

Multimodality Non-rigid Image Registration for Planning, Targeting and Monitoring During CT-Guided Percutaneous Liver Tumor Cryoablation

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Rationale and Objectives: The aim of this study was to develop non-rigid image registration between preprocedure contrast-enhanced magnetic resonance (MR) images and intraprocedure unenhanced computed tomographic (CT) images, to enhance tumor visualization and localization during CT imaging-guided liver tumor cryoablation procedures.

Materials and Methods: A non-rigid registration technique was evaluated with different preprocessing steps and algorithm parameters and compared to a standard rigid registration approach. The Dice similarity coefficient, target registration error, 95th-percentile Hausdorff distance, and total registration time (minutes) were compared using a two-sided Student's *t* test. The entire registration method was then applied during five CT imaging-guided liver cryoablation cases with the intraprocedural CT data transmitted directly from the CT scanner, with both accuracy and registration time evaluated.

Results: Selected optimal parameters for registration were a section thickness of 5 mm, cropping the field of view to 66% of its original size, manual segmentation of the liver, B-spline control grid of $5 \times 5 \times 5$, and spatial sampling of 50,000 pixels. A mean 95th-percentile Hausdorff distance of 3.3 mm (a 2.5 times improvement compared to rigid registration, $P < .05$), a mean Dice similarity coefficient of 0.97 (a 13% increase), and a mean target registration error of 4.1 mm (a 2.7 times reduction) were measured. During the cryoablation procedure, registration between the preprocedure MR and the planning intraprocedure CT imaging took a mean time of 10.6 minutes, MR to targeting CT image took 4 minutes, and MR to monitoring CT imaging took 4.3 minutes. Mean registration accuracy was <3.4 mm.

Conclusions: Non-rigid registration allowed improved visualization of the tumor during interventional planning, targeting, and evaluation of tumor coverage by the ice ball. Future work is focused on reducing segmentation time to make the method more clinically acceptable.

Key Words: Non-rigid registration; B-spline registration; liver tumor cryoablation; multimodal registration.

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Computed tomographic (CT) imaging is used to guide percutaneous liver tumor cryoablation (1–7) and has proven particularly useful when the tumor is not visible with ultrasound (4,5,8). CT can be used to plan the interventional approach, to facilitate the safe placement of the ablation applicators in the tumor, and to monitor the ablation effects in the case of cryoablation (9).

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Despite the benefits of CT imaging, there can be challenges related to the lack of soft tissue contrast for liver tumors on unenhanced CT images, especially for small or poorly marginated tumors and when there are contraindications to the use of intravenous contrast material (10). The tumor selected for ablation and the adjacent structures at risk for injury during the procedure may be invisible or poorly visible (11–13). Suboptimal visibility can lead to improper applicator placement, resulting in inadequate ablation beyond the tumor margins or thermal injury to adjacent structures (14). To overcome this problem, interventional radiologists often rely on preprocedure contrast-enhanced CT imaging or magnetic resonance (MR) imaging (MRI) that depicts tumor margins and surrounding structures, including vascular anatomy. The radiologist then performs a mental correlation of the preprocedure and intraprocedure images to estimate tumor location, tumor boundaries, and adjacent anatomic

structures. This can be challenging because the liver position, shape, and relation to extrahepatic structures may differ significantly between two exams.

Image registration, a technique that attempts to match and correlate two different image data sets, has been proposed to align preprocedure and intraprocedure images (15,16). Most techniques for registering liver images rely on rigid registration approaches (17–19). The main drawback of the rigid registration technique is that it compensates only for rigid whole-organ motion of the liver between data sets but not for liver deformation caused by patient breathing, motion or positional change, or deformation due to pressure from surrounding organs and the presence of any interventional instruments. Others have advanced these registration methods further by developing non-rigid registration techniques (20–24), which take into account the deformation of the liver.

Non-rigid registration methods have yet to be successfully applied to the planning, targeting, and monitoring phases of CT imaging-guided liver cryoablation procedures. This can be ascribed to previous non-rigid registration methods being impractical to use during the time frame of a clinical procedure or requiring large amounts of computational capacity not readily available in most interventional environments (20,25). If these methods could be optimized in terms of computation and time requirements to provide registration in the order of a few minutes or less, they would become more practical for use in the clinical setting. The clinical acceptance of longer registration times is subject to how the normal procedure timing and work flow is affected.

The purpose of this work was to develop an accelerated approach to non-rigid image registration between preprocedure contrast-enhanced MR images and the intraprocedure unenhanced CT images acquired during CT imaging-guided liver tumor cryoablation procedures. First, to accelerate registration, we tested in a retrospective study several combinations of design parameters using a B-spline-based non-rigid registration method and chose those that provided the best compromise between accuracy, timing, and robustness compared to a standard rigid registration approach. Second, we evaluated whether it was faster to directly register the preprocedure MR image to each of the intraprocedure CT images acquired during the ablation or whether resampling the preprocedure MR image with the transformation matrices obtained from registering the intraoperative CT images between themselves would speed up the registration process. Once a suitable non-rigid registration method was developed, it was applied during five CT imaging-guided liver cryoablation procedures, with the intraprocedural CT data transmitted directly from the CT scanner to the workstation.

MATERIALS AND METHODS

Patient Population

We analyzed MR and CT images from 14 patients who had undergone percutaneous CT imaging-guided cryoablation of liver tumors at our institution from January to June 2009.

The patients' medical records were reviewed to determine the sex, age, and diagnosis of each patient. Images from nine patients were retrieved from our departmental picture archiving and communication system (PACS) archive for testing and optimization of the image registration technique. In the five remaining patients, images were transferred for analysis directly from the CT scanner during the liver cryoablation procedures, with the preprocedure MR images previously retrieved from our PACS archive. This study was performed with institutional review board approval and in compliance with Health Insurance Portability and Accountability Act guidelines.

Patients had a mean age of 67 years (range, 49–81 years) and mean liver tumor size of 35 mm (range, 15–65 mm), with five tumors located in segment 7 of the liver, four tumors in segment 8, two in segment 5, two in segment 6, and one occupying both segments 2 and 3. For the nine patients whose images were retrieved from the PACS, the tumors and tumor margins were visible using unenhanced CT imaging in two patients, tumors were faintly visible but with undefined margins in three patients, and both tumors and margins were completely invisible in four patients. For the five patients whose images were transferred directly from the CT scanner, the tumor and margins were visible in one patient, faintly visible in two, and invisible in the other two. All patients underwent CT imaging-guided cryoablation of liver tumors, which required the placement of an average of 5 applicators (range, 4–7 applicators). The cryoablation procedure consisted of three phases. In the planning phase, an initial CT scan of the abdomen was used to select an optimal entry point and plan applicator placement. During the targeting phase, CT images were used to target the applicators at the planned locations. The monitoring phase used CT images to demonstrate the effects of the cryoablation including the extent of the ice ball.

Image Acquisition

The non-rigid registration method was used to register (1) preprocedure contrast-enhanced MR images to the intraprocedure unenhanced planning CT images and (2) intraprocedure CT images obtained at the targeting and monitoring phases of the intervention to the intraprocedure planning CT image. Preprocedure MRI was performed using a 1.5 T Signa scanner (GE Healthcare, Waukesha, WI), using a transverse fat-suppressed T1-weighted dynamic imaging with three-dimensional fast-acquisition multiple-excitation spoiled gradient-recalled echo sequence (repetition time, 5.2–7.3 ms; echo time, 1.5–2.2 ms; matrix size, 512 × 512; flip angle, 10°; section thickness, 2.5 mm; gap, 0 mm; field of view [FOV], 32–40 cm) with an eight-channel torso surface coil, after the intravenous administration of 20 mL of gadolinium-based contrast material (Magnevist; Berlex Laboratories, Wayne, NJ). Intraprocedure CT scans were performed on a 40-channel multi-detector row CT scanner (Sensation Open; Siemens Medical Solutions, Forchheim, Germany), with a matrix size of 512 × 512, 3-mm section

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