no.1, pp. 113-120, 2006.

[4] H. Xu et al., "Accuracy Validation for MRI Guided Robotic Prostate Biopsy", *SPIE Medical Imaging*, Visualization, Image-guided Procedures and Modeling, vol. 7625, 2010.

[5] V. Karnik, et al., "Assessment of registration accuracy in three-dimensional transrectal ultrasound images of prostates," *SPIE Medical Imaging*, Visualization, Image-guided Procedures and Modeling, vol. 7625, 2010.

Support: U.S.NIH 5R01CA111288-04, 5R01EB002963-05