Virtual Bronchoscopy and Other Three-Dimensional Imaging Methods

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Abstract
Flexible bronchoscopy (FB) is the only method that permits real-time direct visualization and dynamic evaluation of the tracheobronchial system. Multidetector computed tomography (MDCT) scanners can generate accurate 2-dimensional (multiplanar reformation) and 3-dimensional (multiplanar volume reconstruction, external volume rendering, VR, and virtual bronchoscopy, VB) images of the airways. Patient breath-holding in suspended inspiration is important but with the new faster scanners volume coverage during quiet breathing can achieve high-quality images. The new imaging techniques offer distinct advantages over FB that include: accurate mapping of airway compression or stenosis, visualization of the airway beyond the area of obstruction, evaluation of smaller airways, and imaging of parenchymal and mediastinal abnormalities. External VR and VB can delineate congenital defects such as pulmonary underdevelopment spectrum, tracheobronchial branching anomalies, tracheo-oesophageal fistula, sequestration spectrum and vascular rings. High-resolution CT is used to evaluate bronchiectasis and air-trapping due to small-airway disease. Newer-generation MDCT scanners can be used to assess dynamic collapse of the airways. Radiation exposure remains a concern in CT; patient- and disease-specific dose reduction should be implemented according to the ALARA (‘as low as reasonably achievable’) principle. Alternative techniques such as magnetic resonance imaging should be considered.

Flexible bronchoscopy (FB) is considered the gold standard for the detection and diagnosis of tracheobronchial disorders in children permitting direct visualization and dynamic evaluation of the airway lumen. Although safe, it is still an invasive procedure that requires patient sedation and cannot be used to evaluate airway morphology beyond high-grade stenosis of the bronchial lumen [1; chapter 2, this vol., pp. 22–29]. In clinical practice, FB is often combined with computed tomography (CT) scanning of the chest for more comprehensive evaluation of the airways and lung parenchyma.

In the last 20 years, a true revolution in CT technology has made possible non-invasive imaging of the airways. Conventional ‘stop-and-shoot’ CT that required long scan times with a single data set per breath-hold evolved into helical (spiral) CT that reduced acquisition time and minimized misregistration due to variation in the depth of respiration as well as respiratory and cardiac motion artefacts. More recently, multidetector (multislice) CT (MDCT) that employs multiple rows of detectors – currently 16- and 64-slice MDCT scanners are widely used, while 128-, 256- and, recently, 320-slice scanners are being actively marketed – along with other technical advancements have made true isotropic imaging of large volumes possible within a few seconds [2, 3]. MDCT provides continuous and complete sets of raw data that are transferred to a picture-archiving and communication system or 3-dimensional workstation for post-processing and analysis. Once the final volumetric data set is obtained, a variety of computer algorithms can be applied to generate accurate 2- or 3-dimensional images by utilizing the information obtained by the scan [2, 4]. The radiological technical terms used in this chapter are explained, in alphabetical order, in the Appendix.

Magnetic resonance imaging (MRI) is an attractive alternative to MDCT because of lack of patient exposure to radiation, fewer adverse reactions to intravenous contrast material (due to the use of non-iodine-based contrast materials), inherently higher soft tissue contrast and ability to perform functional studies. Its main drawbacks are a considerably
longer acquisition time that requires sedation (and in prolonged examinations general anaesthesia) of young children, inferior spatial resolution of lung parenchyma (even with the most current state-of-the-art MRI technology), higher compromise in the presence of metallic devices and a relatively high cost. With technical evolution, MRI may one day replace CT in the evaluation of various congenital and acquired lung disorders but currently it is not commonly used in the evaluation of childhood airway disease [2].

Multidetector Computed Tomography Imaging of the Airways

The axial images obtained with MDCT contain the entire volume data set but have several limitations, including: (a) limited ability to detect subtle airway stenosis; (b) underestimation of the craniocaudal extent of disease; (c) difficulty displaying complex 3-dimensional structures and their relationship to the airway; (d) insufficient representation of airways oriented obliquely (or, even worse, parallel) to the axial plane, and (e) generation of a very large number (MDCT scanners produce hundreds) of images that are very difficult to review. In essence, 3-dimensionally rendered images are creative software solutions to the challenge of depicting 3-dimensional data – organized in a 3-dimensional matrix of volume elements (voxels) – on the 2-dimensional surface of a computer monitor composed of picture elements (pixels). The reformating process uses the CT voxels in ‘off-axis views’ (without changing them in any way), thus displaying the images produced from the original reconstruction process in an orientation other than the one they were originally generated.

Four basic postprocessing techniques of the volumetrically acquired data are used to enhance imaging of airway anatomy: 2-dimensional multiplanar reformation (MPR), 3-dimensional multiplanar volume reconstruction (MPVR), 3-dimensional shaded-surface display (SSD) and 3-dimensional volume rendering (VR) [2, 4, 5].

Multiplanar Reformation
MPRs are 1-voxel-thick 2-dimensional tomographic sections that are as accurate as axial images. By using dedicated algorithms, they can be interpolated along any arbitrary plane (usually coronal, sagittal or parasagittal) or a ‘curved’ tomographic surface (e.g. axis of the trachea, a bronchus or a feeding vessel). Precise cross-sectional and longitudinal images can be constructed along central and segmental bronchi, thus allowing ‘lesion-oriented’ reformations. MPRs have the advantage of high computational speed, thus incorporating information from a large number of axial frames while offering real-time images almost simultaneously with the axial sections. Most importantly, they can detect focal narrowing that may be missed when reading only the axial frames, and they can accurately depict the degree and longitudinal extent of bronchial stenosis. However, the potential decrease in spatial resolution due to partial volume averaging may result in overestimation of the degree of stenosis. This problem can be overcome by the overlapping of thin axial cuts and careful centring of the trace of the airway lumen of interest with concomitant inspection of the axial images is essential for their interpretation.

Multiplanar Volume Reconstruction
MPVR is a 3-dimensional rendering (volume-editing) technique that closely resembles 2-dimensional MPR. It was initially introduced as ‘sliding thin-slab projections’ to improve visualization of blood vessels and airways by ‘stacking’ several contiguous planar images. The method adds ‘depth’ to the anatomical display of airways and blood vessels and allows smoother and quicker visualization of the entire sequence of thin images (fig. 1). The technique allows reformatting under different protocols that enhance specific aspects of the airways or lung parenchyma. For example, the minimum intensity projection takes advantage of the lowest intensity voxels to evaluate airway lumen and areas of uneven attenuation of lung parenchyma (e.g. mild air-trapping), while

Fig. 1. Curved plane minimum intensity projection image showing the trachea and major bronchi of a 4-year-old girl with ring-sling syndrome. There is progressive worsening of tracheal stenosis from the central part of the trachea down to the level of the main carina. The calibres of the main bronchi appear normal.
the maximum intensity projection (highest intensity voxels) allows better visualization of the bronchial wall, improves nodule detection and differentiates between small nodules and vessels. MPVR may be used in selected cases to aid the interpretation of high-resolution CT (HRCT) as it offers an excellent (‘bronchographic’) display of segmental bronchiectasis, or to evaluate small-airway disease.

Shaded-Surface Display
This is an external rendering technique which is based on a predetermined threshold that is chosen to display the organ of interest. Each voxel is classified as either 0 or 100% (0 or 1) of a tissue type. The technique offers striking external 3-dimensional images of the central airways but is susceptible to noise and artefacts due to partial volume averaging (fig. 2).

Volume Rendering
Contrary to surface-rendering techniques that reflect voxel boundaries and not true interfaces, VR is a true volume-rendering technique that offers continuous scaling. Thus, while maximum intensity projection, minimum intensity projection and SSD make use of about only 10% of the acquired CT data, VR incorporates the entire data set into a 3-dimensional image. This technique maintains the original spatial relationships of the volume data, adds depth and enhances detail allowing the reproduction of life-like images. However, despite its sophistication some information is still lost. Therefore, axial images remain indispensable in the evaluation of extraluminal disease. VR can be applied to the airways from both external (‘fly-around’ – virtual bronchography) and internal (‘fly-through’ – virtual endoscopy) perspectives.

External VR
This technique is extremely useful in depicting structures that do not course vertically to the transverse (axial) plane and offers accurate displays of overlapping structures and complex anomalies that extend into multiple planes. It constitutes a ‘clinician-friendly’ imaging modality that is able to detect short-segment airway narrowing, estimate the craniocaudal extent of tracheobronchial stenoses, describe complex tracheobronchial and cardiovascular congenital anomalies, and guide conventional and video-assisted thoracic surgery (fig. 3).
Virtual Bronchoscopy

With the use of dedicated software, intraluminal navigation through the airways by an operator can provide additional information to other established techniques. Due to the non-collapsible air-filled tracheobronchial tree, virtual endoluminal visualization of the airways is much more easily achieved as compared to that of other hollow organs, thus making the demonstration of a variety of tracheobronchial anomalies possible. The main goal of virtual bronchoscopy (VB) is to offer to the clinician a non-invasive diagnostic and follow-up tool, which provides images that closely resemble those of FB (fig. 4–6; online suppl. videos 1 and 2) and is well tolerated by the majority of patients [6, 7]. Although VB images can be obtained from MRI or the digital image of FB itself, MDCT is the most common data source. Current MDCT scanners produce virtual endoscopic images that closely resemble those obtained from conventional bronchoscopy [2, 6–8].

Submillimetre collimation of new MDCT technology can achieve deeper penetration making it possible for VB to accurately depict 6th- to 7th-order airways in adults and 3rd- to 4th-order (segmental/subsegmental) airways in children [8]. VB is of the greatest value in cases where FB is contraindicated or simply not possible [chapter 2, this vol., pp. 22–29]. It is also accurate in the evaluation of significant airway stenosis and, unlike FB, it is able to ‘cross’ such stenosis and assess the integrity of the peripheral airway. In addition, it can be useful in the evaluation of suspected foreign-body aspiration, tracheo-oesophageal fistula and other congenital airway abnormalities (see section on clinical applications of MDCT in paediatric patients) [4, 5]. Similarly to other 3-dimensional reconstruction techniques, VB findings should always be interpreted in conjunction with the axial sections as accurate measurement of lesions as well as of the diameter and length of stenoses is possible only on 2-dimensional images. Selection of the threshold level is of great importance for simulation as VB tends to overestimate airway stenosis and may display severe stenosis as complete occlusion due to partial volume averaging. In an early study using 4-row MDCT, Sorantin et al. [9] showed that, when using FB as gold standard, simultaneous display of axial cuts, MPR and VB on the workstation monitor raised sensitivity, precision and accuracy of the radiological findings in a group of 15 children with various causes of airway stenosis, while 4 additional patients were evaluated for diseases not involving the airways and were used as controls. The advantages and disadvantages of VB vs. FB are summarized in table 1. Adult research has shown that VB can be combined with ultrathin bronchoscopes to enable bronchoscopic biopsy of peripheral lesions by successful previewing and planning of the bronchoscopic routes to the areas of interest [10]; similar use of 3-dimensional technology may prove useful in paediatric cases. The indications of airway stenting for paediatric tracheobronchial obstruction are currently under investigation [chapter 6, this vol., pp. 64–74]. Two- and 3-dimensional CT imaging techniques have been utilized in the management of such cases on an individual basis [11].

Fig. 3. a External VR image of the patient presented in figure 1. H = Head; F = feet; LAO/RAO = left/right anterior oblique; cran/caud = cranial/caudal; R = right; L = left; A = anterior view. b Cardiac MRI of the same patient shows a transverse view immediately above the level of the bifurcation of the trachea. The anomalous left pulmonary artery can be visualized encircling the trachea posteriorly (arrowhead). The oesophagus is displaced to the right (arrow).
Special Considerations

Technical and Patient Characteristics
The parameters used for the CT (e.g. kilovoltage peak, current-time product, pitch (table speed), detector collimation, field of view) determine the quality of images but also the degree of radiation that the patient receives (Appendix). In general, the better the image, the higher the radiation dose. Thus, one should always consider whether the information provided by improved resolution justifies the increase in the radiation dose. In recent years, various institutions that perform MDCT imaging in children have standardized low-dose protocols (adjusted to the child’s weight and the diagnostic question) that best address this conflict [5]. To obtain high-quality 3-dimensional images in children, it is necessary to use fast scan times (≤1 s) and lower collimation (0.625–0.75 mm for a 16-row, and 0.5–0.6 mm for a 64-row detector with a pitch of 1.0–1.5) that increase the radiation dose. In order to improve 3-dimensional imaging, when slice thickness exceeds 1 mm, the volumetric data are reconstructed using slice overlap of approximately 50% (Appendix).

High-resolution scanning is required for imaging short focal stenosis and small-airway disease, and for obtaining CT angiograms, e.g. to delineate cardiovascular anomalies or mediastinal masses. In CT angiograms, careful