Semiautomatic Nonrigid Registration for the Prostate and Pelvic MR Volumes[1]

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Rationale and Objectives. Three-dimensional (3D) nonrigid image registration for potential applications in prostate cancer treatment and interventional magnetic resonance (iMRI) imaging–guided therapies were investigated.

Materials and Methods. An almost fully automated 3D nonrigid registration algorithm using mutual information and a thin plate spline (TPS) transformation for MR images of the prostate and pelvis were created and evaluated. In the first step, an automatic rigid body registration with special features was used to capture the global transformation. In the second step, local feature points (FPs) were registered using mutual information. An operator entered only five FPs located at the prostate center, left and right hip joints, and left and right distal femurs. The program automatically determined and optimized other FPs at the external pelvic skin surface and along the femurs. More than 600 control points were used to establish a TPS transformation for deformation of the pelvic region and prostate. Ten volume pairs were acquired from three volunteers in the diagnostic (supine) and treatment positions (supine with legs raised).

Results. Various visualization techniques showed that warping rectified the significant pelvic misalignment by the rigid-body method. Gray-value measures of registration quality, including mutual information, correlation coefficient, and intensity difference, all improved with warping. The distance between prostate 3D centroids was 0.7 ± 0.2 mm after warping compared with 4.9 ± 3.4 mm with rigid-body registration.

Conclusion. Semiautomatic nonrigid registration works better than rigid-body registration when patient position is changed greatly between acquisitions. It could be a useful tool for many applications in the management of prostate.

Key Words. Automatic nonrigid image registration; mutual information (MI); thin plate spline (TPS); interventional magnetic resonance imaging (MRI); prostate cancer.

We are investigating three-dimensional (3D) nonrigid image registration to be used in applications of prostate cancer diagnosis, staging, and therapy. In particular, we are interested in applications related to the minimally invasive interventional magnetic resonance imaging (iMRI)-guided treatment of patients with prostate cancer. At our institution, we currently use interventional MRI on a low-field open-magnet system to guide radiofrequency (RF) thermal ablation of abdominal cancer (1–3), and we are investigating this method for prostate cancer treatment.

Several applications in prostate imaging require registration. First, comparison of registered MR images acquired before and immediately after RF ablation can be used to determine whether a tumor is adequately treated. This is particularly helpful in instances in which the edematous response to treatment can be confused with a highly perfused tumor. Second, other treatment methods,

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such as radiation therapy, brachytherapy, and surgery, also will be aided by registration of images from pretherapy, intratherapy, and posttherapy for treatment planning, guidance, and assessment. Third, registration of serial examinations can be used to follow up the regression or progression of tumors.

There are challenges to pelvis and prostate registration. First, pelvic regions can change shape significantly. Different patient positions, such as legs up and down, can cause movement and deformation of internal organs. Second, the normal prostate is a small organ that, when healthy, measures only about 3.8 cm in its widest dimension transversely across the base (4). Third, the small prostate is located below a much larger bladder, which can change shape and size. The prostate might move relative to the pelvic bones because of changes in bladder and rectal filling (5). Some reports described methods for image registration in the pelvis or prostate (5–18). Some of these methods require either segmentation or visual identification of structures. For example, manual registration has been used, in which an operator cues on segmented vascular structures (19), other anatomic landmarks (6,20,21), or fiducial markers (15). Others have used automated 3D schemes that match contours of bones and sometimes other structures that are extracted using manual or interactive segmentation (8,9,22). Manual segmentation also has been used to create surfaces for automatic registration (10,11).

We previously described a rigid-body volume-to-volume registration method for pelvic and prostate MR images (23). For volume pairs acquired during a short time span with the volunteer in a similar position, rigid-body registration accuracy of both the prostate centroid (typically <1 mm) and bony landmarks (average, 1.6 mm) was on the order of a voxel (≈ 1.4 mm). With rigid-body registration, we obtained larger prostate centroid displacements (2.8–10.0 mm) when acquisitions were obtained under much different conditions (eg, legs flat and legs raised), giving large anatomic deformations. Rigid-body registration of the pelvis is inadequate under such conditions (23).

Nonrigid registration is a solution, and there are a number of relevant reports on the pelvis and prostate (24–29). Nonrigid registration methods also were used for the brain (30–32), breast (33–35), lung (36,37), and abdomen (38,39). We reported a nonrigid registration method that used many manually selected control points (CPs) (26). After automatic global rigid-body registration, the operator manually selected more than 180 CPs at the prostate center, pelvic surface, and internal structures. The program automatically optimized each CP location by displacing it in the x, y, and z directions with respect to the reference volume until mutual information computed over a small cube of voxels was maximized. Thin plate spline (TPS) transformation then was applied to express deformation of the pelvic region and prostate. This interactive method was applied to pelvic MR images and lung computed tomographic/positron emission tomographic images (37). The time required for CP selection was a limitation.

In this study, we build on our previous experience and develop an almost fully automatic nonrigid registration method. Our goal is to automate the algorithm to save time and labor without losing registration quality. We use image data that show considerable deformation, eg, images acquired in the diagnostic (supine) and treatment positions (supine with legs raised). We qualitatively and quantitatively compare results of the new nonrigid registration algorithm with those of the previous, more manual version and rigid-body registration.

MATERIALS AND METHODS

MRI

All MRI volumes were acquired using a 1.5-Tesla Siemens MRI system (Magnetom Symphony; Siemens Medical Systems, Erlangen, Germany). An eight-element phased-array body coil was used to ensure coverage of the prostate with uniform sensitivity. Typically, two anterior and two posterior elements were enabled for signal acquisition. We used two different MR sequences. First, we used a 3D RF spoiled gradient echo steady-state pulse sequence (FLASH) with repetition time/echo time/flip parameters of 12/5.0/60, which give $256 \times 256 \times 128$ voxels over a $330 \times 330 \times 256$-mm field of view (FOV) to yield $1.3 \times 1.3 \times 2.0$-mm voxels oriented to give the highest resolution for transverse slices. Acquisition time was 5.6 minutes. This sequence was good for pelvic imaging, but was not ideal for the prostate. It was used for volunteer S1. Second, we used a 3D rapid gradient echo sequence (PSIF) designed to acquire the spin-echo component of the steady-state response. The spin echo component formed immediately before the RF pulse and was shifted toward the prior RF pulse through appropriate gradient waveform design. The sequence with 9.4/5.0/60 (repetition time/echo time/flip) yielded $160 \times 256 \times 128$ voxels over a $219 \times 350 \times 192$-mm rectangular FOV