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Method of evaluating respiratory induced organ motion by vector volume histogram

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ABSTRACT

Purpose: Published organ motion data have been collected from measurements of a limited number of points within the organ, the centroid, or the edge of the organ. These are derived from the spatial characteristics of respiratory induced motion; however, this approach does not consider non-rigid organ deformation. We propose a novel quantitative method for evaluating respiratory induced organ motion using Deformable Image Registration (DIR).

Method: Two phases from a 4-dimensional computed tomography (4D CT) dataset at maximum inspiration and expiration were each taken from five patients. The left and right lungs, esophagus, stomach, spinal cord, and liver were manually contoured in the end-expiration phase. The hybrid deformable registration algorithm of the RayStation treatment planning system (TPS) was used to deform the end-expiration phase to the end-inspiration phase. From this, the deformation vector field (DVF) was calculated. DVFs consist of DVF_{LR} (left-right), DVF_{AP} (anterior-posterior), and DVF_{SI} (superior-inferior) as separate files. We calculated the vector volume histogram (VVH) and L_{max} (maximum absolute vector of the organ) to evaluate every vector for each individual organ. We also measured respiratory organ motion from the position of the organ centroid in two phases.

Results: VVH enabled us to find the absolute distance and volume of the organ contributing to motion points on the curve. Organ motion using the centroid method was smaller than L_{max} using VVH. Using the centroid method, it is difficult to evaluate the deformable organ motion.

Conclusion: VVH may be a useful technique in evaluating organ volumetric change during respiratory organ motion.

1. Introduction

Respiratory induced organ motion is an important issue in radiotherapy treatment planning of the thoracic and upper abdominal regions. It produces the greatest movement in the caudal-cranial (CC) direction because the most important muscle used in inhalation is the diaphragm. Several authors previously reported respiratory induced organ motion as studied using several imaging modalities. The lungs, esophagus, liver, pancreas, breast, prostate, stomach, and kidneys, among other organs, are all known to move with breathing [1–7]. Most of these data only measured in limited ways: at several points, the centroid, or the edge of the organ. These are derived from the spatial characteristics of respiratory induced organ motion; however, this approach does not consider organ deformation.

In recent years, deformable image registration (DIR) has been developed as a technology useful in application to image-guided radiotherapy (IGRT) and adaptive radiotherapy (ART) in its ability to create a new deformed image. Applications for radiotherapy include dose accumulation with DIR, auto segmentation, four-dimensional (4D) dose accumulation, and 4D computed tomography (4D CT)-derived ventilation imaging [8–10]. An advantage of DIR in ART is the spatial mapping of corresponding locations between images, and this may be used for structure delineation on a second image when the set of structures is present on the first image. Thus, each phase of the 4D CT image dataset can be deformed to match the objective phase image. With DIR, both end-expiration and end-inspiration phase images may be used to evaluate organ motion due to respiration. Several researchers have investigated the motion and deformation of tumors and normal

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tissue using image registration techniques [11,12]. The plotted trajectories, or 'mesh', were displayed to indicate their calculation results, and results from fixed landmark points, and deformable techniques were compared. Currently, there are no known reports of using quantitative information as a function of the vector-volume for characterizing respiratory induced organ motion.

Here, we propose a novel method for evaluating respiratory organ motion using DIR. This work presents a quantitative method that evaluates the vector with the location of pixels inside each organ. We also measured respiratory organ motion from the displacement of the centroid of the organ in two phases.

2. Methods and materials

We used the 4D CT datasets of the five patients from the DIR website (www.DIR-lab.com). This website provides this set of test data for the specific critical evaluation of DIR spatial accuracy performance in multiple clinical settings. For a detailed description of the datasets, we refer the reader to Castillo et al. [13,14]. The 4D CT images were acquired over the entire thorax and upper abdomen at 2.5 mm slice spacing using a General Electric Discovery ST PET/CT scanner (GE Medical Systems, Waukesha, WI). The voxel dimension was $0.97 \times 0.97 \times 2.5$ mm. We used the end-expiration and end-inspiration phases of the 4D CT image sets.

We focused on the lung, esophagus, stomach, spinal cord, and liver in this study. In the end-expiration phase of the CT images, the left and right lungs, esophagus, stomach, spinal cord, and liver were manually contoured by a radiation oncologist. The hybrid deformable registration algorithm of RayStation version 4.7.4.4 (RaySearch Laboratories, Stockholm, Sweden) treatment planning system (TPS) was used to deform the images from the end-expiration to the end-inspiration phases. We visually verified that the resulting deformable images reasonably outlined the end-inspiration phase images.

The DIR algorithm defines two image sets: the reference and target sets. The DIR algorithm computes a vector field on the deformation grid, the vectors point from the individual voxels on the reference to the corresponding voxels on the target image set. The vector field is defined as the deformation vector field (DVF). RayStation deformation algorithms have been benchmarked using the error metric target registration error (TRE), which provides a general assessment of DIR performance with a set of 10 computational head & neck phantoms [15]. A deformation grid of $2.5 \times 2.5 \times 2.5$ mm was used for each case. The calculated DVF was exported via a script. DVFs consist of DVF_{LR} (left-right), DVF_{AP} (anterior-posterior), and DVF_{CC} separates files. Each DVF value was calculated as an absolute value. Exported DVF data was converted into the Digital Imaging and Communications in Medicine-Radiation Therapy (DICOM RT) Dose file format, using the programming language *Microsoft Visual C#*. The modified DICOM-RT file was then imported into the RayStation TPS.

The vector volume histogram (VVH) calculation approach is a concept similar to that of the dose volume histogram (DVH). The motion vector is a three-dimensional array defining the location of each pixel. Vectors on each direction are stored in separate arrays. 3D-DVF is calculated by $\sqrt{DVF_{LR}^2 + DVF_{AP}^2 + DVF_{CC}^2}$. In comparison, the VVH for each organ is calculated by evaluating the number of magnitude values in the organ.

The following motion indices were used to evaluate the respiratory motion:

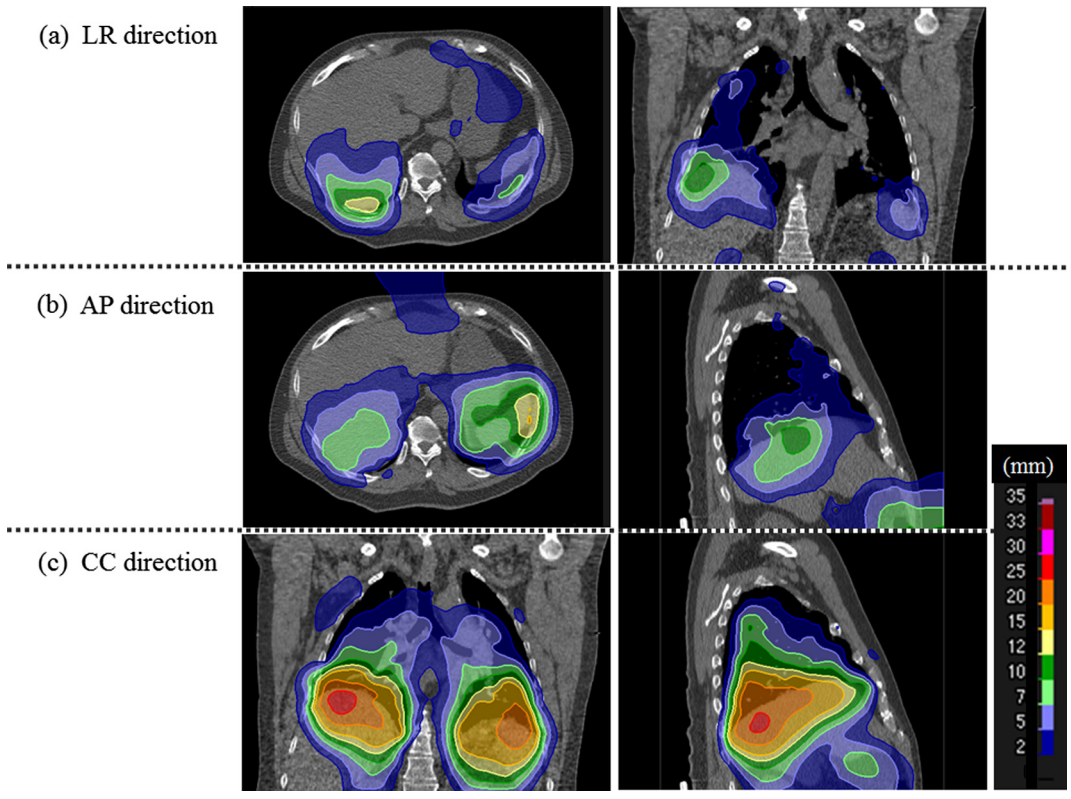

Fig. 1. Vector distributions are in (a) left-right (LR), (b) anterior-posterior (AP), and (c) cranial-caudal (CC) directions for Case 1. The magnitude of the estimated respiratory induced organ motion between end-expiration and end-inspiration phase images are visualized in color. Organ motion in the CC direction is larger than in the AP and LR directions. This method can visualize organ motion in each direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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