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Original paper

Evaluation of deformation parameters for deformable image registration-based ventilation imaging using an air-ventilating non-rigid phantom

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ABSTRACT

Purpose: This study aimed to evaluate different deformable image registration (DIR) parameters for the open-source NiftyReg package in its application to DIR-based ventilation imaging.
Methods: Two three-dimensional (3D)-computed tomography (CT) scans of a non-rigid air-ventilating phantom were acquired at peak exhalation and peak inhalation, with xenon (Xe) gas being used as an air-based contrast agent. We compared four different sets of DIR parameters, including one set with two-step deformation and three sets with four-step deformation. For spatial accuracy, the target registration error (TRE) was calculated for 16 landmarks. For ventilation imaging accuracy, DIR-based ventilation images were generated using Jacobian determinant (JD) metrics, and changes in Hounsfield unit (HU) values between the two exhalation and inhalation CT images were subsequently measured. The correlation coefficients between the JD metrics and changes in HU values were calculated.
Results: The mean TRE values were 4.5 ± 4.7 mm (maximum, 12.3 mm), 1.47 ± 0.71 mm (maximum, 2.6 mm), 1.56 ± 0.70 mm (maximum, 2.8 mm), and 1.53 ± 0.66 mm (maximum, 2.5 mm) for the two-step deformation and three four-step deformations, respectively. The four-step deformations (R = −0.71, −0.65, and −0.61) showed stronger correlation coefficients than the two-step deformation (R = −0.40).
Conclusions: The accuracy of DIR-based ventilation imaging may vary with different DIR parameter settings, even though spatial accuracy may be tolerable and within guidelines. We found adequate parameter settings for four-step NiftyReg DIR for visualization of simulated pulmonary ventilation function.

1. Introduction

In the field of lung radiotherapy, pulmonary ventilation images can provide an accessible method for evaluating lung functionality. Irradiation of healthy lung can be minimized by the use of simulated pulmonary ventilation images at treatment planning [1,2]. These simulated pulmonary ventilation images are acquired using computed tomography (CT) with deformable image registration (DIR) and may be referred to as DIR-based ventilation images.

DIR-based ventilation images can be used as an alternative to clinical pulmonary ventilation imaging techniques such as 99mTc single-photon emission computed tomography (SPECT), 68 Ga positron emission tomography, and hyperpolarized 3He magnetic resonance imaging [3,4]. DIR-based ventilation images have shorter scan time requirements, have a higher spatial resolution, and a lower cost than the other modalities. Most previous studies have demonstrated moderate-to-strong correlations between DIR-based ventilation imaging and other modalities [5–7]. However, there is some concern over the influence that the DIR parameters can have on the visualization accuracy of DIR-based simulated pulmonary ventilation imaging [8]. Castillo et al. [8] reported that small changes in the DIR parameters can result in large relative changes in DIR-based ventilation images. They found that DIR-based images may not demonstrate accurate ventilation functionality, even if the spatial accuracy of the deformation using the target registration error (TRE) is within a tolerable level.

The NiftyReg open-source package is a well-established publicly available DIR tool [9,10]. The spatial accuracy and dose warping accuracy of NiftyReg are comparable or superior to commercially-available software programs, such as Velocity AI (Varian Medical Systems, Palo Alto, CA, USA) and MIM Maestro (MIM Software, Cleveland, OH, USA) [11,12]. NiftyReg therefore appears to be suitable for providing DIR-based ventilation images for clinical practice and research. However, there have not been any published studies on the use of NiftyReg for ventilation imaging, and the influence of the parameters on the

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accuracy of the resulting ventilation images requires investigation.

Our group has previously demonstrated the utility of a phantom for evaluating the accuracy of DIR-based ventilation images for validation [13]. This phantom used non-radioactive xenon (Xe) gas as an air-based contrast agent. Another research group also showed a correlation between the lung ventilation image with CT image after inhalation of Xe and SPECT ventilation image [14].

This study therefore aimed to investigate the influence of the NiftyReg DIR parameters on the accuracy of DIR-based ventilation images, and to thereby determine the appropriate NiftyReg parameters. The evaluations were made in comparison with a new non-rigid deformable air-ventilating phantom, which was used to evaluate the accuracy of the DIR-based ventilation imaging and the spatial accuracy of the DIR. We first evaluated the spatial accuracy of the NiftyReg deformation with four different DIR parameter sets, and then second determined the correlation coefficients between a mapping of the change in Hounsfield units (HU) in a ventilation image obtained using Xe as a contrast agent (XeHU-based ventilation image) and the four different DIR-based ventilation images generated using Jacobian determinant (JD) metrics.

2. Materials and methods

2.1. NiftyReg

NiftyReg is an open-source DIR package (Version 1.4.2) provided by University College London, UK [9], and includes tools for global and local image registration. The algorithm used for global registration is based on a block matching approach, while the local registration implementation uses a cubic B-Spline parameterization (free-form deformation). All registration algorithms are based on symmetric approaches where forward and backward transformations can be optimized concurrently.

2.2. Non-rigid "ventilating" phantom

A phantom was designed and developed to evaluate the spatial accuracy of deformations and the accuracy of the DIR-based ventilation images [13]. The setup of the phantom is presented in Fig. 1. In this phantom, tubes simulating airways and arteries are embedded in polyurethane foam to simulate alveoli, with the airway tubes passing through to the outside of the phantom to converge and form a single tube, thereby simulating the trachea and enabling the simulation of ventilation. A piston to simulate respiratory musculature is secured to a motor via a metal rod to exert upward and downward forces on the membrane, compressing and decompressing the foam, and simulating the respiratory cycle. Various motion patterns can be set to simulate breathing patterns of varying periodicity. The reproducibility of the phantom was previously studied by quantifying the 3D positional error of anatomical landmarks within it, with these being found to be less than the voxel dimension on average [13].

When the simulated diaphragm moved up and down, Xe gas flowed between a balloon reservoir connected to the trachea and the airways and foam. A XeHU-based ventilation image was then acquired by visualizing Xe gas concentrations and comparing them between peak inhalation and peak exhalation phase CT images. A DIR-based ventilation image was then generated using the same inhalation and exhalation phase CT images. Subsequently, the correlation coefficients between the XeHU-based and DIR-based ventilation images were evaluated to determine the accuracy of the DIR images.

2.3. DIR mapping of simulated pulmonary ventilation

DIR-based ventilation images were then created in three stages, CT image acquisition, DIR, and DIR-based ventilation imaging, as outlined in the following subsections.

2.3.1. Acquisition of CT images

CT image acquisition was performed using a 16-detector CT scanner (Aquilion LB, Toshiba Medical Systems, Otawara, Japan) and a helical scanning protocol with an image resolution of 0.78 × 0.78 × 3 mm. The scan parameters included 120 kVp, 300 mA, 0.5 s rotation time, and 3.0 mm slice thickness. The CT images of the phantom were acquired using Xe gas for contrast. Xe has a higher CT-HU value than air. The phantom was operated horizontally with its axis coinciding with the CT z axis and the induced motion following a cosine wave. The respiratory cycle was set to 10 s to reduce the influence of motion artifacts. One CT image dataset was obtained at the peak inhalation phase with the foam fully expanded and filled with Xe, while the other CT image dataset was obtained at the peak exhalation phase with the foam compressed and emptied of Xe.

2.3.2. DIR

In this study, the peak exhalation image was designated as the floating image and was deformed to the peak inhalation image. The peak inhalation image was designated as the reference image because the DIR-based ventilation imaging accuracy was evaluated in comparison with the peak inhalation Xe enhancement image, and the Xe was

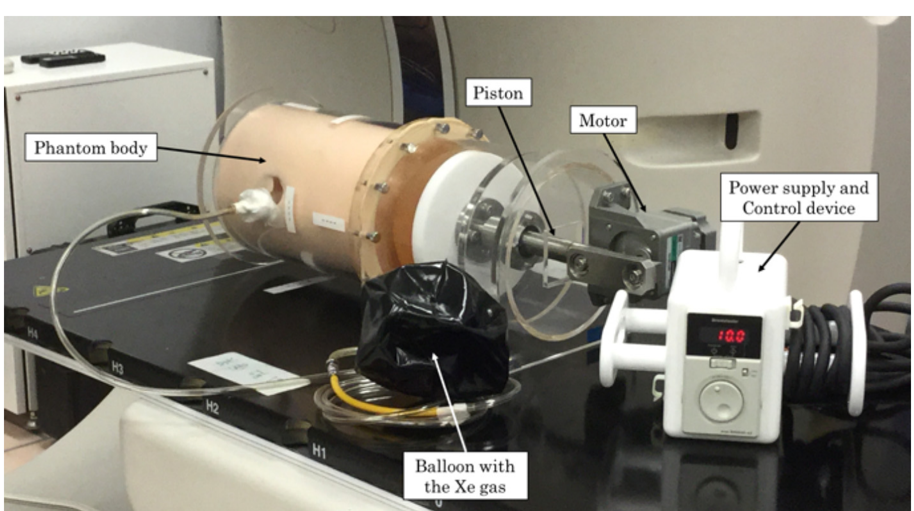

Fig. 1. Ventilating non-rigid phantom setup.