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Supervised recursive segmentation of volumetric CT images for 3D reconstruction of lung and vessel tree

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ABSTRACT

Three dimensional reconstruction of lung and vessel tree has great significance to 3D observation and quantitative analysis for lung diseases. This paper presents non-sheltered 3D models of lung and vessel tree based on a supervised semi-3D lung tissues segmentation method. A recursive strategy based on geometric active contour is proposed instead of the "coarse-to-fine" framework in existing literature to extract lung tissues from the volumetric CT slices. In this model, the segmentation of the current slice is supervised by the result of the previous one slice due to the slight changes between adjacent slice of lung tissues. Through this mechanism, lung tissues in all the slices are segmented fast and accurately. The serious problems of left and right lungs fusion, caused by partial volume effects, and segmentation of pleural nodules can be settled meanwhile during the semi-3D process. The proposed scheme is evaluated by fifteen scans, from eight healthy participants and seven participants suffering from early-stage lung tumors. The results validate the good performance of the proposed method compared with the "coarse-to-fine" framework. The segmented datasets are utilized to reconstruct the non-sheltered 3D models of lung and vessel tree.

1. Introduction

Lung settles the exchange of oxygen and carbon dioxide and is one of the most important organs for human beings. However, it is vulnerable to many deadly diseases such as lung cancer, tuberculosis and pneumonia. Among them, lung cancer which represents the first death cause in men and the second in women, has an impressive rate of about five million deadly cases per year [1]. Air pollution, smoking and occupational hazard make a great contribution to those events.

Generally, X-ray computed tomography (CT) image is regarded as the gold standard in the non-invasive diagnosis [2] and treatment for pulmonary diseases [3]. However, basing on two dimensional (2D) slices, radiologists and surgeons must view hundreds of CT slices in front of a screen or films, which is boring and time consuming. What's more, they have to imagine the three dimensional (3D) features and the spatial relationships between different structures according to their experience. It is not accurate and varies among different radiologists. 3D reconstruction is a powerful medical data visualization technology for physicians and medical

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researchers. 3D reconstruction could manage all the slices of one patient in a single vision. It has the potential to simplify the radiologic study and could be widely used in clinical surgical treatment planning [4,5], radiation therapy [6], plasty [7,8], etc.

3D reconstruction of lung, vessel tree and tumors is an essential reference for lung cancer and other diseases decisions in clinical diagnosis. Because of the lower density compared with the surrounding high-density bones, muscles and vessels, lung will be sheltered by peripheral tissues in the 3D model of whole body. For example, to view the right side of the lung vessels, chest wall in the right side should be cut away. The sheltered lung models will affect the observation, localization and 3D measurement of lung lesions [9]. In order to realize non-sheltered lung and vessel tree, pre-segmentation of lung tissues from volumetric images is necessary. However, the intensities of parenchyma, vessels, bronchus and tumors differ greatly [2,10]. It brings difficulties to realize a global segmentation of all the pulmonary structures [11]. Lung segmentation from the CT volumetric dataset is still one of the challenges in medical image analysis [12]. With the segmented subdatasets, non-sheltered 3D lung models could be realized using 3D reconstruction method. The spatial relationship between different structures will be obvious and radiologists can get the anatomical knowledge of 3D structures [13]. What's more, the segmented dataset could be used in quantitative analysis, for example vital capacity measurement [14], non-invasive pulmonary function tests[15] etc.

1.1. *Related works*

Because of the complex structures in human lung, a single algorithm is not enough to segment all the pulmonary structures, for example thresholding, region growing or cluster analysis methods. Integrated methods have been proposed by many authors. Those methods are divided into two groups: two dimensional (2D) methods [10–13,16,17] and 3D methods [1–3,18–21].

In 2D methods, chest CT datasets are segmented slices by slices. Pu et al. developed an adaptive border marching (ABM) algorithm [10] to segment lung tissues with smooth border and extract all juxta-pleural nodules reliably. The proposed method contains three main steps namely preprocessing, lung border tracking and ABM. First, lung tissues including parenchyma and vessels are extracted with thresholding and flood operation method. Then, lung boundaries are computed with inner border tracing algorithm. In the last, a smoothed border which includes the juxta-pleural nodules is extracted by the ABM algorithm. This method is effective to correct the segmentation defects caused by juxta-pleural nodules.

Zhou et al. introduced a sequential region-splitting process [11] based on normal anatomical structure of the human chest and statistical intensity distributions. The proposed method utilizes the spatial and density relations of the structures within the lung and can segment different structures simultaneously. The segmented slices are used to reconstruct the 3D anatomical lung model. This approach is too complicated, and many technologies are combined together, including threshold, 3D connectivity analysis, surface detection, regions filling, region growing method etc. And the typical computation time of this scheme is about 105 min for one dataset ($512 \times 512 \times 400 - 600$).

Darmanayagam et al. proposed a supervised approach [12] for lung tissues segmentation in chest CT slices which suffer from lung disorders. If one of the two lungs (left and right) is in disorder, another one will be regarded as a template to segment the disordered one. This approach has four main steps: firstly segment the lung with thresholding and morphological operations; secondly, extract the features of left and right lung; third, evaluate whether there is severe pathology attached to the chest borders by a multilayer feed forward neural network method based on the extracted features in the second step. If it happens, this lung suffers from diseases; finally, the left lung is used as template to extract the right lung if the right lung suffers from disorders according to the reflective and translational properties, vice versa. This method is suitable for both normal and diseased lungs. While, it would lead to serious errors where the reflective and translational properties of left and right lungs are not so well. And this method is not suitable for segmentation of volumetric dataset.

Rosell et al. presented a relay method [16] to extract airway tree from the chest CT scans. The relay method contains three stages: a gross segmentation of the main airway tree using adaptive region growing algorithm, a finer segmentation of the smaller bronchi based on the local information, and a final process to merge the segmentation results of the two first stages using a morphological reconstruction process and a path planning technique.

In [17], Sluimer et al. proposed a segmentation-by-registration method. In this method, a segmentation result of a healthy slice is registered elastically to a slice suffering from pathology. And the results are refined with voxel classification. However, not all the cases could be handled successfully [17], and the computation time needs to be reduced from 3 h to a clinically acceptable level.

Li et al. [13] integrated manual and automatic methods together to extract cerebrum tissues. The results are used to construct the 3D digitized Chinese human. If there is distinct difference between adjacent structures, target tissues are segmented using automatic methods and then adjusted manually slice by slice. Otherwise, the target tissues are segmented using magic stick tool in Photoshop software.

A large amount of sequential chest CT slices compose a volumetric dataset and pulmonary tissues in all the slices can be segmented simultaneously by 3D segmentation methods.

Wei et al. proposed a fully automatic segmentation and repairing method for lung parenchyma [18]. This method comprehensively use several methods including optimal iterative thresholding, 3D connectivity labeling, 3D region growing and center position locating method to extract lung tissues, remove the main trachea and separate the left and right lungs. Then repair the segmentation results with a method based on improved chain code and Bresenham algorithm.

Choi et al. [2] introduced a method to extract lung tissues for further automatic pulmonary nodule detection. First, thresholding and 3D connected component labeling methods are utilized to extract lung tissues. Then, fill the holes in the lung tissues using a hole-filling method. And finally, refine the coarse results with a contour correction method