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A fast and robust level set motion-assisted deformable registration method for volumetric CT guided lung intervention

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ABSTRACT

This paper describes the accurate deformable registration method for image-guided lung interventions, including lung nodule biopsy and radiofrequency ablation of lung tumours. A level set motion assisted deformable registration method for computed tomography (CT) images was proposed and its accuracy and speed were compared with those of other conventional methods. Fifteen 3D CT images obtained from lung biopsy patients were scanned. Each scan consisted of diagnostic and preoperative CT images. Each deformable registration method was initially evaluated with a landmark-based affine registration algorithm. Various deformable registration methods such as level set motion, demons, diffeomorphic demons, and b-spline were compared. Visual assessment by two expert thoracic radiologists using five scales showed an average visual score of 3.2 for level set motion deformable registration, whereas scores were below 3 for other deformable registration methods. In the qualitative assessment, the level set motion algorithm showed better results than those obtained with other deformable registration methods. A level set motion based deformable registration algorithm was effective for registering diagnostic and preoperative volumetric CT images for image-guided lung intervention.

1. Introduction

Image-guided intervention is a medical procedure that was developed as an alternative to the traditional surgical process. Image-guided procedures have a lower risk of complications than traditional procedures because of the short operating times and small incisions. A fast patient recovery is another advantage of image-guided intervention. Advances in computer technologies and medical image processing have

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enabled the development of image-guided intervention over the past 20 years [1]. The first surgical planning system using a personal computer-based workstation was developed in 1989 [2]. At this time, the framework for typical image-based surgery planning for computed tomography (CT), magnetic resonance (MR) imaging, or digital subtraction angiography was proposed. This attempt triggered the expansion of image-guided surgery by other researchers, who designed and tested various image-guided surgical planning and intervention systems [3–7].

Among the techniques used in image-guided intervention systems, image registration is essential [1]. Image registration is based on a process of geometrical transformation that aligns points in one coordinate system with the corresponding points in another coordinate system [8]. In the medical field, image registration algorithms are important because they can improve the accuracy and robustness of radiation therapy by tracking anatomical changes and estimating organ deformation [9,10].

Image registration is performed using either rigid registration or deformable registration algorithms [8]. Various rigid image registration algorithms have been described [11–14], and several deformable image registration techniques have been developed for use in medicine as rigid registration algorithms were implemented. Nigris et al. [15] developed a novel technique of image registration in the context of image-guided neurosurgery. Lee et al. [16] proposed a brain image registration technique based on the use of shell registration in positron emission tomography and MR/CT brain imaging. Li et al. [17] estimated lung deformation using a proposed tool based on a demons algorithm. Rubeaux et al. [18] compared cardiac motion registration methods, level-set and demons, for the reference standard of using only diastolic PET image. Su et al. [19] described a noble registration algorithm for CT and CT-fluoroscopy images designed to overcome the disadvantages of typical image registration techniques. However, the validation of registration algorithms is difficult. To solve this problem, Urschler et al. [20] proposed a standardized method for evaluating nonlinear intra-subject image registration algorithms.

Medical imaging applications based on these registration techniques are undergoing wide-scale development for specific purposes and in different medical environments. The use of the appropriate deformable registration technique in each case may improve the results of image-guided intervention.

The purpose of the present study was to suggest appropriate image registration procedures and suitable deformable registration methods for image-guided intervention in the lung. We used a level set motion method and compared it with other deformable image registration techniques such as the demons, diffeomorphic demons, and b-spline algorithms.

The initial rigid registration was computed using an affine transformation approach, and level set motion registration was used for preoperative image registration. Application of the level set motion registration approach improved the computational efficiency and run time for image-guided intervention. The results of evaluation tests showed that the level-set motion method is a promising approach.

2. Material and methods

2.1. Material

The images were selected form clinical data sets obtained from 15 patients. All data sets were resampled to a resolution of $512 \times 512 \times 30$ voxels to compare the registration performance and computation time. All experiments were performed using a 64 bit Intel Processor (2.4 GHz and 16 GB of RAM) running Windows because algorithms tend to use a large amount of system memory.

2.2. Methods

In general, the image-guided intervention in the lung requires the registration of images of different respiratory states of the same patient, thus establishing a correspondence between the same lung structures in both images. There are two main approaches towards image registration. The overall procedure for a proposed registration method for robotic intervention consists of the following two main steps as outlined in Fig. 1; (1) computing geometric transformation that aligns the planning CT image and preoperative CT images given a set of pair landmarks and (2) matching of the lung structure with the deformable registration method. Fig. 2 shows preoperative (fixed) CT and planning CT (moving) images for the application of landmark-based transformation algorithms. In this case, the planning CT scans were performed with the patient in the supine position, whereas the preoperative CT images were acquired in the prone position because of the intervention procedures. To align the positions, the clinical experts extracted three landmark points from consolidations, lung anatomy or nodules on these images. The following sequence of steps is typical for the extraction of landmarks using preoperative and planning images. The first step is planning and preoperative CT images are acquired, and the clinical experts check the position (i.e. supine or prone) the patient for CT scanning. After checking the patient position, the clinical experts search for anatomical landmarks such as lesions, consolidations, or vessels in the planning and preoperative CT images. Next, the clinical experts use the computer system to extract the central point of the anatomical landmarks on display.

Finally, CT images with a set of point landmarks are obtained upon procedure completion. After extracting landmarks, the planning and preoperative CT image is aligned by the affine transformation algorithm [21,22]. The affine transformations include scaling, shearing, translating, and rotating, and can be described with six parameters. The transformation algorithm can be written as:

$$\begin{bmatrix} p' \\ q' \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & t_x \\ c & d & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p \\ q \\ 1 \end{bmatrix} \tag{1}$$

where (p, q) is pixel points the original CT image and (p', q') is pixel location of the transformed image.

$$p' = ax + b + t_x \tag{2}$$

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