Reproducibility Analysis of 4DCT Derived Ventilation Distribution Data

An Application of a Ventilation Calculation Algorithm based on 4DCT

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Abstract: Deriving lung ventilation distribution from 4-dimensional CT (4DCT) using deformable image registration (DIR) is a recent technical development. In this study, we evaluated the serial reproducibility of ventilation data derived from two separate 4DCT data sets, collected at different time points. A total of 33 lung cancer patients were retrospectively analyzed. All patients had two stereotactic body radiotherapy treatment courses for lung cancer. Seven patients were excluded due to artifacts in the 4DCT data sets. The ventilation distributions in the lungs for each patient were calculated using the two sets of planning 4DCT data. The deformation matrices between the expiration and inspiration phases generated by DIR were used to produce ventilation distributions using the ΔV method. Ventilation in the lung regions that received less than 1 Gy was analyzed. For the 26 cases, the median Spearman correlation coefficient value was 0.31 (range 0.18 to 0.52, p value < 0.01 for all cases). The median Dice similarity coefficient value between the upper 30% ventilation regions of the two sets was 0.75 (range 0.71 to 0.81, Figure 1). We conclude that the two ventilation data sets in each case correlated and the reproducibility over time was reasonably good.

1 INTRODUCTION

Perfusion and ventilation can be used to characterize lung function. Clinically, ventilation imaging is mostly performed using SPECT (Harris et al., 2007) or PET (Melo et al., 2003). Deriving lung ventilation distribution from 4-dimensional CT (4DCT) using deformable image registration is a recent technical development (Zhang et al., 2009; Guerrero et al., 2005; Reinhardt et al., 2008). Several studies have shown that this technique agrees reasonably well with other established techniques such as SPECT, Xe enhanced dynamic CT or PET (Ding et al., 2012; Kipritidis et al., 2014; Yamamoto et al., 2014). Theoretically, one could determine regions of high lung ventilation in thoracic cancer patients and use these regions as avoidance structures in radiotherapy treatment planning, without the need of an additional imaging procedure such as SPECT or PET. This new ventilation calculation method using 4DCT has also been applied in lung disease detection (Castillo et al., 2012), radiotherapy treatment planning studies (Huang et al., 2013; Siva et al., 2015) and assessment of radiotherapy response (Ding et al., 2010).

In this study, we evaluated the serial reproducibility of ventilation data derived from two separate 4DCT data sets in the same patient collected at different time points.

2 MATERIALS AND METHODS

2.1 Patient Data

A total of 33 lung cancer patients were retrospectively analyzed following a protocol approved by our institutional review board. All patients had two lung cancer stereotactic body radiotherapy treatment courses (different isocenters) with a median interval between them of 9.6 months (range: 0.7-39 mo). Separate treatment planning 4DCT datasets were acquired each treatment course. Seven patients were excluded due to obvious mushroom artifacts in the 4DCT datasets, thus 26 valid cases were included in data analysis and presented in this study.

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2.2 Deformable Image Registration

Based on a previous DIR selection study (Latifi et al., 2013c), the Diffeomorphic Morphons (DM) method (Janssens et al., 2009) was applied for the deformable image registration (DIR) between the expiration and inspiration phases in each 4DCT dataset.

2.3 Ventilation

The ventilation distributions in the lungs for each patient were calculated using the two sets of 4DCT data, with the tumor volumes excluded. The generated deformation matrices were used to generate ventilation distributions using the ΔV method, which is a direct geometrical calculation of the volume change (Zhang et al., 2011; Zhang et al., 2009). In the expiration phase of a 4DCT dataset, each voxel is a cuboid defined by 8 vertices. In the inspiration phase, this cuboid is changed into a 12-face polyhedron which is still comprised of the corresponding 8 vertices which can be determined by the DIR calculation. Any hexahedron or 12-face polyhedron can be divided into 6 tetrahedrons. The volume of a tetrahedron can be calculated using

$$V = (\boldsymbol{b} - \boldsymbol{a}) \cdot [(\boldsymbol{c} - \boldsymbol{a}) \times (\boldsymbol{d} - \boldsymbol{a})] / 6, \quad (1)$$

where $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{c}$, $\boldsymbol{d}$ are the vertices' coordinates of the tetrahedron expressed as vectors.
Ventilation is defined as

$$P = \Delta V / V_{ex}, \quad (2)$$

where ΔV is the volume change between expiration and inspiration and V_{ex} is the initial volume at expiration (Simon, 2000).

In each case, the second set of ventilation distributions was mapped onto the first one using DM DIR between the expiration phases of the two 4DCT sets, and the two ventilation distributions were normalized (Latifi et al., 2013a) and compared. Since radiation dose can alter regional lung ventilation (Latifi et al., 2015), the high dose regions were excluded to prevent introduction of systemic error in the ventilation calculations. We chose to analyze lung regions that received less than 1 Gy of radiation dose to minimize the effect of radiation changes on ventilation estimates since it has been established that large dose of radiation reduce ventilation.

As DIR may introduce errors due to artifacts and noise in CT images, consequently, errors may be introduced into ventilation distributions (Latifi et al., 2013b). Smoothing the ventilation distributions may reduce such errors. The calculated ventilation distributions were smoothed with a 9×9×9 mm^3 average filter and analized.

2.4 Correlation and Reproducibility

The voxel-wise Spearman correlation coefficient (SCC) between the ventilation data sets in each case was calculated. The absolute ventilation data (without normalization) were used in the SCC analysis. The Dice similarity coefficient (DSC) (Dice, 1945) was also calculated between the upper 30% ventilation regions of the two sets:

$$DSC(A,B) = \frac{2 \times |A \cap B|}{|A| + |B|}, \quad (3)$$

where A and B are the two involved volumes.

3 RESULTS

Figure 1 shows a representative dose distribution.

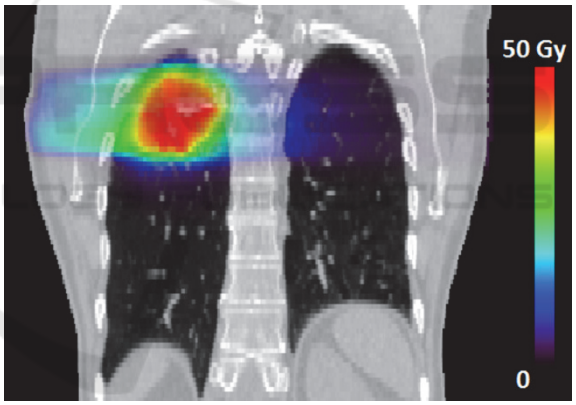

Figure 1: Dose distribution for a representative case.

Figure 2 shows the ventilation distributions for the case shown in Figure 1.

For the 26 cases, the median SCC value was 0.31 (range 0.18 to 0.52, $p < 0.01$ for all cases; original in Figure 3). The median DSC value was 0.75 (range 0.71 to 0.81; original in Figure 4).

After the ventilation distributions were smoothed with 9x9x9 mm^3 average filter, the SCC and DSC improved, with median values of 0.44 (smooth in Figure 3) and 0.77 (smooth in Figure 4), respectively.

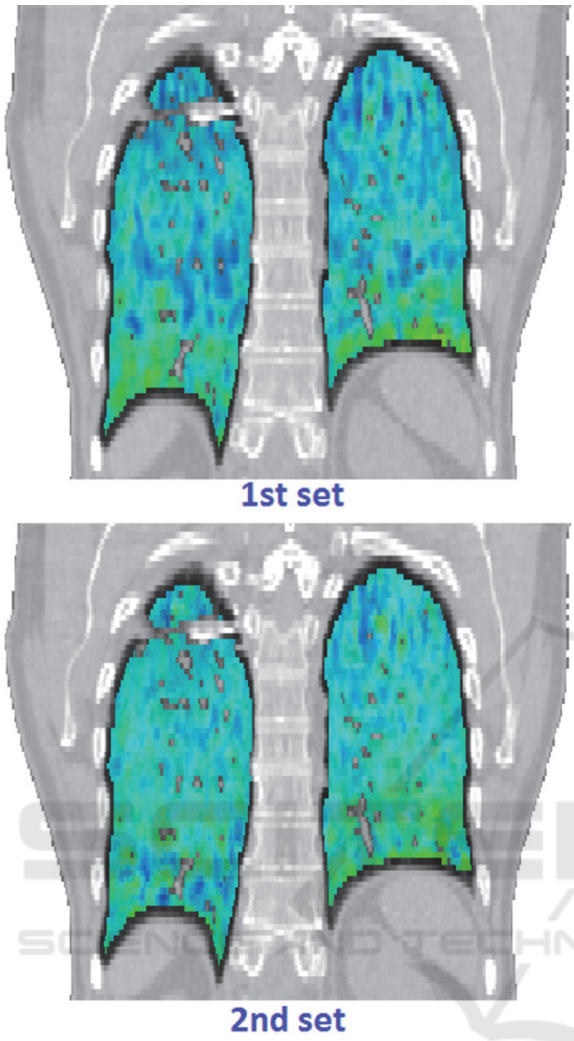

Figure 2: Ventilation distributions for a representative case.

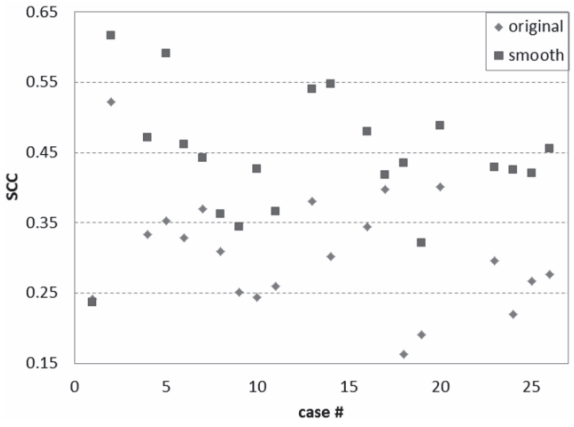

Figure 3: SCC for all cases. Blue points are the original data points, while the red ones are after smoothing.

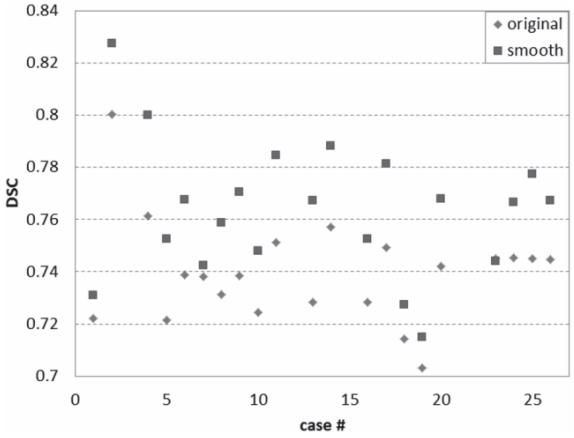

Figure 4: DSC for all cases. Blue points are the original data points, while the red ones are after smoothing.

4 DISCUSSION

Mushroom artifacts often appear in 4DCT data due to irregular diaphragmatic motion. This imaging artifact introduces errors in DIR and consequently errors in the derived ventilation distributions. Because of these errors, the SCC value could be very low, close to 0. This was the reason why 7 cases were excluded from the analysis.

The DIR errors due to noise in CT images are the other major concern in ventilation calculation using DIR on 4DCT (Latifi et al., 2013b). Smoothing can reduce the effect of such errors as demonstrated in Figure 3 and 4. Improving the quality of 4DCT should improve the accuracy of ventilation calculation using this technique, and the reproducibility may be higher as a consequence.

In this study, post-treatment ventilation was mapped to pre-treatment ventilation using DIR. This DIR application may introduce additional errors in the final results.

5 CONCLUSIONS

Based on the SCC and DSC values, we conclude that the two ventilation data sets in each case correlated and the reproducibility over time, especially for the high ventilation regions, was reasonably good when there were no obvious artifacts in the 4DCT. Ventilation data smoothing can reduce errors introduced in the DIR and thus improve the reproducibility. High quality 4DCT is essential for good reproducibility in ventilation distributions.

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