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Original paper

Dose warping performance in deformable image registration in lung

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ABSTRACT

Purpose: It is unclear that spatial accuracy can reflect the impact of deformed dose distribution. In this study, we used dosimetric parameters to compare an in-house deformable image registration (DIR) system using NiftyReg, with two commercially available systems, MIM Maestro (MIM) and Velocity AI (Velocity).

Methods: For 19 non-small-cell lung cancer patients, the peak inspiration (0%)-4DCT images were deformed to the peak expiration (50%)-4DCT images using each of the three DIR systems, which included computation of the deformation vector fields (DVF). The 0%-gross tumor volume (GTV) and the 0%-dose distribution were also then deformed using the DVFs. The agreement in the dose distributions for the GTVs was evaluated using generalized equivalent uniform dose (gEUD), mean dose (D_{mean}), and three-dimensional (3D) gamma index (criteria: 3 mm/3%). Additionally, a Dice similarity coefficient (DSC) was used to measure the similarity of the GTV volumes.

Results: D_{mean} and gEUD demonstrated good agreement between the original and deformed dose distributions (differences were generally less than 3%) in 17 of the patients. In two other patients, the Velocity system resulted in differences in gEUD of 50.1% and 29.7% and in D_{mean} of 11.8% and 4.78%. The gamma index comparison showed statistically significant differences for the in-house DIR vs. MIM, and MIM vs. Velocity.

Conclusions: The finely tuned in-house DIR system could achieve similar spatial and dose accuracy to the commercial systems. Care must be taken, as we found errors of more than 5% for D_{mean} and 30% for gEUD, even with a commercially available DIR tool.

1. Introduction

The locations and volumes of organs inside a patient's body can change significantly during irradiation and between treatments [1,2]. Anatomical changes over an entire course of treatment can compromise the value of the initial treatment plan and therefore the treatment outcomes [3]. Adaptive radiotherapy (ART) has therefore been proposed to overcome this challenge; it allows the plan quality to be maintained by modification or re-optimization of the treatment plan according to changes in a patient's anatomy [4,5]. Inter- and intra-fraction organ motion is especially significant in lung radiotherapy, and ART can provide a more accurate final dose distribution from the information on the accumulated dose distribution. This is obtained using fraction-by-fraction dose distributions deformed according to a reference transformation between the planning CT and treatment CT. Deformable image registration (DIR) is therefore an essential tool for ART. The use of four-dimensional computed tomography (4DCT) has also facilitated treatment planning by allowing the respiratory motion of the target and critical organs to be incorporated into the analysis. The tumor volume and shape can be estimated more accurately in a phased 4DCT image than they can from a maximum or mean intensity projection formed from the 4DCT scan. A typical planning also usually considers only a static tumor, even though the tumor will move during the irradiation. An accumulated 4D dose calculation is therefore useful for achieving a more realistic estimation of the dose delivered to the tumor in the lung and the surrounding organs [6–9]. Information on the delivered 4D dose accumulation can help the physician evaluate the treatment and decide when and how a re-plan should be performed. Accurate dose warping is therefore one of the most important factors in the ART methodology.

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Many investigators have reported on methods for evaluation of the accuracy of DIR, including the use of the Dice similarity coefficient (DSC), landmark comparisons, mean slice-wise Hausdorff distance to agreement, volume differences, receiver operating characteristics, and target registration error [10–14]. However, few studies have directly evaluated dose deformation. Yeo et al. evaluated the accuracy of dose warping using DEFGEL, which is a deformable three-dimensional-dosimetry gel phantom [15–17]. Dosimetry using DEFGEL can provide direct measurements of dose, taking into consideration deformable media. However, the dosimetry information available from gel phantoms is limited, as they lack geometric complexity and are unable to provide assessments for individual patient cases. Additionally, dosimetry with deformable gel phantoms requires specialized and expensive equipment.

In addition to dose monitoring in the lung, DIR may be applied in various other fields, such as radiotherapy and nuclear medicine [18,19]. There are several publicly available DIR systems, which may be suitable for contributing to clinical practice and the research environment, provided that the system is at least comparable to commercially available DIR systems.

The purpose of this study was twofold; the first part was to build an in-house DIR system with a graphical user interface and image registration using the publically available NiftyReg (free-downloadable software library package, NiftyReg), while the second part of the study compares the in-house NiftyReg DIR system with two commercially available systems, MIM Maestro (MIM Software Inc., Cleveland, OH, USA) and Velocity AI (Varian Medical Systems, Palo Alto, CA, USA), with the evaluations being made using mean dose (D_{mean}), generalized equivalent uniform dose (gEUD), and three-dimensional (3D) gamma index evaluation. These dosimetric parameters are common in clinical practice and are easy to use, with a previous study having applied the generalized equivalent uniform dose (gEUD) as an index to quantify plan quality [20]. D_{mean} and gEUD were investigated as indices of the accuracy of dose warping using the DSC representing the spatial accuracy of image registration under the DIR.

2. Materials and methods

2.1. 4D-CT scan acquisition and patients

All 4DCT scans were acquired on a 4-slice clinical scanner (Brilliance CT Big Bore, Philips Healthcare, Andover, MA). The respiratory cycle signal was monitored using an abdominal bellows pressure belt system (Philips Medical Systems). Other imaging parameters (e.g. tube voltage [kV] and tube current exposure time product value [mAs]) were set according to site-specific standard imaging protocols. CT data were reconstructed with a field of view of 50 cm on a 512×512 grid with a slice thickness of 2.0 mm. The longitudinal scan length was determined on a scout view. Nineteen patients treated with lung stereotactic body radiation therapy underwent 4DCT scans. The peak inspiration (0%) and peak expiration phases (50%) of the 4DCT image datasets were used in this study. Tumor displacement was defined as the vector sum from the centroid of the 0%-gross tumor volume (GTV) to the centroid of the 50%-GTV.

The tumor displacement varied from 0.30–1.55 cm across cases. The volumes of the gross tumor volume (GTV) ranged from 0.89–99.0 cm^3 for the 0% phase and 1.06–99.0 cm^3 for the 50% phase (Table 1). The mean percentage difference between the GTVs at the 0% and 50% phases was 0.98 ± 0.38% (Maximum: 28.2%).

Table 1
Tumor displacement, GTV obtained at the peak inspiration phase (0%) and the peak expiration phase (50%), and the percentage difference of the volume change in the 19 patients evaluated.

Case no.	Tumor displacement [cm]	GTV at 0% (inspiration) phase [cm^3]	GTV at 50% (expiration) phase [cm^3]	Percentage difference of volume change [%]
1	0.62	2.46	2.50	1.6
2	1.55	60.81	60.55	0.4
3	1.51	29.46	29.28	0.6
4	0.86	9.30	8.19	11.9
5	1.37	5.35	6.86	28.2
6	1.22	9.13	9.57	4.8
7	1.36	25.30	28.13	11.2
8	0.30	1.58	1.19	24.7
9	1.54	13.50	13.98	3.6
10	0.82	0.89	1.06	19.1
11	1.12	16.32	16.07	1.5
12	0.96	14.46	16.06	11.1
13	0.38	99.00	99.84	0.8
14	0.91	4.58	4.40	3.9
15	1.07	4.37	3.85	11.9
16	0.61	4.25	4.03	5.2
17	1.01	92.43	85.84	7.1
18	0.77	8.32	8.33	0.1
19	0.62	14.07	11.62	17.4

2.2. Planning and dose warping

Treatment planning (structure contouring, treatment field setting, and dose calculation) was performed on the 0%-4DCT image dataset using Eclipse treatment planning software (Version 10.0, Varian Medical Systems, Palo Alto, CA, USA). Radiation oncologists were asked to draw contours defining the GTVs on the 50%-4DCT image dataset. A medical physicist with five-years of experience delineated the GTVs on the 0%-4DCT image datasets, under the observation of a radiation oncologist who also checked them all. The mean DSC value representing the inter-observer variability for GTV volume on the 0%-4DCT images was 0.85 ± 0.05 (Range: 0.73–0.92), a value that is comparable to the inter-observer delineation variation found in a previous study [21]. The clinical target volume (CTV) was set as equivalent to the GTV, and the planning target volume (PTV) was created by adding a 5 mm margin to the CTV in all directions. The number of treatment fields ranged from 9 to 13. The aperture shapes of the multileaf collimator were adjusted in the beam's eye view to cover the PTV with an additional 5 mm margin, to take into consideration the inaccuracy of dose calculation in the border region between the tumor and lung. All plans were generated with the prescription dose (54 Gy/3 fr) covering 95% of the PTV. A dose calculation grid size of 2.5 mm was used for the anisotropic analytical algorithm (AAA) calculations, and a dose volume histogram (DVH) of the GTV was subsequently computed. The 0%-4DCT image dataset was then deformed to the 50%-4DCT image dataset using the three DIR systems, thereby facilitating the computation of the deformation vector field (DVF) for each system. The dose distribution in the 0%-4DCT was also deformed according to each of the three DVFs obtained. The deformed dose distributions were then superimposed onto the 50%-4DCT image datasets with the corresponding contoured structures, and the DVHs of the GTVs were computed.

2.3. Dose warping algorithm

2.3.1. In-house deformable image registration system using NiftyReg

The in-house DIR system included a graphical user interface and image registration using NiftyReg. The image registration process consisted of three major steps. In the first step, a rigid registration was performed using a block-matching algorithm for the whole body of the patient [22]. The second step entailed a deformation inside the lung using a fast free-form deformation (FFD) algorithm, with the third step involving a larger-scale deformation inside the body. The second step focused on the tumor and lung, which have