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Region-based geometric modelling of human airways and arterial vessels

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ABSTRACT

Anatomically precise geometric models of human airways and arterial vessels play a critical role in the analysis of air and blood flows in human bodies. The established geometric modelling methods become invalid when the model consists of bronchioles or small vessels. This paper presents a new method for reconstructing the entire airway tree and carotid vessels from point clouds obtained from CT or MR images. A novel layer-by-layer searching algorithm has been developed to recognize branches of the airway tree and arterial vessels from the point clouds. Instead of applying uniform accuracy to all branches regardless of the number of available points, the surface patches on each branch are constructed adaptively based on the number of available elemental points, which leads to the elimination of distortions occurring at small bronchi and vessels.

1. Introduction

Over the last decade, flow parameters in human respiratory and vascular systems have become increasingly important in assisting the diagnosis and management of diseases like asthma and stroke [1,2]. An anatomically precise geometric model of airways or vessels is critically important in flow simulation for the calculation of relevant parameters [3–5]. An inaccurate model may lead to incorrect conclusions, which increases the risk of misleading medical practitioners.

Geometric modelling is an important step in the reconstruction of geometric models from medical images. Much research on the reconstruction of the geometry of human organs has been performed based on data obtained from CT or MR images [6–8], and some commercial software programs are available in the global market for research and clinical applications [9,10]. However, by using the published algorithms or the commercial packages currently available in the market, many flaws emerge in the generated geometries, which impair the use of the models directly in downstream studies. Extensive work must be done to convert the geometries into workable numerical models. This hinders research on air and blood flows for which large amounts of testing are needed to be run with different models.

This paper presents a new region-based algorithm to reconstruct geometric models of human airways and carotid vessels from point clouds obtained from CT and MR images. The generations of the airway tree and the branches of the vessels are firstly recognized from the entire point clouds through use of a new searching algorithm. The points on the same branch are grouped together. Different numbers of points or tolerances are applied in the approximation of surface patches on different branches. Meanwhile, the bronchi in the same region or on the same generation may have similar diameters although their physical locations in the lung are different, and the same accuracy may be used in the approximation process. With this strategy, the number of elemental points used in the construction of different branches is adaptive to the locations of the branches, distortions occurring at small bronchi and vessels are eliminated, and the overall quality of the surface patches is improved.

2. Geometric characteristics of airway and blood vessels

2.1. Geometric characteristics of airway and blood vessels

Human airways and blood vessels can be classified as related human organs in terms of their geometric profiles: both have similar tube-like shapes with air or blood flowing inside. Anatomically the human airway is a tree-like structure which consists of tubular geometries (trachea and bronchi) with large differences in diameters [11]. The diameter of the trachea (the first generation of the tree) of a male adult is approximately 21.6 mm; while that of the bronchus at the 4th generation is approximately 3.8 mm, which is approximately 1/6 of the dimension of the trachea at the first generation. The diameter of a bronchus at higher generations is even smaller. This special characteristic affects the accuracy of models generated with the methods commonly used in Reverse Engineering (RE).

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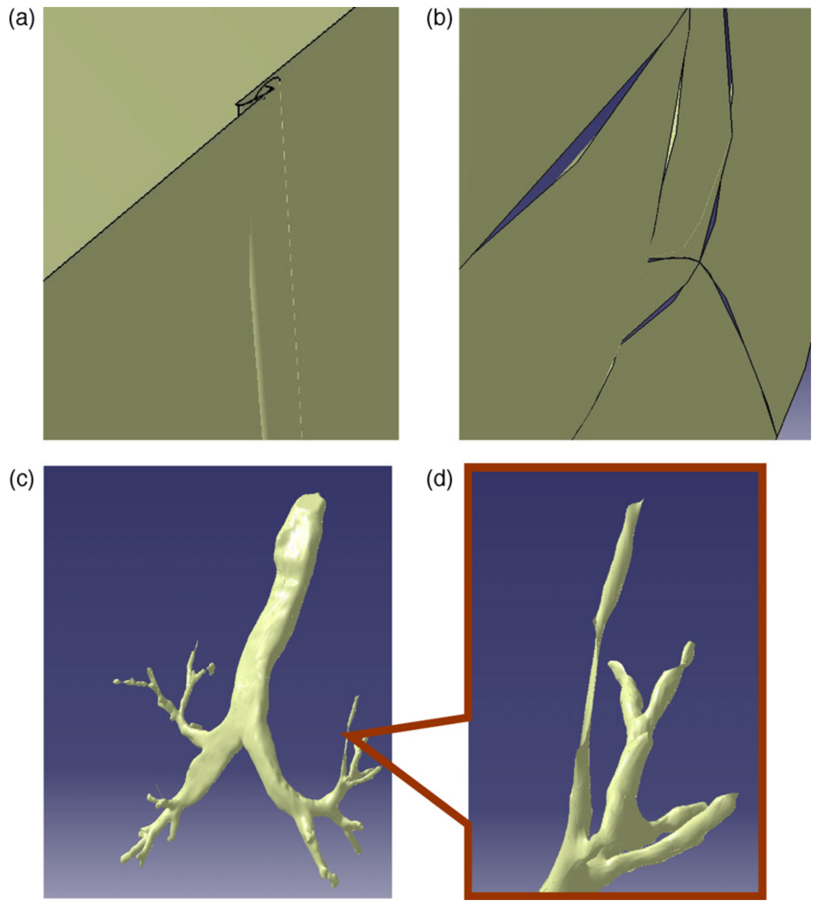

Fig. 1. Geometric model of airways generated by a commercial package. (a) Overlap on surfaces. (b) Gaps between surface patches. (c) Solid model of airways. (d) Enlarged view of bronchus.

2.2. Various flaws in the model

The number of elemental points used in the approximation process is a key factor controlling the number of surface patches used in describing a model. The general procedure for reconstructing such a model in RE is to initially set up the tolerance for the first approximation. The model is then approximated by applying this overall tolerance to the entire model.

Owing to the special topologies of human airways and vessels, this RE procedure cannot be applied in the development of geometric models of these organs. Various flaws including overlap and gap (Fig. 1) emerge in models generated by using the commercially available packages. Severe errors, as shown in Fig. 1, occur at locations where the dimensions of the structure are small. In the enlarged view (Fig. 1(d)) it can be clearly seen that the bronchus which is tubular becomes a flat surface patch. Similar errors occur in the reconstruction of arterial vessels. These types of error occur in many cases and much work is required before the model is preprocessed for the generation of meshes.

2.3. Analysis

One possible cause of the errors described is the redundant or insufficient number of surface patches used in the approximation process for the small structures.

In the point clouds obtained from medical images, fewer points can be obtained at the locations of small structures due to the noise and limited resolution of the images. If a uniform number of points is used in the approximation process regardless of the dimension of the patch, errors will occur at locations where less points are available. On the other hand, if the size of a surface patch is reduced to satisfy the requirements of small bronchi, a large number of small surface patches will be generated redundantly in the trachea or larger bronchi in the airway tree, which is unhelpful in clinical practice.

To solve this problem, an "adaptive tolerance" modelling strategy was developed. A larger tolerance is used in approximating the main branches of the airway, which are the first or second generations of the airways tree. A smaller tolerance is applied at the fifth or sixth generations of the airway. With this strategy, the numbers of points used to construct the surface patches at different locations of the airway tree are different. Although the tolerance is small at the smaller bronchi, the overall number of surface patches does not increase significantly and correct geometries can be generated.

3. Surface reconstruction

The method consists of two phases. A new searching algorithm is developed in the first phase and the method developed by Eck and Hoppe [12] is used in the second.

3.1. Recognition of branches

With current image processing algorithms, it is not difficult to segment medical images and output the results as point clouds in STL (Stereolithography) format. The three-dimensional (3D) coordinates of each point in 3D Cartesian space are obtainable from