Intraoperative Prostate Tracking with Slice-to-Volume Registration in MR

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Abstract: A slice-to-volume registration algorithm, to be used for prostate tracking, is presented. The technique is designed to provide patient tracking information for prostate biopsy performed under MR guidance. Interventional MR slices are acquired from a static physical plane just prior to needle insertion. These slices are registered to a high resolution volume of the patient. Registration is performed at two resolutions, with the result of the low resolution registration used as the initial alignment of the high resolution step. Two versions of the algorithm are implemented: registration with a transverse slice and registration with intersecting transverse and sagittal slices. Validation is performed on five high resolution patient data sets. After segmentation of the prostate, an interventional MR slice is simulated and subsequently translated and rotated from its original position. Registration performed to recover the original position resulted in average target registration errors below 1 mm, for both the single transverse slice and the combination of a transverse and a sagittal slice.

Keywords: Intra-operative registration, Prostate, MR

1. Purpose

Magnetic Resonance Imaging (MR) has shown great promise in targeted therapy, such as brachytherapy, and biopsy of early stage prostate cancer (D'Amico *et al.* 2001). Intraoperative registration of the planned and actual positions of the target is of paramount importance in these interventions. As the intervention proceeds, the prostate tends to shift position, change orientation and even deform, making the initial registration invalid. This can lead to, inaccurate biopsy, poor localization of therapeutic radiation and excessive exposure of healthy tissue to ionizing radiation. The goal of this work is to track the prostate and update the registration between the preoperative plan and the patient throughout the procedure. We propose a slice-to-volume registration technique to be used in a framework where the intervention is performed within an MR machine and intermittent interventional MR slices are used to track the prostate. As this algorithm is to be used in a clinical setting, the speed of the registration is of great importance. Fei *et al*. performed registration at three resolution levels and applied several random restarts to ensure a valid registration (Fei *et al.* 2003). Chandler *et al.*, whose application had little concern for temporal performance, ran an all-out mutual information registration (Chandler

et al. 2006). In our case, constraints on prostate motion allows for streamlining these approaches to improve upon computational cost, while retaining an accurate registration.

2. Materials and Methods

We propose to track the prostate through intermittently acquired, spatially fixed interventional MR slices. The current implementation assumes that a high resolution volume image of the prostate is acquired immediately before the procedure. Our registration algorithm builds upon those proposed earlier (Fei *et al.* 2003, Chandler *et al.* 2006, Xu *et al.* 2005). Interventional MR slices tend to have lower resolution and larger slice thickness than those in preoperative MR volumes. We simulate an interventional slice by averaging the pixel values, within the preoperative volume, across a predefined interventional MR slice thickness. In our experiments we used a slice thickness of 5 mm. In essence, tracking maximizes the similarity between the real interventional MR slices and the simulated interventional MR created at its corresponding location within the high resolution preoperative volume.

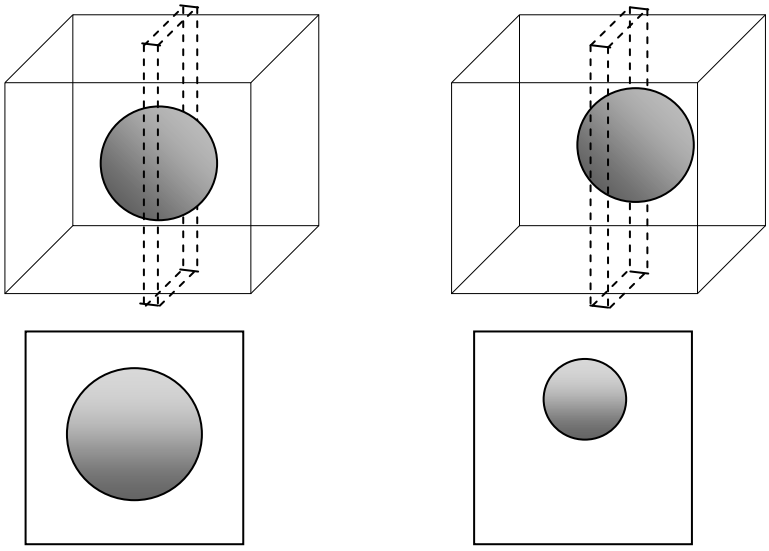

Fig. 1. Interventional MR slices are intermittently acquired from the same physical plane (top). As the target shifts, the resulting MR slice (bottom) is used to update the registration of the preoperative plan.

Our algorithm maintains the multi-resolution approach from previously methods (Fei *et al.* 2003) but entirely removes the random restarts and only uses two consecutive levels of resolution: one quarter resolution and full resolution. This was done to improve the running time of the registration should not have an adverse effect on the, due to the constraints on prostate motion. Initially this algorithm was designed to register a single interventional MR slice; however a single slice may not be contain enough information to accurately register to the volume. As such, the algorithm was extended to register two slices in unison. The real interventional MR slice is acquired and initially aligned with the preoperative volume. An interventional MR slice is then simulated from the initial location of the real slice. This simulated slice is updated at each step of the registration, according to the new alignment of the real slice. The first stage of the registration is performed at one quarter of the full resolution (Fig. 2, left) where correlation coefficient is used as similarity metric. The resulting transformation is then used as initial alignment for

registration at full resolution (Fig. 2, right) applying mutual information as similarity metric. The Nelder-Mead Simplex algorithm is used as the optimization algorithm at both stages of the slice-to-volume registration (Nelder and Mead, 1965).

Fig. 2. Segmented prostate from a simulated interventional MR slice at one quarter resolution (left) and at full resolution (right).

3. Experiments and Results

Five clinical MR prostate volumes are used in the validation of our slice-to-volume registration. Datasets for all patients were acquired as a set of transverse slices, have pixel spacing within the range of 1.5-1.75mm and have a slice thickness of 3 mm. Due to the thickness of the slices, any extracted sagittal slices are of comparatively low resolution. For this reason we included a test where the algorithm was modified to keep the sagittal slices at full resolution throughout the registration process. In an actual clinical setup, as the prostate moves, the MR slice is still acquired from the same physical plane. In our validation experiments, the motion was reversed, in that we fixed the volume and computationally moved a simulated interventional image plane around, thereby creating an accurate ground truth. Due to observed constraints on the prostate's motion, we assume a maximum 10 mm of displacement and 10º of rotation about each axis. We assume negligible deformation of the prostate gland which is generally true until needle insertion begins, an assumption also used by Xu *et al*. (Xu et al. 2005). A tight region of interest around the prostate was selected, because otherwise the registration would be unduly influenced by deformations in the surrounding soft tissue. In our case, this was accomplished by a manually selected bounding box around the prostate.

We performed two sets of tests: the first measuring the accuracy of our slice to volume registration using a transverse interventional MR slice and the second measuring the accuracy of the registration when using a transverse slice and an intersecting sagittal slice. For the first test, we simulated a transverse interventional MR image with cutting out a slice from the volume and degrading its fidelity by adding Gaussian noise. Slice-to-volume registration was performed five times for each patient dataset, with an initial alignment randomly chosen from a uniform distribution of 10 mm displacement along each axis and 10º of rotation about each axis. Accuracy was measured by the target registration error (TRE), calculated as the mean Euclidian distance of the slice pixels from the correct alignment in the volume. In the second test, we used two intersecting transverse and sagittal interventional MR planes. The third test also used two intersecting transverse and sagittal slices, but kept the sagittal slice at full resolution throughout the registration. This was done to compensate for the low axial resolution of our datasets.

Results are summarized in Table 1. Registration with a solo transverse slice resulted in a TRE of 2.97 mm and standard deviation of 3.22 mm. Registration with transverse and sagittal slices resulted in a TRE of 1.14 mm and a standard deviation of 1.41 mm. Registration with transverse and sagittal slices, while keeping the sagittal slice at full resolution, resulted in a TRE of 0.75 mm and a standard deviation of 0.79 mm. Clearly, an additional sagittal slice provides a significant benefit to the registration. Similarly, keeping the sagittal slice at full resolution greatly improved the registration accuracy. We believe that this was primarily due to the low axial resolution of the datasets. Had the MR volume been acquired with a smaller slice thickness, the results for the registration with low resolution sagittal slices would have produced comparable results.

The algorithms were implemented in Matlab; average running time of registration was 36 s, 79 s and 107 s, for the three versions of the algorithm, respectively.

Tab. 1. Target registration error of the slice-to-volume registration. Ten sets of slice-to-volume registrations were performed for each patient. Initial misalignment was chosen randomly from the uniform distribution of ±10mm displacement and ±10º of rotation about each axis.

	Target Registration Error (mm) / Standard Deviation		
Patients	Transverse Slice	Transverse and Sagittal Slice	Transverse and Sagittal Slice (Full Resolution)
P1	3.22 / 3.44	1.04 / 0.96	0.80 / 0.77
P2	5.06 / 5.08	2.07 / 2.56	0.90 / 1.26
P3	1.72 / 1.57	1.00 / 0.90	0.56 / 0.47
P4	1.62 / 1.62	0.92 / 0.89	0.87 / 0.68
P5	3.24 / 2.25	0.67 / 0.70	0.63 / 0.67
Average	**2.97 / 3.22**	**1.14 / 1.41**	**0.75 / 0.79**

4. Conclusions

The relevant size of prostate cancer foci is approximately 4 mm, the diameter of the slimmest needle used in prostate interventions is about 2 mm and the diameter of implanted brachytherapy seeds is close to 1 mm. In this light, the accuracy and robustness of this prostate tracking method is promising, though it must be validated in more patients and under deformations. The current implementation was not designed for real-time tracking; it will be used to validate organ position before needle insertion. As such, the current speed of the registration is acceptable; however, we do expect a significant reduction in running time when the algorithm is implemented in a lower level language. This will become more important in our future work where we plan to extend the registration to account for deformations in the prostate after needle insertion.

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