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A three-stage method for the 3D reconstruction of the tracheobronchial tree from CT scans

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ABSTRACT

This paper proposes a method for segmenting the airways from CT scans of the chest to obtain a 3D model that can be used in the virtual bronchoscopy for the exploration and the planning of paths to the lesions. The method is composed of 3 stages: a gross segmentation that reconstructs the main airway tree using adaptive region growing, a finer segmentation that identifies any potential airway region based on a 2D process that enhances bronchi walls using local information, and a final process to connect any isolated bronchus to the main airways using a morphologic reconstruction process and a path planning technique. The paper includes two examples for the evaluation and discussion of the proposal.

1. Introduction

Bronchoscopy is an interventional medical procedure used to analyze the tracheobronchial tree, mainly to obtain samples from a specific lung site identified by chest X-ray computed tomography (CT) for the diagnosis of lung cancer. The planning of the path to the lesion is usually done on 2D images, which is difficult, error prone and may result in long execution times of the bronchoscopy. Virtual bronchoscopy (VB) can improve this. VB it is a computer-generated 3D reconstruction that allows medical staff to explore interactively the tracheobronchial tree and also automatically obtain a path to the lesion. Recent clinical studies [1] have proved that VB navigation system shortens the examination and operation times.

A key point in VB is, therefore, the reconstruction of a 3D model of the tracheobronchial tree from the CT scans. Since manual segmentation is prohibitively time consuming, automatic or semi-automatic methods are necessary, which poses a difficult and challenging problem. The difficulty arises because it is not easy to implement efficient and flexible algorithms to cope with all possible clinically relevant cases. Bronchi appear on CT images as dark regions (airway lumen) surrounded by a clear region (the airway wall), but, due to noise, low definition scanner or interpolation artifacts for small-diameter segments, their radio-density vary across the image, and therefore it is not possible to define a global threshold to segment them all. Moreover, the completeness of the reconstruction is becoming even more important now that the new ultra-thin bronchoscopes permit exploration through bronchi as small as 2 mm in diameter.

1.1. Related work

Since the early nineties, several approaches have been proposed to solve the airway segmentation and reconstruction problem. The most common are those based on region growing, on mathematical morphology and on multi-rule or fuzzy logic using anatomical knowledge.

Region growing is a procedure that groups pixels or subregions into larger regions based on predefined criteria [2, chap. 10]. This technique is maybe the most used in the field of airway segmentation and many algorithms often include a region-growing phase. The most common method locates the seed at the beginning of the trachea and grows the region based on voxel connectivity and on a threshold of the HU[2] values. Despite of its simplicity and velocity, 3D region growing suffers from partial volume effects and noise, since it is based on a global threshold used during

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[2] HU stands for Hounsfield Units, that is the scale that measures the radiodensity. The darker voxels correspond to the air, that has a value of −1000 HU.

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the segmentation, and the "optimal" threshold for big airway differs a lot from the one required for small airways. The use of an inappropriate threshold may result in the occurrence of parenchyma leakages, mainly in noisy or low-contrasted images. A global threshold may be determined either manually [3] or automatically, based, for instance, on a repeated segmentation process [4]. Other alternatives propose the subdivision of the image in different regions, sometimes called volumes of interest, where the threshold is locally adapted [5–7]. The occurrence of leakages can also be reduced if algorithms to detect bronchi walls, as that proposed in [8], are used as a pre-processing step.

Airway segmentation methods using *mathematical morphology* [9] are also very common. These methods usually start searching for candidate airways using binary or gray-scale morphologic operations and, then, exclude the false candidates with a 3D reconstruction or analyzing the 3D relationships and shape properties [10]. These techniques are also combined with region growing methods, i.e. a first region growing step is performed to segment the trachea and biggest bronchi and then a second step copes with the segmentation of finer bronchi using the morphological gradient (the difference between 3D greyscale dilation and 3D greyscale erosion) [11], or using a morphological filtering based on a closing with structure elements of different sizes, and a reconstruction applied to all slices in all the three planes: axial, sagittal and coronal [12].

Rule-based or fuzzy logic methods have also been proposed, which allow the use of anatomical knowledge of the airway tree. For instance, [13] described a rule-based method based on a combination of 3D seeded region growing that is used to identify large airways, rule-based 2D segmentation of individual CT slices to identify probable locations of smaller diameter airways, and merging of airway regions across the 3D set of slices. The work in [14] refined the method of [13] improving the specificity of the rules introducing fuzzy logic techniques. Fuzzy logic has also been used in [15,16] to define a multiseeded fuzzy connectivity functions to segment voxels as lumen or wall, using different affinity relations like homogeneity-based affinity to detect similarity of intensity values over a neighborhood, or directional affinity to indicate the growing direction of the airway being reconstructed.

Many of the previous methods and techniques described above result in the main airway tree plus isolated non-connected branches. Therefore, some approaches include a final connection step. For instance, in [17] tubular structures are detected in the data volume and then the different structures are connected together according to branching angle (angle between the central axis of the two branches), branch radius and distance. A more sophisticated and precise method [18] searches for new candidates, calculates the cross sectional surfaces of the branches and connects the disjoint branches minimizing a connection cost based on the directions of the branches to be connected, the gray values of the voxels and other specific characteristics. The connection is made interpolating the cross sectional surfaces.

The topological and geometrical correctness has also been tackled, like the work in [19] that presents a method to guarantee that airway segmentations do not have loops or invalid voxel-to-voxel connections, or the work in [20] that presents an algorithm where surface patches are constructed adaptively based on the number of elemental points, leading to the elimination of geometrical distortions usually occurring at small bronchi.

1.2. Proposal overview

The paper presents a method for the 3D reconstruction of the tracheobronchial tree from the chest CT images that, after the selection of the lung region and the performance of some basic filtering, is organized in three stages:

(1) A first stage, called *raw segmentation*, devoted to segment the biggest airways using a region growing method with adaptive thresholds.
(2) A second stage, called *fine segmentation*, devoted to detect any small region that can be segmented as airways based on a 2D process that first enhances bronchi walls using local information, and then executes a basic segmentation and filtering process.
(3) A third stage, called *reconstruction*, devoted to connect any isolated bronchus to the main airways. It first uses a morphological reconstruction process, and then a procedure based on a path planning technique considering proximity and directional information as well as the gray values of the image.

The proposal is framed within a VB system described in [21], that permitted a guided navigation using a haptic device. The system included three main modules: a simple reconstruction module based on morphological processing to obtain a 3D model of the airways, a path planning module to find a path from the trachea to the lesion taking into account the geometry and the kinematic constraints of the bronchoscope and detailed in [22], and a navigation module using a haptic device that receives guiding forces to follow the computed path and whose movements are constrained to mimick those allowed by the bronchoscope. The present paper is a new proposal for the reconstruction module, able to segment thinner bronchi and obtain a more complete model of the tracheobronchial tree in order to make the haptic-based VB system apt to simulate ultrathin bronchoscopies.

The paper is structured as follows. Section 2 describes the preprocessing step to select the lung region and Sections 3, 4 and 5 describe, respectively the three stages of the proposal. Finally Section 6 presents some examples and evaluates and discusses the contribution.

2. Pre-processing

In order to reduce the processing time, the airway reconstruction algorithm must be focused only on the lung region, i.e. all other parts found in the chest CT data must be cleared off. This is done with a mask applied to the original CT data (Fig. 1a), and that is computed as follows. The darkest part of the original CT image is first obtained with a binarization operation using a threshold between the minimum value of the image (i.e. −1000 HU that correspond to the air) and −200 HU. As a result, the lung region as well as those air regions exterior to the body are segmented (Fig. 1b). After an opening operation that eliminates little regions due to noise (Fig. 1c), the lung component is recovered by a binary reconstruction operation from a seed located at a point at the beginning of the trachea (Fig. 1d). Finally, a closing operation with a big structuring element is performed to close those holes corresponding to those structures inside the lung but not selected due to the threshold operation (Fig. 1e). The obtained image is the mask used to recover all the original gray values of the whole lung region of the initial data set (Fig. 1f). The pixels not belonging to the selected lung region are labeled as background and will be not considered in the next stages, shortening the computing time.

3. First stage: raw segmentation

The aim of this stage is to segment the biggest airways, which are easier to detect because of their dimensions, the thickness of their walls and the more homogeneous gray-scale values. The

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