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Technical note

Impact of deformable image registration accuracy on thoracic images with different regularization weight parameter settings

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ABSTRACT

Purpose: We assessed the deformable image registration (DIR) accuracy of thoracic images under different regularization weights using commercially available DIR software.
Methods: The thoracic 4-dimensional (4D) CT images of 10 patients were used. The datasets for these patients were provided by DIR-lab (www.dir-lab.com) and included a coordinate list of 300 anatomic landmarks that had been manually identified. The ANAtomically CONstrained Deformation Algorithm (ANACONDA) of RayStation (RaySearch Laboratories, Stockholm, Sweden) was used to deform the peak-inhale to peak-exhale images under different regularization weights (4, 40, 400-default setting, 1500, 4000, 10,000, 15,000, 20,000, 30,000, and 40,000). The regularization weights were changed using a script. The registration error (RE) was determined by calculating the difference at each landmark point between the displacement calculated by the DIR software and that calculated by the landmark. We measured the computation time for each regularization weight setting.
Results: High regularization weights resulted in a smaller RE than that observed with lower regularization weights. The RE decreases rapidly with increase in regularization weight before reaching a plateau. No significant difference was found between a regularization weight of 400 and regularization weights of 4, 40, 4000 or 40,000 (P value > 0.05). The range of the average time was 8.4–12.2 s.
Conclusions: We concluded that the default setting for ANACONDA is stable with respect to regularization weight in the thoracic region.

1. Introduction

Deformable image registration (DIR) is essential for linking the anatomy of one image set to another, and it is a fundamental principle of adaptive radiotherapy and image-guided radiotherapy. DIR is widely used for multimodality image fusion, anatomic image segmentation, 4-dimensional (4D) dose accumulation, and lung function imaging [1–5]. The similarity measure, which acts as a driving force for the registration computation, is required to compute the DIR, based on geometrical structures or image intensities. Several researchers have discussed the advantages and disadvantages of these approaches [6–15]. Several commercial DIR programs are available for use in clinical practice to deform an image. Most commercial systems employ either geometrical structures or image intensities approaches. Raystation (RaySearch Laboratories, Stockholm, Sweden) has the benefit of being able to use both the geometric and the intensity based approaches to avoid the limitations of each; this is called a hybrid solution. Hybrid solutions have been proposed by Christensen et al. and are becoming increasingly popular as topics of research in the field of radiotherapy [6]. The ANAtomically CONstrained Deformation Algorithm (ANACONDA), which is formulated as a nonlinear optimization problem with an objective function consisting of a weighted linear combination of four terms, using a hybrid solution, is available in RayStation [7]. Weistrand et al. reported the algorithmic details for ANACONDA to avoid “a black box” and benchmarked using thoracic 4D computed tomography (CT) data and CT/Cone Beam CT (CBCT) data of the pelvis, head, and neck regions [7]. Kadoya et al. evaluated the DIR accuracy of three commercially available DIR programs for thoracic 4D CT images at multiple institutions [8]. The DIR accuracies differed among the institutions because they were dependent on the DIR software and procedures. The DIR parameters that can be adjusted to improve the DIR accuracy were not changed. If the optimal parameter settings are used, the DIR accuracy may alter the maximum performance. The DIR accuracy contributes to a higher performance of the dose accumulation, 4D CT

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ventilation, and auto-contouring [4,5]. Therefore, improvement of the DIR accuracy is still required. A user of RayStation cannot easily change the DIR parameters and is usually restricted by the vendor recommended default DIR parameters. However, the DIR parameters of RayStation can be changed using a script. There are currently no known reports of using this function of RayStation to alter the DIR parameters in order to improve the DIR accuracy.

The purpose of this study is to assess the DIR accuracy for thoracic images under different DIR parameters using RayStation. RayStation has several DIR parameter settings that can be changed using a script; these include the number of resolution levels, grid regularization weight, Gaussian smoothing sigma, and the maximum number of iterations per resolution level. The highest grid regularization weight can be used to achieve deformation vector field (DVF) invertibility. Weistrand et al. presented results for thoracic 4D CT data when the regularization weight was varied slightly (10%) [7]. Therefore, we have focused on the grid regularization weight in this study. The ANACONDA and regularization weight are briefly introduced in the Methods and Materials section.

2. Methods and materials

We used the publicly available 4D CT datasets of 10 patients from the DIR website (www.DIR-lab.com). These 4D CT images were acquired as part of the standard planning process for the treatment of thoracic malignancies at the University of Texas M. D. Anderson Cancer Centre in Houston. A detailed description of the datasets can be found in Castillo et al. [11,12]. The 4D CT images were acquired over the entire thorax and upper abdomen at a 2.5 mm slice spacing using a General Electric Discovery ST PET/CT scanner (GE Medical Systems, Waukesha, WI). The voxel dimension was approximately 1 mm × approximately 1 mm × 2.5 mm. Extreme inhale and exhale phases of the 4D CT images with 300 landmark sets were used in this study (Fig. 1). The 300 expert landmarks consist of left-right (LR), anterior-posterior (AP), and superior-inferior (SI) coordinate locations. The 300 expert landmarks, which were marked as the inhale phases with corresponding positions of the exhale phases, were used for evaluating the DIR spatial accuracy in the lung region. Extreme inhale and exhale phases of the 4D CT image were imported from the RayStation (version 4.7.4.4) treatment planning system (TPS). During the inhale phase of the CT images, the left and right lungs were manually contoured by a radiation oncologist. The inhale phase image was deformed to the corresponding exhale phase image by using hybrid intensity and structure-based DIR (ANACONDA) implemented in RayStation. A detailed description of ANACONDA of RayStation can be found in Weistrand et al. [7]. To summarize, ANACONDA is based on a mathematical formula in which the registration is described as a non-linear optimization problem, combining image and anatomical information obtained from contoured image sets. ANACONDA is a versatile algorithm which uses a correlation coefficient to measure image similarity. If we define the reference image **R**, the registration problem is described by a non-linear optimization problem with the objective function, f: $\mathbf{R^n} \rightarrow \mathbf{R}$, using the following equation:

$$f(v) = \alpha C(v) + (\beta H(\boldsymbol{v}) + \gamma S(\boldsymbol{v})) + \delta D(\boldsymbol{v})$$

,where α, γ, and $\delta\mathbf{R}$ are the non-negative weights; $\mathbf{n}$ is the number of variables; and β: $\mathbf{R}^3 \rightarrow \mathbf{R}$ is a non-negative, real valued weight function. The image similarity is measured by the correlation coefficient $C(v)$. The regularization of the deformation grid is controlled by the term $\beta H(v) + \gamma S(v)$. The first part of the regularization term, $\beta H(v)$, determines the smoothness and invertibility of the DVF. When a large β is used, the DVF becomes invertible. To prevent the generation of inverted elements, the algorithm uses a restart strategy to increase β when needed. The second part of the regularization term, $\gamma S(v)$, penalizes any large shape deviations of the regions of interest (ROIs) defined in **R**. $D(v)$ is a penalty term which is added to the optimization problem when the controlling structures are used.

The ANACONDA provided in RayStation 4.7.4.4 for DIR uses default settings, and the real valued weights are $\alpha = 1.0$,$\gamma = 0.5$,$\delta = 0.5$, and $\beta(v) = 400$, where β indicates a regularization weight. RayStation can use the contours as the focus or controlling ROI. The penalty term is not added to the optimization problem because the contours are only used to define the focus regions of the DIR. The DIR using focus ROI had the highest DIR accuracy for the lung region because focus ROI could precisely match the anatomic changes [8]. Consequently, we used both lungs as focus ROIs. The DIR algorithm computes a vector field on the deformation grid, with the vectors pointing from the individual voxels on the reference to the corresponding voxels on the target image set. The vector field is defined as the DVF. We performed the DIR under regularization weights of 4, 40, 100, 400 (default setting), 1500, 4000, 10,000, 15,000, 20,000, 30,000, and 40,000. A deformation grid of 2.5 × 2.5 × 2.5 mm^3 was used for each case.

The registration error (RE) is defined as the difference between a calculated result using DIR and the designated reference landmark. In this study, the manual deformation vector field (mDVF) and automatic deformation vector field (aDVF) were calculated using the landmark coordinate list and ANACONDA, respectively. The RE between the mDVF and aDVF were calculated for each direction. Expert-determined landmark correspondences have become a widely adopted reference for evaluating DIR accuracy for lung image data. A combination of the DVF assessment and landmark-based measurements of spatial accuracy may be an effective method for deciding the values of the DIR parameters

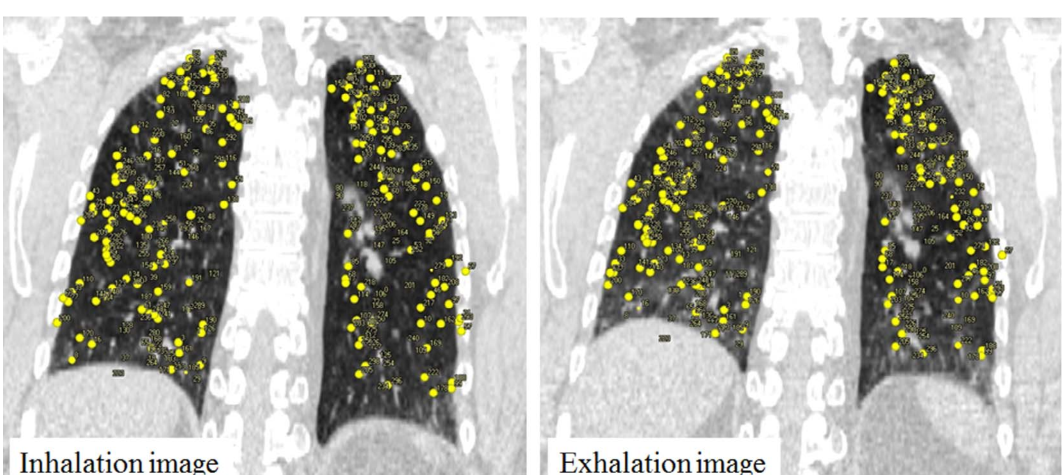

Fig. 1. An example of maximum-inhale and -exhale images with expert landmark pairs.