Proceedings of the 10th WSEAS International Conference on COMMUNICATIONS, Vouliagmeni, Athens, Greece, July 10-12, 2006 (pp50-55)

BronWall: a software system for volumetric quantification of the bronchial wall remodeling in MDCT

A. SARAGAGLIA, C. FETITA, and F. PRETEUX
ARTEMIS Department, GET/INT
9, Rue Charles Fourier, 91011, Evry-France

Abstract: - This paper develops an original volumetric quantification approach of the bronchial wall remodeling, based on MDCT acquisitions prior/post-medication delivery. The methodology is implemented as a software system -BronWall- integrating 3D segmentation, interaction, navigation, representation and 2D/3D quantification facilities. Such a system provides higher robustness with respect to the existing quantification approaches and MDCT acquisition protocol variability. BronWall may thus become a clinical tool for estimating the impact of therapeutic protocols designed to reverse the airway remodeling induced by chronic obstructive pulmonary diseases.

Key-Words: Volumetric quantification, Software system, 3D segmentation, bronchial reactivity, wall remodeling, 3D image processing.

1 Introduction

This paper presents a quantification software tool dedicated to the automated analysis of bronchial reactivity and wall remodeling from multi-detector computed tomography (MDCT) successive examinations conditional to a treatment. Airway remodeling may be assessed non-invasively by measuring bronchial thickening in multi-detector computed tomography (MDCT) images [1].

Different image analysis methods have been developed to perform measurements of airway dimensions in CT scans. Methods based on manual contouring of the internal and external perimeters [2,3] using high-resolution CT involved severe drawbacks: inter- and intra-observer variability, absence of tilt angle estimation of the bronchus, quantification errors due to partial volume effects with 3-mm slice thickness and bronchial wall thickness variability from one slice to another. The full width at half maximum (FWHM) approach [4] or ameliorations based on this technique [5,6] made it possible to overcome some of the mentioned drawbacks. These edge-based detection methods are less user-dependent and faster than manual estimation. Conversely, FWHM can yield inaccurate measurements for small airways, or for those having very thin walls (10% to 15% of inner diameter [7]). More recent approaches were developed to automatically detect circular or ellipsoidal shape patterns [8]. These methods are fast and seem to be efficient on phantom studies and excised animal lungs [9] for bronchus section shapes appearing as circular or elliptical. However, such techniques are not highly accurate for irregular wall bronchi and may lead to large errors when quantifying shape variations due to wall remodeling. A recent 3D extension of the shape-based techniques is presented in [10]. It relies on the assumption of cylindrical shape of the bronchi, which is seldom confirmed in clinical practice. Measuring the section area of airway lumen and airway wall for bronchi which are not perpendicular to the scanning plane may lead to significant errors. More recent 2D/3D methods [11] exploit the 3D segmentation of the bronchial lumen and medial axis computation of the airways which allows the quantification of the airway cross-section in a plane perpendicular to this axis. While proved to be accurate for airway cross-section area estimation in clinical studies, the major inconvenient of such techniques is that measurements are limited to bronchi regions far from subdivision points. The investigation zone is thus restricted to the medial part of a bronchus segment. In addition, a cross-section area estimation cannot discriminate between bronchus wall variations due to remodeling and to the inspiratory lung volume during the CT acquisition.

In order to overcome the previous limitations, this paper develops a 3D quantification system of the airway remodeling in MDCT, relying on a fully 3D segmentation of the inner/outer bronchus wall using 3D deformable mesh models. Section 2 addresses the different functionalities developed in the software. Section 2.1 specifies the data acquisition protocol. Data processing providing interactive analysis of targeted bronchi involves successively: (1) 3D reconstruction of the bronchial tree (Section 2.2), (2) medial axis computation (Section 2.3), (3) user-interaction (Section 2.4), (4) bronchus wall segmentation (Section 2.5) and (5) bronchus quantification (Section 2.6). The approach validation using a phantom model is presented in Section 3.

2. Quantification of bronchial parameters: Methods and functionalities

Quantifying the same bronchial segments for a comparative analysis before/after treatment imposes: (1) a reproducible MDCT acquisition protocol, (2) automatic extraction of the airways morphology from the MDCT data by means of 3D reconstruction, (3) easy interaction and definition of measurement point locations by means of Medial-Axis (MA)-based description, (4) accurate and fast 3D segmentation of the bronchial wall and (5) comparative statistics before/after medication.

The developed software, BronWall, implements several functionalities addressing the previous requirements, within a user-friendly visual environment (Fig. 1). The following sections provide a detailed description of each module involved in the platform.

2.1 MDCT acquisition protocol

In order to ensure similar measurement conditions before and after treatment, a specific MDCT acquisition protocol was requested. Spiral acquisitions were performed at low dose radiation with 0.6 mm collimation and 0.3 mm reconstruction interval of axial images (16-row General Electric LightSpeed scanner).

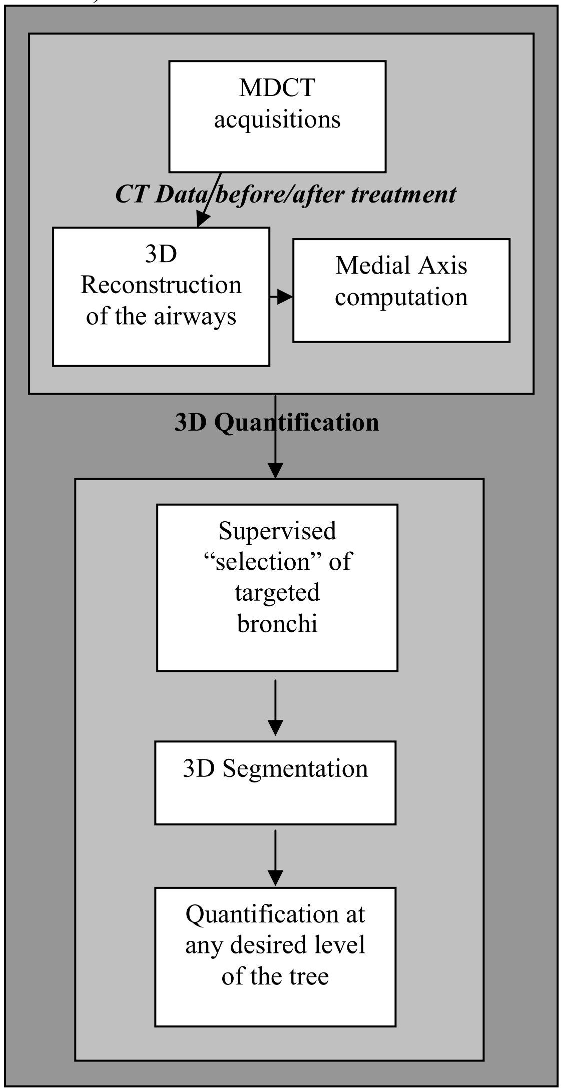

Fig.1. Synopsis of the BronWall software system.

The field of view was set to 18-20 cm according to the patient morphology, focusing the right lung, thus providing *quasi*-isotropic data volumes free from cardiac motion artifacts. All acquisitions were made after interruption of the slow expiration phase following a deep inspiration, at 65% of total lung capacity, using a spirometric gating system (V2000; Sensormedic, Yorba Linda, USA).

2.2 3D-reconstruction of the bronchial tree

Airway segmentation from CT images is a challenging problem due to the inhomogeneity of the bronchial lumen and bronchial wall gray-levels along different subdivision orders.

The system implements a 3D reconstruction approach which involves energy-based modeling and robust morphological operators [12]. The airway 3D reconstruction approach overcomes the main limitations encountered by the existing 3D techniques (such as reconstruction depth and robustness with respect to semi-obstructive pathologies) and provides a fully-automated segmentation of the airway tree lumen down to the sub-sub-segmental subdivision order. The 3D reconstructed bronchial tree is displayed together with the native CT images in axial, coronal and sagittal views (Fig. 2).

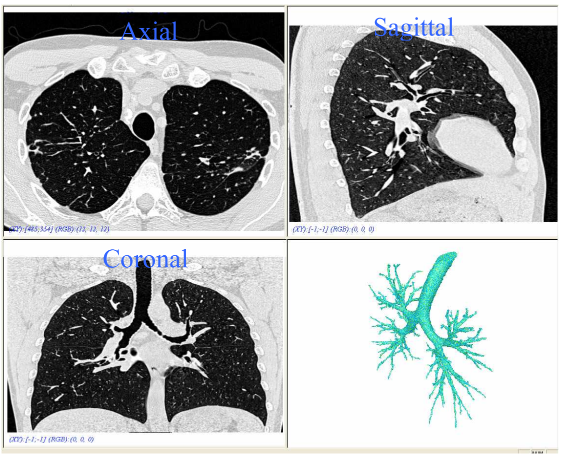

Fig.2: 3D segmentation and reconstruction of the bronchial tree from MDCT images, presented in a three-slice view by the software.

2.3 Medial Axis computation

Providing navigation and quantification capabilities with the 3D reconstruction of airways requires a compact description of the geometry and topology of the segmented bronchial tree. Such a description is achieved by computing the Medial Axis [13].
The bronchial tree morphology can be described as a (quasi)-tubular structure presenting a recursive subdivision topology. Extracting the MA of such a structure raises several issues: besides the estimation of each segment medial axis, the procedure should ensure an accurate detection of the subdivision points and the preservation of the subdivision hierarchy. Because of the topology complexity, the caliber variability with the bronchial order and the bronchial wall irregularities, these problems appear particularly challenging. The methods presented in literature for MA extraction refer to three main classes which are Voronoï diagram-based algorithms, iterative thinning and methods relying on distance transforms. This latter type turned out to be the most appropriate one in the case of branching objects represented by volumetric data. However, most of the existing methods applied to the bronchial tree show a common drawback related to the inaccurate detection of the subdivision locations, which may lead to a wrong subdivision hierarchy of the medial axis.
The method developed in [13] overcomes these limitations by combining a 3D distance map with a geodesic front propagation initialized at the top of trachea. A space partionning-based criterion ensures the accuracy of the segment subdivision detection and the correct geometry/hierarchy preservation of the MA, irrespective to the degree of the subdivision (bifurcation, trifurcation, etc.). Fig. 3a illustrates the MA of a tree. BronWall implements this approach [13] in order to provide interaction and selection functionalities.

2.4 3D interaction and bronchus selection

The MA-based description supplies the navigation and interaction tools required for selecting the fraction of the bronchial tree under investigation. An experienced radiologist defines the measurement zone by selecting points along the Medial Axis (Fig.3a) at different desired levels. The data structure of the MA is implemented as a binary tree to automatically identify the MA region delimited by the selected points. Such region should include the same topological neighborhood. It is thus defined either as the MA region enclosed by the set of selected points if they include a common parent node, or as the MA region comprised between the set of the selected points and their common parent node on the MA (Fig.3b). During point selection process on the MA, BronWall displays the updated MA region enclosed (Fig. 3c). Once the selection process finished, an automatic clipping of the reconstructed bronchial tree lumen along planes orthogonal to the MA at the selected points provides the sample measurement volume data used for quantification (Fig.3d).

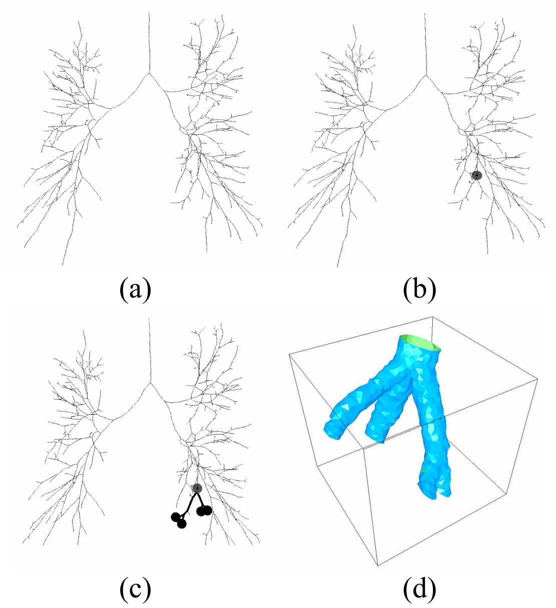

Fig.3: (a) 3D interaction on the MA. (b) Parent (top sphere) and (c) nodes (bottom spheres) selections, and (d) part of the bronchial tree clipped perpendicularly at the level of the selected nodes.

2.5 Bronchial wall extraction

The bronchial wall is detected using a model-based segmentation technique, patient specific, which is presented in the following.
A mesh model of the inner bronchial wall is build-up from the clipped lumen (Fig. 3d) by using a restricted Delaunay triangulation approach with a specific adaptative distance criterion [14,15]. Such technique provides a regular mesh, robust in term of topology and geometry preservation (Fig. 4a). The inner wall mesh model is then deformed in the direction of the external surface normal at each vertex until it matches the external surface of the bronchial wall. The deformation is controlled by an energy functional relying on antagonist forces, externals vs. internal. The external force tends to dilate the contour while the internal force mainly constrains the model shape regularity.
The external force is defined as a combination of two components and represents the influence of the image on the embedded surface. The first component guides the surface toward the image high intensity values while the second one drives the surface to regions of strong gradient. In this way, the model is attracted to strong contours of the wall, which allows to match wall irregularities, while preserving the surface smoothness at the level of low-contrast zones (such as bronchus-artery or bronchus-vein contact).

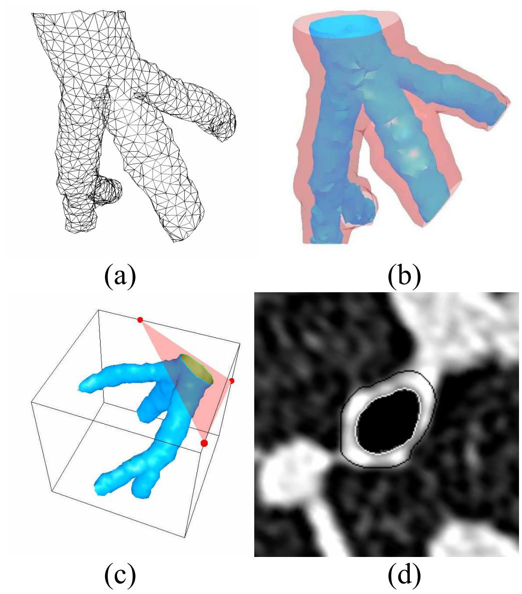

Fig.4: (a) Lumen mesh. (b) 3D segmentation result (inner/outer wall surfaces). (c) 3D selection of the cutting plane location and (d) Cross-section image reconstruction orthogonally to the MA at the selected cutting plane location.

In order to equilibrate the external forces, the internal force will be defined as a composition between an elastic force, which linearly penalizes local wall thickness variations, and a regularization force, which locally smoothes the shape. The shape of the external contour of the bronchus at the level of the vessel-bronchus contact zone is mainly constrained by the elastic component.
The outer contour evolves until internal forces equilibrate external forces. In order to preserve the model mesh resolution and a high computational efficiency, the edge length is constrained according to initial mesh resolution. Mesh subdivision is thus performed any time when required and self-intersections are checked during deformation. Fig. 4b illustrates the bronchial inner/outer wall segmentation mesh result.

2.6 Bronchial wall quantification

Using BronWall, bronchial wall quantification can be performed both in a cross-sectional plane orthogonal to the MA, at a selected location, and in a volume data delimited by a set of cutting planes defined by the user. The latter facility is the main improvement of the BronWall with respect to the 2D/3D techniques [11], by allowing the investigation of airway remodeling at the level of bronchus subdivision zones, and irrespective to the lung inspiratory volume (inducing elastic deformation of the bronchus wall) during the CT data acquisition.

3. Experimental result

The 3D bronchial quantification methods and software described in this paper were validated with respect to a 3D image model synthesizing a cylindrical bronchus subdivision geometry of different calibers and lumen/wall textures.
The phantom consists of two cylinders that simulate the bronchus inner/outer wall. Parameters such as bronchus size, bronchial wall thickness, number of subdivision may be varied in order to test the efficiency of the segmentation algorithm. The model can be deformed, by including a trigonometric function in the implicit function of the cylinder, in order to evaluate the robustness of the segmentation with respect to irregular borders of the wall. The textures of the bronchus lumen, wall, vessel and lung parenchyma were simulated as normal distributions with a specific mean value and a standard deviation corresponding to each type of tissue seen on MDCT images.
The developed algorithm was tested by changing several parameters of the previously described model, such as wall thickness, topology (Fig.5a) and bronchus shape (Fig.5b) in order to assess the accuracy of the 3D quantification. In all the tested cases, the bronchus cross-section area was estimated with a relative error less than 5%, which situates BronWall in the same accuracy range as the best 2D/3D airway wall quantification approaches [11]. Note however that, the advantage provided by a volumetric quantification with respect to cross-section area estimation is the independence of both measurement location on the bronchus axis and the inspiration lung volume.
A clinical study concerning the BronWall measurements reproducibility in the same patients, at different inspiratory lung volumes and in the absence of any medication, is currently under implementation. Such a study will make it possible to assess the expected quantification robustness/accuracy of BronWall with respect to previous 2D/3D techniques [11].

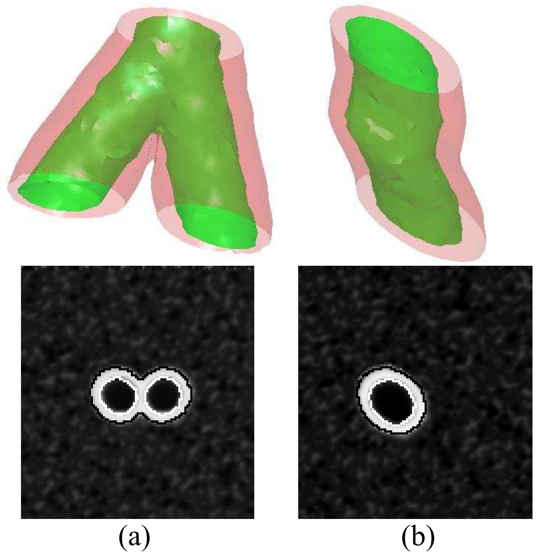

Fig.5: 3D synthetic model quantification samples. (a) Subdivided bronchus (top) and resulting segmentation at the level of the branching subdivision (bottom). (b) Deformed shape simulation (top) and the resulting segmentation (bottom).

4. Conclusion

This paper developed an original software for new therapies assessment based on MDCT acquisitions. Such a system is able to produce, manipulate and analyze 3D anatomical contents extracted from clinical data in order to quantitatively assess the bronchial reactivity and wall remodeling in successive examinations, before and after a therapeutic protocol. The system passed the first-step validation on 3D image models simulating a cylindrical bronchus subdivision. Future work will address the manipulation of the software in the framework of clinical studies in order to demonstrate the feasibility of therapy efficiency in case of diseases such as chronic obstructive pulmonary diseases and asthma.

References:

[1] Nakano Y, Muller NL, King GG, et al. Quantitative assessment of airway remodeling using high-resolution CT. Chest 2002;122:271S-275S.

[2] Matsuoka S, Kurihara Y, Nakajima Y, Niimi H, Ashida H, Kaneoya K, Serial Change in Airway Lumen and Wall Thickness at Thin-Section CT in Asymptomatic Subjects, Radiology, February 1, 2005; 234(2): 595 - 603.

[3] Niimi A, Matsumoto H, Amitani R, et al. Effect of short-term treatment with inhaled corticosteroid on airway wall thickening in asthma. Am J Med 2004;116:725-31.

[4] Baxter BS, Sorenson JA, Factors affecting the measurement of size and CT number in computed tomography, Invest. Radiol., pp. 337-341, 1981.

[5] Saba OI, Hoffman EA, Reinhardt JM. Maximizing quantitative accuracy of lung airway lumen and wall measures obtained from X-ray CT imaging. J Appl Physiol 2003;95:1063-75.

[6] Reinhardt JM, D'Souza ND, Hoffman EA. Accurate measurement of intrathoracic airways. IEEE Trans Med Imaging 1999;16:820-7.

[7] Hoffman EA, Reinhardt JM, Sonka M, et al., Characterization of the intersistal lung diseases via density based and texture-based analysis of computed tomography images of lung structure and function, A Rad. 2003; 10:1104-1118.

[8] Chabat F, Hu XP, Hansell DM, Yang GZ, "ERS transform for the automated detection of bronchial abnormalities on CT of the lungs", IEEE transactions on medical imaging, Vol. 20, NO, September 2001.

[9] King GG, Muller Nl, Whittal KP, An analysis algorithm for measuring airway lumen and wall areas from high-resolution computed tomographic data. Am J Respir Crit Care Med 2000;161:574-80.

[10] Wiemker R, Blaffert T, Bülow T, Renisch S, Lorenz C, Automated assessment of bronchial lumen, wall thickness and bronchial tree using high-resolution CT, International Congress Series 1268, 967-972, 2004.

[11] Saragaglia A, Fetita C, Prêteux F, Brillet PY, Grenier P, Accurate 3D quantification of bronchial parameters in MDCT, Proc. SPIE Conf. on Math. Methods in Pattern and Image Analysis, 5916, pp.323-334, 2005.

[12] Fetita CI, Preteux F, Beigelman-Aubry C, et al. Pulmonary airways: 3-D reconstruction from multislice CT and clinical investigation. IEEE Trans Med Imaging 2004;23:1353-64.

[13] Perchet D, Fetita CI, Vial L, et al. Virtual investigation of pulmonary airways in volumetric computed tomography. Comp Anim Virtual world 2004 ;15 :361-76.

[14] Boissonnat J-D. and Oudot S., Provably Good Surface Sampling and Approximation, Eurographics Symposium on Geometry Processing, 2003.

[15] Chew LP, Guaranteed-Quality Mesh generation for Curved Surfaces, Proc. 9th Annu. ACM Sympos. Comput. Geom., pp. 274--280, 1993.