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Biomedical image segmentation using variational and statistical approaches

Segmentation of the pulmonary vascular trees in 3D CT images using variational region-growing

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Abstract

Objectives. – The long-term goal of this project is to quantify the aeration of lung parenchyma in 3D CT scans of patients with acute respiratory distress syndrome. This task requires lung delineation, as well as elimination of airways and vessels. The objective of this article was to present and evaluate the method used to segment out the vascular trees.
Materials and methods. – Vascular trees are segmented by variational region growing. This process is performed within a lung mask, where the airways and bronchial walls were previously eliminated by adaptive multi-scale morphological operations. The region growth starts from seeds defined as the most salient points on a "vesselness" map. The "vesselness" function based on the eigenvalues of the Hessian matrix is also used in the region descriptor that controls variational region growing. The formulation of this descriptor, as well as the method used to eliminate the bronchial walls, are the original contributions of this work. The method was evaluated using the full set of 20 chest scans from the VESSEL12 challenge framework.
Results. – Overall specificity of 0.938 and sensitivity of 0.772 were achieved. The method successfully differentiated vessels from bronchial walls (specificity, 0.848) but failed to detect the smallest vessels (sensitivity, 0.418).
Conclusion. – To the best of our knowledge, similar formulations of variational region growing have never been used to segment pulmonary vascular trees. The method seems to be suitable for the intended application, although its validation on actual images with acute respiratory distress syndrome remains to be done.

1. Introduction

Pulmonary vessel analysis from computed tomography (CT) images is an important step in the diagnosis, treatment planning, and follow-up of lung diseases [1]. Since the pulmonary vessel trees are very complex and have a huge number of branches, computerized methods may be helpful to reduce the reader's effort. For example, delineation of vascular trees may simplify the detection of pulmonary emboli on these images by reducing the search space and thus the number of false alerts outside the vascular structures [2]. Differentiation of vasculature from focal opacities is very useful for the detection of lung cancer and other localized pathologies. Quantitative assessment of the vascular tree can also provide important information for the functional understanding of pulmonary anatomy and objective measures of lung diseases [3,4]. For instance, quantitative assessment of artery diameters may determine over distension of a pulmonary artery, an index of pulmonary hypertension [5]. The vascular trees can also serve as a roadmap for the tracking of lung tissues across lung volume changes or across time as the lung is serially monitored [6].

Our interest in the extraction of pulmonary vascular structures is related to a medical research project studying the effects of mechanical ventilation on lung aeration (assessed with CT) in patients with acute respiratory distress syndrome (ARDS). ARDS is defined as intense pulmonary inflammation and hyper-permeability caused by different parenchyma aggressions that

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can be related to a set of clinical, radiological, and physiological manifestations [7]. The management of patients with ARDS in intensive care units includes the use of mechanical ventilation. However, mortality was consistently estimated around 40% in adults across the last decade [8,9], although a study published in 2008 [10] suggested a slight decrease (1.1% per year). It is estimated that 25% of these deaths might be avoided by better adapting the ventilation parameter settings for these patients. In order to assist the clinicians in setting up ventilation parameters, lung aeration has to be quantified and monitored. In this context, we seek to develop a method to automatically quantify lung aeration in ARDS CT images. This quantification requires a preliminary segmentation of the lung envelope and the elimination of both the airway and blood-vessel trees, in order to only quantify the air contained inside the lung parenchyma. This article focuses on presenting and evaluating the method devised to segment out the pulmonary-vessel tree.

There is a rich literature on 3D vessel enhancement and segmentation methods. To the best of our knowledge, the currently most general and extensive vascular segmentation review can be found in [11], with a highly detailed categorization of the existing work. Most of these techniques focus solely on single-branch segmentation based on the extraction of the centerline of the vessel of interest, which is very useful for display, segmentation, and quantification purposes. Another important category deals with segmentation of simple vascular trees (in terms of the number of ramifications) such as carotid [12] and coronary [13] trees. However, most of these techniques cannot be applied to the pulmonary trees due to their tiny size, complex patterns, and the huge number of ramifications, *e.g.*, a method using a sophisticated geometrical model devised to identify bifurcations and branch terminations [14], can hardly process a whole chest CT in a reasonable time. For these reasons and despite a relatively good contrast with respect to the background, vascular segmentation in the lungs is challenging.

Pulmonary vessel segmentation from CT images has been studied with a focus on different applications. Proposed approaches vary from thresholding operations to front propagation techniques. We refer the readers to [1] and [15] for extensive reviews of pulmonary vessel segmentation methods. Many of the algorithms therein cited are based on the enhancement or detection of tubular structures by computing features from the eigenvalues of the Hessian matrix [3,6,16–19]. This helps better differentiate between vessel and non-vessel regions in the segmentation process.

The method presented in this article also performs a vessel enhancement, prior to the actual vessel tree segmentation. These tasks are carried out in a volume of interest, which is automatically delineated by segmenting the lung envelope and eliminating the airways. The most salient points after the vessel-enhancement process are used as seeds in the final segmentation by variational region growing (VRG). VRG formalism describes region growing as an optimization process that aims to minimize an objective function called energy [20]. While the conventional region growing is based on homogeneity criteria calculated within the region, VRG can include region shape information via an appropriate energy choice.

Section 2 describes the segmentation method in three subsections: the first one summarizes the theoretical background of the main components implemented in this method, the second one explains our contributions devised for the target application, and the third one outlines the data and criteria used to evaluate the method. The results are presented in Section 3, and then a discussion and conclusions are given in Section 4.

2. Methods and materials

Our image-processing pipeline consists of three main steps: delineation of the volume of interest (VOI) where the pulmonary vessel tree will be sought, vessel enhancement, and actual vessel tree segmentation. Fig. 1 represents the overall workflow. The VOI generation involves lung segmentation and bronchi elimination. The most salient points after the vessel-enhancement process carried out within the VOI are used as seeds in the final segmentation by VRG. The lungs and bronchi are segmented using state-of-the art methods that will not be detailed in this article. Lung segmentation is based on thresholding and morphological operations [21], whereas the airway tree is segmented by region growing with leakage detection, introduced by [22], which iteratively increases a threshold value until the number of voxels aggregated in one iteration becomes excessive. We rejected a more complex bronchi-segmentation approach requiring an initial segmentation of the arterial tree. Although this approach is powerful, it is limited to the images acquired after injection of an arterial contrast-agent. Hereafter, we focus on the main contribution, *viz.* an application-adapted implementation of VRG, and then we briefly explain why and how the bronchial wall is removed.

2.1. Background

This section summarizes the theoretical background of the main components implemented in the method. The first subsection describes the general formulation of the VRG approach introduced in [23]. The second subsection outlines how the Hessian matrix eigenvalues are used to enhance thread-like structures such as vessels, by means of so-called “vesselness” (or “tubularness”) criteria.

2.1.1. VRG formulation

Let $\Omega \in \mathbb{R}^D$ denote the image domain ($D = 3$ for a three-dimensional image), $\Omega_{\text{in}} \in \Omega$ being the currently segmented region and $\Omega_{\text{out}} = \Omega \backslash \Omega_{\text{out}}$ its complement. The region Ω_{in} iteratively evolves toward a minimum of an energy function denoted J. To formulate this energy, the Ω_{in} region is represented by a discrete binary function ϕ such that for a voxel $\mathbf{x} \in \Omega$:

$$\phi(\mathbf{x}) = \begin{cases} 1, & \text{if} \quad \mathbf{x} \in \Omega_{\text{in}} \\ 0, & \text{if} \quad \mathbf{x} \in \Omega_{\text{out}} \end{cases} \tag{1}$$