A SURVEY FOR CT-BASED AIRWAY DIGITAL RECONSTRUCTION AND APPLICATIONS

by

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Lung is the most important gas exchange organ of human, and the smooth airway is the basis of lung function. The condition of the trachea is associated with a variety of diseases. In this paper several methods of tracheal simulation based on CT-based data since 2003 are reviewed. Reasonable algorithms and image processing methods are important development directions for airway scanning reconstruction. The development of airway reconstruction needs to be closely integrated with mathematical modelling to improve the accuracy and precision of reconstruction.

Key words: *airway, reconstruction, CT data, simulation, segmentation, deep learning*

Introduction

The airway is commonly divided into the upper and lower airways, with the lower boundary typically marked by the inferior margin of the cricoid cartilage. The upper airway consists of the nose, pharynx, and larynx, serving as the gateway for air entering the lungs. The nasal cavity is divided into the nasal vestibule and the intrinsic nasal cavity. The pharynx, descending from top to bottom, communicates with the nasal cavity, oral cavity, and laryngeal cavity, referred to as the nasopharynx, oropharynx, and laryngopharynx, respectively. The lateral walls of the larynx each have two pairs of folds made of laryngeal mucosa, with the upper pair called vestibular folds and the lower pair known as vocal cords. The space between the vocal cords is called the glottis, allowing air to pass through as a result of the contraction of the diaphragm and other accessory respiratory muscles. The primary functions of the upper airway include not only conducting air-flow but also warming, humidifying, and purifying air, as well as performing functions such as swallowing, smelling, and vocalization [1]. The lower airway is mainly composed of the trachea, bronchi, bronchial tree, and alveoli. Based on different functions, it is further divided into the conducting airways (trachea, bronchial tree) and the respiratory zone. The human trachea bifurcates into two main bronchi at the carina and terminates at each lung hilum. The trachea is constructed with a cartilaginous framework to prevent collapse during the negative pressure generated during the inhalation cycle. The first tracheal cartilage is located below the cricoid cartilage and forms the only continuous cartilaginous ring. The blood supply to the cervical segment of the trachea mainly comes from the inferior thyroid artery, while the thoracic segment is primarily supplied by intercostal arteries [2].

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Pneumonia is the most common pulmonary disease and often results in radiographic changes in the airways, as illustrated in fig. 1. Data from the 2019 Global Burden of Disease (GBD) study shows that lower respiratory tract infections (LRTI), including pneumonia and bronchiolitis, affected 489 million people worldwide [3]. The most common symptoms of pneumonia include cough, difficulty breathing, chest pain, sputum production, and fatigue. Most bacterial pneumonias result from microorganisms migrating from the nasopharynx down to the lower respiratory tract, causing infection. The body's defence against pneumonia involves the interplay between anatomical structures of the airways, normal flora in the upper respiratory tract, resident and recruited immune cells in the lower respiratory tract, and various immune mechanisms [4-6].

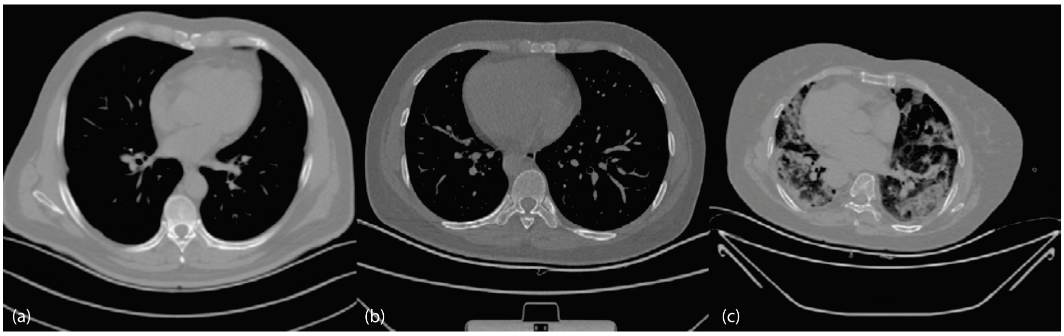

Figure 1. (a) Chest CT from a healthy individual, (b) chest CT from a mild COVID-19 patient, and (c) chest CT from a severe COVID-19 patient

The role of CT in pulmonary imaging

Computed tomography (CT) plays a crucial role in imaging the lungs and airways, providing medical imaging professionals and clinicians with rich and detailed anatomical information. In recent years, with continuous technological advancements, the use of CT in early detection, quantitative analysis, and personalized treatment plans for pulmonary diseases has become increasingly widespread. High resolution CT (HRCT) can clearly display tiny structures such as alveoli, bronchi, and blood vessels, offering more detailed anatomical information crucial for accurate localization and assessment of pulmonary lesions [7]. Modern CT technology has made significant progress in the detection and evaluation of pulmonary tumors, including AI-based automatic detection systems that enable doctors to more accurately understand the size, morphology, and location of tumors [8]. The application of low dose CT technology in lung cancer screening is gaining attention, providing sufficient image quality while reducing radiation exposure, offering new possibilities for early lung cancer detection (Reduced lung-cancer mortality with low dose computed tomographic screening). Functional techniques such as CT angiography and perfusion imaging, such as dynamic CT pulmonary perfusion imaging (CTP) and dynamic contrast-enhanced CT, can provide information about lung blood flow and perfusion, contributing to a more comprehensive assessment of pulmonary diseases [9]. Techniques like CT bronchial angiography (CTBA) and multi-slice spiral CT provide clear imaging of airway anatomy, aiding in the detection of bronchial narrowing, obstruction, and other abnormalities, offering patients more comprehensive diagnostic information [10]. In summary, the continuous innovation and development of modern CT technology in pulmonary and airway imaging provide clinicians with comprehensive and precise imaging information, offering robust support for the diagnosis, treatment, and follow-up of pulmonary diseases.

Relevant research on airway reconstruction

As shown in fig. 2, articles related to ischemic stroke have been on the rise over the past 15 years. With the rapid development and widespread application of artificial intelligence in the medical field, papers related to airway reconstruction have been steadily increasing year by year. In comparison, research utilizing CT as modelling data represents only a small fraction of papers on airway simulation.

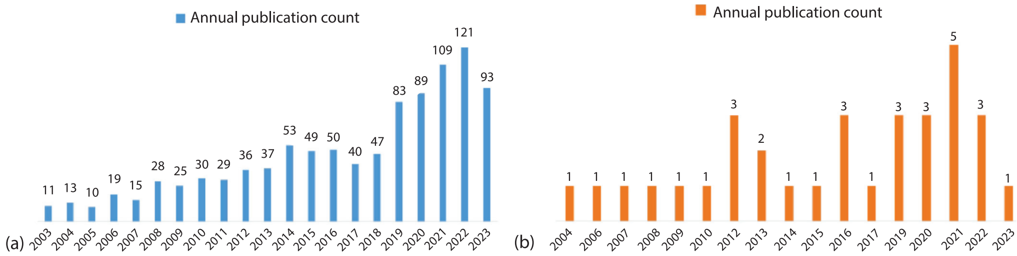

Figure 2. (a) Research related to airway simulation starting from 2003 and (b) research related to airway simulation starting from 2003 that utilizes CT as data

Airway simulation methods

Current methods

With the development of computer technology, especially computer vision, artificial intelligence (AI) is playing an increasingly important role in trachea simulation. As time progresses, the segmentation of the trachea has gradually shifted from machine learning methods to deep learning. However, machine learning has not been abandoned, instead, it is often used as post-processing for the results obtained from deep learning. Considering the challenges in data acquisition, the use of CT data for trachea simulation is the most common research direction. The CT, as a simple, practical, and cost-effective imaging modality, is widely favored by clinicians and emergency patients. The CT enhancement or perfusion imaging methods, performed on the basis of routine CT scans, have also been proven to have powerful detection and assessment capabilities. With the widespread adoption of 3-D printing technology, using 3-D printed models for airway simulation is also beneficial for studying the application of interventions and surgical treatments in pulmonary diseases. We can see that there are a large number of trachea simulation methods.

Airway reconstruction based on MRI

The use of pulmonary MRI in clinical settings has traditionally been limited, primarily because MRI is mainly employed to measure the morphology of the lungs. Currently, MRI can also achieve functional imaging of the lungs. Perfusion imaging of the lungs can be used for visualization in various diseases such as lung cancer, COPD, and pulmonary embolism. Diffusion-weighted imaging of the lungs has been able to detect lung cancer and pulmonary metastases while minimizing artifacts from respiratory and cardiac motion [11].

Astley *et al*. [12] from the Department of Oncology and Metabolism, the University of Sheffield, Sheffield, UK, collected 759 hyperpolarized gas MRI scans (23, 265 2-D slices) from 341 subjects, including healthy individuals and patients with various lung diseases. They evaluated the segmentation performance of several 3-D convolutional neural networks (CNN) on ventilated lungs and compared them with traditional segmentation methods, Spatial Fuzzy C-Means (SFCM) and K-means clustering algorithm. The study found that using 3-D nn-UNet for joint training on ^{129}Xe and ^{3}He MRI outperformed other deep learning (DL) methods, with a mean ± SD Dice coefficient of 0.963 ±0.018, average boundary Hausdorff distance of 1.505 ±0.969 mm, Hausdorff 95th percentile of 5.754 ±6.621 mm, and a relative error of 0.075 ±0.039. Additionally, CNN produced more accurate segmentation than the two traditional methods for all evaluation metrics.

Xie *et al*. [13] from the School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu, China, used static and dynamic MRI datasets (including 160 patients and over 20000 MRI slices). For static MRI, a Generalized Region of Interest (GORI) strategy was applied to separate the nasal cavity and other upper respiratory areas into two distinct sub-objects, which were then segmented independently by two 2D U-Nets. The segmentation results were integrated into the entire upper respiratory tract. The GROI strategy was also applicable to other MRI modalities. To minimize false-positive and false-negative rates in the segmentation results, a novel loss function was employed to train the segmentation network. The proposed method in this study can be used for routine upper airway segmentation in static and dynamic MR images, with high accuracy and efficiency.

Airway reconstruction based on tracheoscopy

Tracheoscopy is the insertion of a flexible bronchoscope through the mouth or nose into the lower respiratory tract, reaching the trachea or bronchi, and allowing clear observation of lesions in the trachea and bronchi, with imaging displayed on a screen or directly through an eyepiece. Given the limited field of view of the tracheoscope camera, accurately determining the anatomical position of the tracheoscope is crucial for successful procedures.

Guo *et al*. [14] and colleagues from the Institute of Biomedical Engineering, Karlsruhe Institute of Technology, Karlsruhe, Germany, proposed a cGAN-based Broncho DepGAN for network bronchoscope depth estimation. They developed a method for directly estimating the depth of bronchoscope images. Depth estimation serves as the foundation for 3-D reconstruction of airway structures from 2-D bronchoscope scenes and can be further applied to developing vision-based bronchoscope navigation systems.

Chen *et al*. [15] from the State Key Laboratory of Respiratory Disease, National Clinical Research Center for Respiratory Disease, Guangzhou Institute of Respiratory Health, The First Affiliated Hospital of Guangzhou Medical University, Guangzhou, China, retrospectively collected bronchoscope images from 272 patients at nine anatomical locations of the airways. They used CNN for classification learning and U-Net for segmentation learning to identify 10 bronchial segments. The average accuracy for recognizing the nine anatomical locations of the airways was 91%, with the area under the curve (AUC) consistently above 0.98. However, the study's limitation was that it only utilized bronchoscope images of normal airway anatomy, making the model unable to identify locations with abnormalities (such as tumors).

Conclusion and summary

The airway is the initial site in the lungs through which gas exchange occurs. Therefore, the unobstructed passage of the airway is fundamental for the normal functioning of the lungs. As a result, simulating the airway using data available in routine diagnostics has been a focal point of research.

With the development of digital image processing technology, there has been a significant transformation in airway simulation methods. Deep learning has replaced machine learning as the mainstream approach for airway segmentation and reconstruction. Currently, airway simulation based on CT imaging has made substantial progress.

The CT-based airway simulation techniques can often achieve excellent results on data from different centers, using various devices and imaging protocols, and involving patients with different health conditions. However, these algorithms face challenges in achieving acceptable results when dealing with data from patients with severe lung infections.

As respiratory infections become increasingly prominent, simulating the airways of patients with serious lung infections to infer their airway patency and the impact on lung function represents a promising research direction.

In addition, the high precision reconstruction for closely depends on the reasonable algorithms and image processing methods. In future, the new mathematical model should be introduced to improve the efficiency and accuracy of airway reconstruction.

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