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, VBI) 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 VBI 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 bronchectasis 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- 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
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 calibre of the main bronchi appears normal.

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 cranio-caudal 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 reformatting 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’ reformatations. 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
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 cranio-caudal 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. 4.** VB image of the trachea and main bronchi of the patient presented in figure 1 (online suppl. video 1). a The tip of the virtual bronchoscope is at the level of the normally sized extrathoracic portion. Progressively worsening stenosis of the tracheal lumen is demonstrated. b Image obtained immediately above the main carina at the level of maximal tracheal stenosis. c The tip of the virtual bronchoscope has 'crossed' the level of maximal tracheal stenosis and is entering the normally sized orifice of the left main bronchus. d The virtual bronchoscope has just entered the normally sized orifice of the right main bronchus. e The virtual bronchoscope has been advanced into the right main bronchi at the point of the take-off of the right upper lobe bronchus (arrowhead). The orifice of the bronchus intermedius is partially visualized (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
selection of dose, rate and timing of administration of the intravenous contrast medium is essential for the accurate imaging of the specific area of interest. In current practice, non-ionic low-osmolarity contrast material is used to minimize discomfort at the injection site and systemic side effects, such as nausea and vomiting. Intravenous contrast medium should be injected by a mechanical pump when a 22-gauge or larger cannula is in place, otherwise it should be administered manually. Although conventional HRCT achieves optimal resolution of lung parenchyma in diffuse interstitial or airway disease (including bronchiectasis) at relatively lower than MDCT radiation dosage, it does not provide volumetric data because sampling is not continuous. Therefore, true volumetric scanning can be selected for the initial diagnostic evaluation in such cases, while HRCT, at a lower radiation dose, can be used for patient follow-up [12].

In cooperating patients, scans are performed in suspended inspiration, ideally at total lung capacity. However, this is often not possible in young children. Children older than 6 years can be instructed to hold their breath, and scans are obtained in suspended inspiration although not always at total lung capacity. Children between 6 and 10–12 years usually require support in order to cooperate, while after the age of 12 years most children comply with the instructions used for adults. In sedated children and those under 6 years (with the exception of an unusually cooperative child), the examination is performed during quiet breathing. When investigating tracheobronchomalacia (TBM) or peripheral obstruction, usually 3–5 additional slices during expiration are obtained in order to reveal tracheobronchial collapse or air-trapping [5]. In young children in whom breath-holding is not possible, scans are obtained during quiet breathing in both left and right lateral decubitus positions [12]. When performing this manipulation, the dependent lung is compressed due to the increased compliance of the young child’s chest, thus behaving as in the expiratory phase; conversely, the non-dependent lung behaves as in the inspiratory phase. Therefore, trapping can be visualized. On occasion, non-invasive controlled ventilation of infants – which takes advantage of the Hering-Breuer reflex similarly to infant pulmonary function testing – or general anaesthesia that provides complete control of breathing may be required.

Patient Handling and Sedation
As with any procedure, an effort should be made to prevent or minimize the discomfort that the patient may experience and ease the anxiety of the patients and their parents. The intravenous catheter, if required, should be placed beforehand. A resuscitation cart, wall oxygen and suction should be readily available as well as heating blankets or warming lamps for young infants. Staff should be familiar with techniques of immobilizing infants and young children while maintaining patient comfort and fulfilling imaging requirements. Radiation-sensitive organs such as the breasts and thyroid gland need to be protected, and a lead apron may be used to protect adjacent regions from scattered radiation. It should be remembered that protection may inadvertently increase the radiation dose when an automated dose-control protocol is in place because the CT tube can sense the decrease in radiation penetrating the patient and will automatically increase the emitted dose of radiation.

The fast scanning time of current MDCT scanners has dramatically reduced patient sedation requirements. Children over 3 years after becoming familiar with the environment usually cooperate and breathe calmly during the scan, while recently fed infants less than 3 months of age remain peaceful through the short duration of the examination. Children that require sedation or intravenous administration of contrast material should be fasted before the examination (2 h for clear liquids, 4 h for breast milk and 6 h for bottle milk or solids). Children from 4 months to 5 years can be sedated using the same precautions used for sedation during invasive procedures [13; chapter 2, this vol., pp. 22–29]. A quiet area for sleep should be available in the radiology department.
Fig. 6. a MPR image of an endotracheal haemorrhage in a 16-year-old adolescent male who presented with a 6-month history of shortness of breath, wheezing and cough misdiagnosed and treated as asthma. b V8 image demonstrating almost complete occlusion of the tracheal lumen by the haemorrhage. The virtual bronchoscope was able to visualize the airway distally to the mass (images not shown).

Table 1. Advantages and disadvantages of V8 as compared to FB in children

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Non-invasive technique (but may require mild sedation of young uncooperative patients)</td>
<td>Relatively high radiation dose requirements</td>
</tr>
<tr>
<td>Accurate localization and evaluation of the extent and degree of airway stenosis – improved diagnostic confidence</td>
<td>Inability to distinguish mucus from ‘true’ obstruction or foreign body</td>
</tr>
<tr>
<td>Interactive evaluation of the volumetrically acquired data with simultaneous display of axial, coronal and sagittal views, MPRs and 3-dimensional externally and internally rendered reconstructions of the airways by using different algorithms without additional radiation or inconvenience to the patient</td>
<td>Inability to assess colour, vascularity and texture of airway mucosa or subtle mucosal lesions</td>
</tr>
<tr>
<td>Precise localization of extraluminal cause of airway compression through ‘transparent’ rendering of airway wall with simultaneous visualization of airway lumen and mediastinal structures</td>
<td>Reluctance to perform BAL or invasive procedures (but may have a complementary role in procedure planning)</td>
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<tr>
<td>Ability to rotate images in order to better define their spatial relationships</td>
<td>Restricted ability to adequately assess ‘dynamic’ airway abnormalities (i.e. tracheo-/bronchomalacia and vocal cord dysfunction) mainly due to high radiation dose requirements</td>
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<tr>
<td>Ability to ‘cross’ severe stenosis and evaluate airway geometry distally to the obstruction</td>
<td>Limitations due to lack of patient cooperation</td>
</tr>
<tr>
<td>Improved planning of invasive procedures (mapping of abnormal structures and guidance of transbronchial biopsies, stent deployment, laser treatment, cryotherapy and endobronchial brachotherapy, surgical planning)</td>
<td>(infants, young children, seriously ill patients)</td>
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<tr>
<td>Bronchoscopy training without risk for the patient</td>
<td>Workload burden due to postprocessing of raw data</td>
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<td></td>
<td>Cannot be performed at the bedside and requires potentially hazardous transport of seriously ill patients</td>
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</table>

BAL = Bronchoalveolar lavage.

Clinical Applications of 3-Dimensional Imaging in Paediatric Patients

Airway obstruction can be classified on the basis of its location (intrathoracic vs. extrathoracic, intraluminal vs. extraluminal) and its characteristics (diffuse vs. focal, fixed vs. dynamic). Combinations of these components may coexist and airway wall involvement may need to be assessed. The diagnostic process may include pulmonary function tests, FB and imaging studies. Chapters 10 and 12 of this volume (pp. 114–119 and 130–140) discuss the anatomical variations of the normal bronchial tree, and chapters 11 and 12 [this vol., pp. 120–129 and 130–140] describe the main congenital and acquired abnormalities of the upper and lower airways, respectively. Table 2 lists airway lesions the diagnosis and management of which may benefit from CT scanning, especially the newer MDCT imaging technology. A discussion of specific situations where 2- and 3-dimensional imaging can complement airway endoscopy is presented below.
<table>
<thead>
<tr>
<th>Table 2. Disorders causing tracheobronchial airway compromise in children the diagnosis of which may be assisted by CT</th>
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<tbody>
<tr>
<td><strong>Congenital</strong></td>
</tr>
<tr>
<td>Intraluminal</td>
</tr>
<tr>
<td>Bronchial agenesis, aplasia, hypoplasia (including scimitar syndrome, horseshoe lung etc.)</td>
</tr>
<tr>
<td>Bronchial atresia (bronchocle &amp; foregut communication)</td>
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<tr>
<td>Tracheobronchial branching anomalies (bronchial isomerism, tracheal bronchus, cardiac bronchus, tracheal diverticulum)</td>
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<tr>
<td>Tracheo-oesophageal fistula (oesophageal atresia)</td>
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<tr>
<td>Tracheal stenosis (focal, carrot-shaped trachea/complete tracheal rings)</td>
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<tr>
<td>Tracheal webs, cartilaginous sleeves, oesophageal remnants</td>
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<tr>
<td>Laryngotracheo-oesophageal cleft</td>
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<tr>
<td>Tracheo- and/or bronchomalacia (dynamic airway collapse)</td>
</tr>
<tr>
<td><strong>Extraluminal</strong></td>
</tr>
<tr>
<td>Foregut duplication cysts (i.e. bronchogenic cysts, enteric cysts/oesophageal atresia pouch, neurenteric cysts)</td>
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<tr>
<td>Sequestration spectrum (intra- or extralobar sequestration*, cystadenomatoid malformation, mixed lesion)</td>
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<tr>
<td>Cardiovascular malformations (vascular ring)</td>
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<tr>
<td><strong>Infectious/inflammatory</strong></td>
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<tr>
<td>Intraluminal</td>
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<tr>
<td>Bacterial tracheitis</td>
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<tr>
<td>Tuberculosis</td>
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<td>Histoplasmosis</td>
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<tr>
<td>Relapsing polychondritis</td>
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<tr>
<td>Wegener granulomatosis</td>
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<tr>
<td>Bronchial inflammatory myofibroblastic tumour (inflammatory pseudotumour, plasma cell granuloma, fibrous histiocytoma)</td>
</tr>
<tr>
<td>Peripheral airway disease (CF and non-CF bronchiectasis, bronchopulmonary dysplasia, aspiration, constrictive or obliterative bronchiolitis, cryptogenic organizing pneumonia, follicular bronchiolitis, neuroendocrine cell hyperplasia of infancy, hypersensitivity pneumonitis)</td>
</tr>
<tr>
<td><strong>Extraluminal</strong></td>
</tr>
<tr>
<td>Neck abscess</td>
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<tr>
<td>Enlarged lymph nodes (tuberculosis, histoplasmosis, granulomatous disease)</td>
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<tr>
<td>Fibrosing mediastinitis (histoplasmosis, mucormycosis, blastomycosis, cryptococcosis, Behçet disease, methysengride use)</td>
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<tr>
<td><strong>Neoplastic</strong></td>
</tr>
<tr>
<td>Intraluminal</td>
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<tr>
<td>Capillary haemangioma</td>
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<tr>
<td>Papilloma</td>
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<tr>
<td>Neurofibroma</td>
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<tr>
<td>Hamartoma (chondroma)</td>
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<tr>
<td>Juvenile xanthogranuloma</td>
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<tr>
<td>Muco-epidermoid tumour</td>
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<tr>
<td>Bronchial carcinoid</td>
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<tr>
<td>Pleuropulmonary blastoma</td>
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<tr>
<td>Adenoid cystic carcinoma (cylindroma)</td>
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<tr>
<td>Malignant fibrous histiocytoma</td>
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<tr>
<td>Bronchogenic carcinoma (extremely rare)</td>
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Table 2. Continued

Extraluminal

| Haemangioma |
| Lymphangioma |
| Lymphoma (Hodgkin, non-Hodgkin) |
| Germ cell tumours (e.g. various grades of teratoma, seminoma, embryonal carcinoma, choriocarcinoma, yolk sac tumours and mixed type) |
| Ewing sarcoma |
| Rhabdomyosarcoma |
| Parenchymal tumours (rarely malignant) |
| Pulmonary nodules (usually benign) |
| Thymic tumours |
| Thyroid tumours |
| Metastatic (e.g. Wilms tumour, rhabdomyosarcoma, osteosarcoma, hepatoblastoma, peripheral neuroectodermal tumour, Askin tumour) |

Other

Intraluminal

| Vocal cord paralysis (unilateral, bilateral), vocal cord dysfunction |
| Foreign-body aspiration |
| Mucocele plug |
| Postintubation/tracheostomy stricture, granuloma, malacia |
| Partial lung resection with bronchial anastomosis, lung transplantation |
| Acquired tracheo-bronchomalacia (intubation, tracheostomy, extrinsic compression, trauma, infection, surgery) |
| Macropolyascharidosis |

Extraluminal

| Oesophageal foreign body |

CF = Cystic fibrosis.
* Rarely cause airway compromise.

Tracheobronchial Stenosis/Atelectasis, Tracheo-Oesophageal Fistula, Branching Anomalies

MPRs and VRs are the most commonly utilized adjuncts to axial CT for elucidating fixed stenoses and complex structures, communicating the radiographic findings to clinicians, and planning the surgical approach (fig. 1–3, 6) [6, 14, 15]. In suspected congenital or acquired tracheobronchial stenosis, the CT may reveal parenchymal involvement (e.g. infiltrates) with or without airway disease and thus help to explain the clinical and/or chest X-ray (CXR) presentation or re-orient the investigation. MPRs and VRs help to describe intraluminal lesions (e.g. webs, haemangiomomas, hamartomas, granulomas, papillomas; table 2) and aid the exact measurement of the calibre and extent of airway stenosis as well as the distance between the oesophageal pouches in oesophageal atresia [16]. Axial CT is the imaging modality of choice for the confirmation of congenital bronchial atresia revealing the cylindrical mucoid impaction within the dilated bronchus distally to the atretic segment, which is associated with hyperlucency and decreased vascularity of the relevant lung segment (usually apical or apicoposterior to the upper lobes). VB and external rendering can highlight the findings of axial images but do not usually add important diagnostic information [17]. Although MDCT usually performs well in the diagnosis of tracheo-oesophageal fistulas and VB can depict the tracheal ostium of the fistula, false-positive findings (as compared to FB) have been reported [18]. Visualization of tracheal diverticuli can be enhanced by MPR and external VR [14], while VB provides an excellent image quality of tracheobronchial branching anomalies [19].
Foreign Body Aspiration

It has been proposed that low-dose MDCT with VB can serve as a first-line non-invasive examination to rule out suspected foreign-body aspiration in children [20]; the authors of the article correctly suggest that because a mucous plug or an alternative diagnosis (e.g., tumour), which cannot be differentiated from foreign body by this method, may be responsible for the presence of obstruction, a positive finding should prompt evaluation by conventional bronchoscopy in order to confirm the diagnosis and remove the foreign body. It should be noted, however, that conventional bronchoscopy was not performed in patients with normal MDCT findings in this study; and that foreign body was ‘ruled out’ by following the patients for 5–20 months. Thus, we believe that conventional bronchoscopy should remain the gold standard for diagnosis, and FB should be performed even in cases of low clinical suspicion [chapter 12, this vol., pp. 130–140].

Peripheral Airway Disease

HRCT is usually the method of choice for evaluating peripheral (small) airway disease. Airways as small as 1–2 mm in diameter with wall thicknesses of 0.2–0.3 mm—which by definition cannot be inspected by FB—can be visualized. Airtrapping, best seen on expiratory images, is the most common finding in peripheral airway disease, and it is the predominant finding in constrictive (obliterative) bronchiolitis. Ground-glass opacities predominate in fibrosing bronchiolitis and neuroendocrine hyperplasia of infancy. MPVRs provide excellent images of bronchiectasis, while use of the maximum intensity projection algorithm helps to better appreciate the relation between peripheral nodules and the relevant bronchus when planning transbronchial biopsy [5].

Dynamic Airway Compression

TB can be conclusively diagnosed under direct real-time visualization of the airways during breathing manoeuvres (forced inspiration/expiration and coughing) [chapter 12, this vol., pp. 130–140]. However, patient cooperation during the procedure is important, and careful ‘titration’ of sedation is required.

Newer-technology high-resolution fast MDCT scanners provide a dynamic imaging tool to assess the airway. Although still somewhat limited in z-axis coverage, such scanners are able to completely ‘sample’ the entire airway during a single forced or coughing manoeuvre, or to at least obtain complete anatomical coverage with several acquisitions. Axial images are indispensable for the evaluation of TB but they may underestimate the craniocaudal extent of disease. Therefore, 2- and 3-dimensional images, including VB, can assist in mapping the exact location of malacia and its longitudinal extent as well as in grading the severity of collapse by obtaining exact measurements of airway diameters at end-inspiration and comparing them with those at end-expiration or during a forced expiration/cough manoeuvre. In addition, 3-dimensional renderings can provide a comprehensive assessment of tracheomalacia associated with mediastinal vascular malformations or non-vascular paratracheal masses.

This technique has been studied in infants [21] and children [22]. Children 5–6 years or older can usually be coached to perform successful forced inspiratory/end-expiratory or forced expiratory manoeuvres. Using 64-MDCT (or a scanner of more advanced generation), cine CT can also be performed during a coughing manoeuvre, especially when investigating focal airway malacia. Infants, preschoolers and non-cooperating older children require general anaesthesia and endotracheal intubation in order to achieve the breath-hold that is necessary for paired end-inspiratory/end-expiratory manoeuvres. End-inspiratory pressure in such cases should be maintained at 15–20 cm H2O to avoid ‘artificial’ distension of the airway lumen. The recently introduced 320-MDCT shows great promise for the evaluation of TBM because it can cover the entire central airway of infants and young children in a single acquisition, thus offering excellent anatomical precision. Intravenous contrast medium is not necessary for routine assessment of TBM; however, it may prove very useful and should at least be considered in the settings of known or suspected vascular anomalies. As is the case for FB, the standard CT criterion for TBM is an at least 50% reduction in the cross-sectional luminal area of the trachea and/or bronchi during expiration as compared to end-inspiration [23]. However, since forced expiration and cough result in greater collapse of the large airways than the end-expiration manoeuvre, different threshold criteria may be more appropriate for different techniques (e.g., a 60 or 70% reduction in the luminal area with the coughing manoeuvre). The need for normative CT data for both manoeuvres in the paediatric population is obvious.

Despite the fact that drastic dose reduction is possible without significant negative influence on measurements of luminal dimensions, the radiation dose to the patient is still of concern in these studies. MRI is an attractive alternative for the evaluation of TBM, especially due to the lack of radiation exposure that permits repeated assessments. New fast cine MRI techniques provide acceptable contrast resolution and temporal resolution as low as 150 ms/slice, which yields multiple images during a forced manoeuvre. Therefore, MRI can demonstrate dynamic tracheal compression that varies.
with the respiratory cycle and integrate information regarding relationships of mediastinal structures [15].

**Vascular Anomalies**

The term 'vascular ring' in its broad sense encompasses aortic arch (e.g., double aortic arch, lesions associated with right or left aortic arch, anomalous innominate artery, cervical aortic arch) and pulmonary artery (e.g., pulmonary artery sling) anomalies in which the trachea and usually the oesophagus are completely or partially surrounded by vascular structures that are not necessarily patent. Vascular rings can cause compression (usually pulsating) of the trachea, bronchi and oesophagus. Pulsating airway compression may also be the result of congenital heart disease such as dilated pulmonary arteries, left atrial enlargement, massive cardiomegaly or aortopulmonary collaterals (typically tetralogy of Fallot and pulmonary atresia) [15, 24].

Apart from FB, a number of imaging studies is available for the diagnosis of vascular ring, and the imaging approach may vary according to the clinical setting [chapter 12, this vol., pp. 130–140]. Traditionally, CXR and upper gastrointestinal study (barium swallow) are the initial imaging modalities used when a vascular ring is suspected. The diagnostic accuracy of barium swallow is acceptable regarding tracheal compression but it does not adequately describe the anatomy of the vascular anomaly. Evaluation of the patient with echocardiography for associated congenital heart disease is of vital importance. It should be noted that when vascular abnormalities are present the narrowing of the tracheal lumen is not always due to malacia but can be due to complete tracheal rings that in up to 50% of cases are associated with an anomalous left pulmonary artery originating from the right pulmonary branch (ring-sling syndrome) [6].

MRI and MDCT, usually with contrast in order to depict the great vessels (MR angiography and MDCT angiography), are used interchangeably and occasionally together in the surgical planning of vascular ring. The intrinsic properties of MRI along with its 3-dimensional reconstruction capabilities and its ability superior to CT for the assessment of cardiac anatomy and physiology have made it, until recently, the standard imaging method (fig. 3B). However, the role of MDCT in evaluating tracheobronchial narrowing associated with mediastinal vascular anomalies in neonates and children has rapidly expanded in recent years. Indeed, MDCT is a much faster examination that usually places substantially fewer airway management demands upon patients with a compromised airway and provides exquisite detail of the lung parenchyma and central airways. Axial cuts, external VR of the airways and VB images help to visualize the airway beyond severe narrowing, reveal additional airway anomalies and further contribute to presurgical planning [6]. On the down side, MDCT does not usually provide adequate details of intracardiac defects and in a study of 12 children with various types of vascular ring contrast-enhanced 16-MDCT failed to detect 1 bronchoscopically proven tracheal stenosis due to innominate artery compression, which nevertheless did not require surgery [25].

The degree and craniocaudal extent of coarctation of the aorta can be precisely assessed by MPR and external VR. MDCT angiography with 3-dimensional rendering can be very useful for the detection and accurate delineation of other complex congenital vascular anomalies, such as proximal interruption of the pulmonary artery (associated with hypoplastic ipsilateral lung and enlarged contralateral pulmonary vessels), unilateral pulmonary agensis, pulmonary vein stenosis, pulmonary varix (i.e., enlarged pulmonary vein without a large feeding artery or nihus), scimitar syndrome (hypogenetic lung syndrome), patent ductus arteriosus and pulmonary arteriovenous malformation [17].

Although not relevant to airway disease, the recent literature supports pulmonary MDCT angiography as the new reference standard for the diagnosis of pulmonary emboli. In a study using 64- and 64-MDCT angiography, successful visualization of 100% of segmental and 80% of subsegmental pulmonary arteries was achieved in 98 studies of children investigated for pulmonary embolism [26]. The need for careful attention to the protocol of contrast administration to the patient in order to prevent incomplete evaluation and misdiagnosis cannot be overemphasized [27].

**Non-Vascular Mediastinal Masses**

These are conveniently categorized for diagnostic purposes into anterior (approx. 45%), middle (approx. 20%) and posterior (approx. 35%) masses. Depending on their location and size, mediastinal masses may cause compression of the trachea and/or the main bronchi, thus creating the need for evaluation of the airways. Initial investigation typically involves anteroposterior (AP) and lateral CXR, which is usually followed by additional imaging studies that may include ultrasonography, CT or MRI. The potentially important role of MRI in evaluating non-vascular mediastinal and pulmonary masses – due to its superior soft tissue characterization as compared to other currently available imaging modalities – is limited by its disadvantages (previously described), especially in young children; however, the utility of MRI has been demonstrated particularly in the evaluation of posterior mediastinal neurogenic tumours and foregut duplication cysts with high attenuation on non-contrast CT [28].
Anterior mediastinal non-vascular masses are basically comprised (85%) of thymic enlargement, Hodgkin (typically in the first decade of life) and non-Hodgkin lymphoma (in both the first and second decades of life) and germ cell tumours (mostly benign, usually teratomas). Evaluation of the CXR by an experienced reviewer is usually sufficient to diagnose an enlarged thymus, but ultrasound (the unclassified sternal and costal cartilages in the first year of life provide an adequate acoustic window), MRI (on occasion) and CT (hardly ever) may be performed to confirm the diagnosis. The diagnosis of lymphoma and germ cell tumours requires confirmation by CT or MRI, while positron emission tomography (PET) scanning has been proven valuable for initial staging of lymphomas and assessment of treatment response. Three-dimensional imaging enhances the perception of tumour anatomy, and hybrid ("fused") PET/CT imaging can combine functional and anatomical information, thus offering a complete evaluation of paediatric lymphoma [14, 28]. Perger et al. [29] have described an algorithm for the management of children with severe airway compromise due to compression by an anterior mediastinal mass, usually due to lymphoblastic lymphoma or Hodgkin disease.

Middle mediastinal non-vascular masses are mostly comprised of embryonic foregut malformations (i.e. bronchogenic, enteric and neuromeric cysts), lymphoma and lymphadenopathy of infectious or inflammatory aetiology (i.e. tuberculosis, histoplasmosis, granulomatous disease, sarcoidosis). When the lesions become large enough, symptoms may occur due to mass effect on adjacent mediastinal structures such as the central airways and the oesophagus [28, 29]. On CT the degree of attenuation of a bronchogenic cyst depends on the amount of its proteinaceous content. With intravenous contrast medium, a non-enhancing or minimally enhancing thin wall is typically seen and, in case of an air-fluid level or a thick wall, a superimposed infection should be considered [17]. Acutely inflamed lymph nodes can also show peripheral enhancement with low-attenuation centres or enhance homogeneously. Three-dimensional external rendering MDCT images accurately delineate these masses and may assist with surgical planning [14, 15].

The great majority (88%) of posterior mediastinal non-vascular masses is neurogenic in origin. These tumours are primarily derived from ganglion cells of the paravertebral sympathetic chain and do not impinge on the central airways. They include neuroblastoma (most common), ganglieneuroblastoma and ganglioneuroma, while the remaining are usually nerve sheath tumours such as schwannoma and neurofibroma. CT or MRI is usually necessary to confirm the diagnosis and evaluate the disease extent. MRI is probably the imaging method of choice due to its high sensitivity in detecting intraspinal extension without exposing the patient to radiation [28].

Non-Vascular Pulmonary Lesions
These include a wide spectrum of conditions such as congenital anomalies, neoplasms, inflammatory pseudotumour, infections and pseudomasses. Excluding neoplasms, these lesions do not usually affect the airways; however, they are briefly presented because MDCT with external 3-dimensional rendering is particularly useful in describing the anatomy of some of these lesions.

Congenital cystic adenomatoid malformation (CCAM) results from disorganized proliferation of the airways (usually the bronchioli) of unknown aetiology; the dysplastic airway communicates with the bronchial tree. There are 3 types of CCAM with distinct radiographic and pathologic appearances (type 1: at least 1 cyst >2 cm in size; type 2: numerous small cysts with diameters 1–10 mm; type 3: solid in appearance with numerous microcysts). CT is very useful in the identification and characterization of CCAM, the evaluation of mass effect and the differentiation of CCAM from sequestration although there may be overlap between the two malformations (e.g. systemic arterial supply of CCAM). External VR images improve delineation of the malformation and assist in pre-operative evaluation [14, 15].

Pulmonary sequestration is a congenital malformation characterized by dysplastic non-functioning pulmonary tissue that is not normally connected to the tracheobronchial tree; its arterial supply comes from systemic vessels. Extralobar sequestration is contained in its own pleura, its venous drainage is in the systemic circulation (usually through the azygos and less commonly through the portal vein) and is often associated with other congenital malformations. Intralobar sequestration manifests itself within the lung (not contained in its own pleura), its venous drainage is typically in the inferior pulmonary vein, and it is associated with recurrent infections while coexistent congenital anomalies are quite rare; in fact, it is considered by certain experts as a secondary lesion due to recurrent infections that produce the aberrant systemic feeding vessels. CT imaging is integral to the management of sequestration. MDCT angiography with external VR offers 3-dimensional images that are particularly helpful in pre-operative planning by delineating the anomalous veins and therefore differentiating between extra- and intralobar sequestration, also in detecting the anomalous arterial vessels and thus avoiding potentially life-threatening haemorrhage during surgery [17, 30]. The area scanned should be extended to below the
diaphragm in order to include feeding vessels that originate from the abdominal aorta [14].

Congenital lobar emphysema may appear in the newborn period as an opacity on CXR or CT owing to the retention of foetal lung fluid. As the fluid is cleared by the lymphatic circulation and replaced by air, the affected lobe becomes hyperlucent with a mass effect on adjacent lobes. CT is useful for diagnosing multilobar involvement and defining the anatomy; 3-dimensional imaging does not usually add important diagnostic information [17].

Pulmonary neoplasms are rare in children but should be considered in the differential diagnosis of a persistent abnormality on CXR. Most often they involve the large airways and present as airway obstruction. Primary airway neoplasms are usually benign although malignant lesions do occasionally occur (table 2). With the use of FB, the intraluminal and the mucosal components of the airway tumour can be identified, and biopsy can be performed but extraluminal extension of the mass cannot be assessed. Enhanced MDCT with external VR can demonstrate the extraluminal mass extent, configuration, homogeneous, heterogeneous or peripheral rim enhancement (depending on the vascularity of the tumour), while VB offers excellent images of intraluminal masses (fig. 6 and table 2) [15, 30]. This information is important when planning biopsy or assessing surgical resectability.

Pulmonary inflammatory pseudotumour (also termed bronchial inflammatory myofibroblastic tumour, plasma cell granuloma or fibrous histiocytoma) is a non-neoplastic reactive proliferative process histologically characterized by (myo)fibroblasts, histiocytes, lymphocytes and plasma cells. Affected children can be asymptomatic or quite ill. CT, including external VR images, shows a well-marginated mass with variable contrast enhancement and calcifications that is usually situated at the periphery of the lungs and typically (but not always) does not invade adjacent structures [30].

Pulmonary mass-like lesions of infectious cause include [30]: (a) lung abscess, which typically is a low-attenuation cystic structure on axial CT with an enhancing wall of variable thickness and border definition that depend on the degree of abscess maturity and inflammation of surrounding lung parenchyma; (b) fungal infection (invasive pulmonary aspergillosis), which occurs in immunocompromised children and appears on axial CT as ill-defined macronodules, often bilateral, with a ‘halo’ sign (ground-glass opacity due to alveolar haemorrhage surrounding the nodule), and possibly cavitation (the so-called air crescent sign that may represent either disease progression or a favourable response to treatment); (c) hydatid (echinococcal) cyst, which presents on axial CT as a cystic mass with homogeneous water density content, is indistinguishable from other pulmonary cysts and, when ruptured, may produce the ‘water lily’ sign (ruptured cyst membranes floating on the remaining fluid); (d) round pneumonia (more commonly seen in children), which may occasionally lead to CT imaging if the consolidation persists despite appropriate antibiotic treatment and the suspicion of an underlying abnormality is raised, and (e) round atelectasis (quite rare in children), in which even CT findings may not be able to resolve the diagnostic confusion.

Vocal Chord Paralysis and Vocal Cord Dysfunction
Laryngoscopy is the gold standard for evaluating vocal chord motion (chapter 11, this vol., pp. 120–129). Fluoroscopy and ultrasound of the vocal chords are currently used as non-invasive diagnostic methods of vocal chord paralysis and vocal chord dysfunction [31]. Cine MRI, similarly to TBM, has been shown to adequately demonstrate vocal chord motion and its abnormalities [15]. Laryngeal CT reconstructed images during vowel phonation have been shown to effectively demonstrate functional changes in the larynx and to diagnose vocal chord paralysis in adult patients [32]. Although patient cooperation is important in order to achieve sustained phonation in these studies, given the ongoing advances in technology, such problems are expected to be overcome in the near future.

Radiation Exposure and Dose Reduction

Radiation Dose
The ionizing effect of X-rays in tissues may lead to permanent DNA alterations and carcinogenesis [33]. The risk of radiation-induced fatal cancer is considered to be 1/20,000 per millisievert (mSv) in adults. This risk is estimated to increase approximately 10-fold in children (between 1:1,000 and 1:10,000 depending on their age) who are considerably more sensitive to radiation. Indeed, children have a higher proportion of dividing cells, a wider window of opportunity to express radiation damage due to longer life expectancy and suffer higher organ doses as a result of their small size [34, 35]. Most available quantitative data on the risk of low-dose radiation-induced cancer and cancer fatality come from the atomic bomb survivors in Japan [36, 37]. Despite the obvious differences in uniformity of radiation exposure between A-bomb survivors and patients undergoing CT, most authorities consider it valid to extrapolate specific organ cancer risk calculated from the A-bomb low-dose exposure data to equivalent radiation exposure by CT.
Figure 7. Mean radiation-related additional relative risk and standard error for solid cancer mortality in Japanese A-bomb survivors of any age at exposure. The graph focuses on exposure to radiation doses relevant to those used in paediatric CT, especially when multiple examinations are performed (redrawn from Pierce et al. [36]).

Figure 7 illustrates that A-bomb radiation exposure within the range of effective doses delivered by paediatric CT increases fatal solid cancer mortality, especially when dose reduction is not implemented.

It is estimated that the mean annual background radiation dose is 2.6 mSv in the UK and 3 mSv in the USA, while the dose of a round-trip transatlantic flight is 0.1 mSv. In paediatric hospitals with carefully selected low-dose radiation protocols, the dose of an AP CXR ranges, depending on the child's size, from 0.00487 to 0.0176 mSv for children up to 44 kg. The radiation dose of a typical HRCT of the lungs is equivalent to approximately 45–90 AP CXRs and that of a thoracic 'combiscan' (CT angiography with use of intravenous contrast medium and concomitant high-quality imaging of lung parenchyma) to 100–220 AP CXRs, according to the size and sex of the patient [5, 12]. In a multiphase CT that involves 2–4 scans per study, the scanned area, depending on the machine settings, may receive a radiation dose as high as 15 mSv in the adult and 30 mSv in the neonate, while follow-up scanning is not unusual [34]. These doses are associated with a small, albeit distinct, increase in cancer risk that is important at a population level. There appears to be a linear dose-response relationship between radiation dose and solid cancer risk, and there is no evidence for a threshold.

The annual collective population radiation dose for diagnostic purposes has increased by a dramatic 750% over the last 20 years, while paediatric CT examinations have increased during the same period by about 800%. CT comprises today approximately 9–12% of all radiological examinations in the USA and UK and is responsible for 45–47% of the medical radiation dose; over 10% of the studies are conducted in children [35, 38]. It is estimated that the current use of CT accounts for 1.5–2.0% of all cancers in the USA [34].

Dose Reduction
The radiation dose in CT is considered to be a major issue by several national and international organizations and radiation protection boards [39]. Continuous communication between clinicians and radiologists is imperative in order to eliminate unnecessary examinations, take advantage of alternative imaging modalities and minimize patient exposure. The CT image quality is determined by image contrast and noise, which depend on scan parameters and patient size (i.e. radiation dose). At this time no large-scale long-term epidemiological data are available on cancer risk from CT, although at least one such study is under way [34]. In the meantime, adherence to the 'as low as reasonably achievable' (ALARA) principle must be observed [35, 39].

In CT, unlike film screen radiography, overexposure is not visually evident as it does not directly alter film quality. The operator makes the necessary computer adjustments, and therefore radiologists may remain unaware of the potential danger. CT demonstrates variations in delivered dose within the scan plane and along the z-axis. A number of CT-specific dose descriptors have been developed. The ones most commonly used are the weighted CT dose index (CTDIw), the dose-length product and the effective dose [38]. The CTDIw provides a weighted average of the central and peripheral contributions to dose within the scan plane. The dose-length product descriptor takes into account the CTDIw, the pitch and the scan length. Both CTDIw and dose-length product are readily displayed by the scanner and help to visualize the impact of scan parameters on patient dose. They are useful for quality control but they are not directly related to organ dose or risk. The effective dose is a more relevant descriptor that represents the weighted sum of organ doses resulting from the examination, while taking into account their radiation risk factors. The effective dose is difficult to calculate but complex mathematical patient models have been developed for its estimation. It is measured in millisieverts and it constitutes the best single parameter for quantifying the radiation that an individual receives during any radiographic examination. Therefore, it allows comparison of possible CT radiation effects to those of other radiation
exposures. Selection of scanning parameters such as photon beam energy, tube current, scanning time, tube collimation, pitch, field of view, adjustment and dose modulation function affect the radiation dose administered to the patient (Appendix). In addition, careful patient preparation, patient size (smaller patients receive larger radiation doses), inherent tissue contrast (e.g., air-tissue contrast of the lung) and individual scanner design contribute to the radiation doses administered to particular organs. Last but not least, clinician-radiologist communication should consider alternative imaging modalities (e.g., sonogram or MRI), assure that the CT scan is necessary for diagnosis and minimize the number of scans required for the examination (e.g., precontrast scans are rarely needed during follow-up) [38].

There is always a trade-off between the quest for high-resolution low-noise imaging and the need for a low radiation dose administered to the patient. As CT scanners evolve, all major components such as X-ray filters, beam collimators and detectors are optimized, new features are implemented, and paediatric scanning protocols are updated in order to reduce the dose by adjusting the settings according to the characteristics of the patient, the scanned areas and the relevant clinical question.

Future Trends

CT is a powerful non-invasive tool for quantifying airway dimensions, and the rationale behind the strengths and the limitations of MDCT imaging of the lung has been addressed in previous sections. Although accurate and precise measurements in airways as small as 2 mm in diameter are currently possible, there is a need for deeper penetration into the bronchial tree and for reliable measurements in even smaller airways. Therefore, further advancements in CT-based measurement techniques will have important clinical implications: (a) thinner slices (cubic voxel scanners) will further improve resolution and reduce partial volume-averaging effects; (b) faster tube revolution speeds will achieve acquisition of the entire lung in shorter time periods; (c) refined automated (as opposed to manual) tracing systems will improve speed, reproducibility and accuracy, and will reduce subjectivity of measurements, and (d) improved skeletonization algorithms will facilitate the reconstruction of CT data orthogonal to the airway axis, thus reducing the effects of partial volume averaging and aiding navigation through the tracheobronchial tree.

The ability to combine functional with precise anatomical information by the merging of PET scan and 3-dimensional MDCT images (hybrid PET/CT imaging) in the case of paediatric lymphoma has already been mentioned. Another example of 'merging' of different techniques is the integration of CT and digital bronchoscopic images (colour bronchoscopy and fluorescence detection systems). By using highly sophisticated techniques, the coloured bronchoscopic picture is 'pasted' onto the VB image derived from MDCT, producing a virtual bronchoscopic image in true colour from which airway dimensions can be accurately measured and subtle mucosal colour changes can be assessed [40].

Until recently, despite the ability of MRI to provide functional information without ionizing radiation, its limited signal from the lung tissue and the longer – as compared to MDCT – acquisition time have limited its use in lung imaging. MRI with hyperpolarized helium that diffuses rapidly into the air spaces of the lungs can greatly improve the lung signal, thus resulting in high spatial and temporal resolution images of the airways and the alveolar spaces. Clinical studies in children with asthma and cystic fibrosis have been conducted, and a strong correlation has been shown between forced expiratory volume in 1 s and ventilation defects [41]. This technique, which is free from the harmful effects of ionizing radiation, may prove to be extremely useful in the follow-up of lung microstructure and function of these patients as well as those with chronic resection of lung transplant or other chronic lung diseases. Recently, hyperpolarized xenon has emerged as the gas imaging agent of choice due to its improved ability to measure chemical diffusion, its unlimited supply in nature and its modest production costs [42]. Nevertheless, availability of these techniques is limited, and further research on their clinical applications and cost-effectiveness is required.

Future trends with respect to videobronchoscopy in paediatric patients, including endobronchial ultrasound and confocal fluorescent laser microscopy (alveoloscopy), are touched upon in chapter 4 of this volume [pp. 42–53]. Despite the great advancements in overcoming optical limitations such as distal and radial distortion that are inherent to the system, the 'holy grail' of real-time quantitative videobronchoscopy is still elusive. Newer technologies such as optical coherence tomography and the already mentioned confocal fluorescence endomicroscopy are light microscopy techniques with enhanced 'optical sectioning' (effective resolution in depth) that is beyond that of conventional microscopy. These technologies, recently presented in more detailed reviews [43, 44] and actively being researched [45], have made imaging of terminal airways and even alveoli possible and may hold an important future role in the assessment of small-airway remodelling.
Appendix

Glossary of Radiological Technical Terms

Collimation: The width of the radiation detectors in the scanner. It represents the z-axis dimension of the voxel and is often used interchangeably with the term 'slice thickness'. On the one hand, narrow collimation improves z-axis spatial resolution and decreases artefacts; however, a much larger number of narrow slices is required to cover a given anatomical area. Such coverage of the lung is impossible in one breath-hold by single-slice CT but has become feasible with the introduction of multrow detector arrays (MDCT). On the other hand, narrow collimation increases image noise; therefore an increase in kilovoltage peak and/or current-time product (in order to obtain a sufficient number of photons) may be required for compensation, which in turn increases radiation dose to the patient.

Current-time product (milliamperes x seconds): The tube current (milliamperes) represents the electron flux from the cathode to the anode of the X-ray tube and ultimately controls the number of photons generated. The tube current is an important determinant of image quality. Scan time (seconds) represents the time interval required for tube rotation during which the patient is being irradiated, also affecting the number of photons generated; the subsecond scan time that can be achieved by the newer scanners is important in order to minimize heart and/or breathing motion artefacts. The tube current-time product proportionally affects the radiation dose administered to the patient. By using the dose modulation function, the computer samples patient thickness along the z-axis and adjusts the radiation dose accordingly. However, operators should be aware that the time-current product is usually adjusted automatically according to the pitch in order to improve resolution; therefore, low current-time product selection may not translate to the expected dose reduction.

Detectors: Rows of radiation detectors (detector array), which vary in number from 1 (single detector) to tens or hundreds of rows (multidetector, i.e. 16; 64; 128; 256- or 320-MDCT).

Field of view: The field within the gantry opening from which scan data are generated. The field of view should closely approximate the largest cross-sectional area to be scanned. Spatial resolution is improved by using a smaller field of view because as it decreases, the pixel size also decreases. An inappropriately large field of view results in wasted matrix space, loss of resolution and increased partial volume averaging.

Kilovoltage peak: Measure of the energy of the X-ray beam generated by the CT scanner tube (photon beam energy). Kilovoltage peak is selected by the operator; it is influenced by the filtration used for the scan, and it directly affects the radiation dose administered to the patient. In paediatric patients, kilovoltage peak should be adjusted according to the child's weight in order to minimize the radiation dose without compromising diagnostic image quality.

Matrix: The field of view from a cross-sectional (2-dimensional) image is usually displayed upon a digital matrix of 512 x 512 pixels.

Misregistration: Failure to image portions of the lung due to differences in respiratory excursion when repeated breath-holds are required for total lung volume acquisition.

Partial volume averaging: The term refers to the inaccurate representation of scanned detail (e.g. airway wall thickness and lumen area) resulting from the inclusion of elements of different densities (e.g. airway wall and intraluminal air) into a single voxel. In such a case, the voxel's grey scale value reflects the mean weighted average of the different tissue densities. Partial volume averaging leads to overestimation of airway wall thickness and underestimation of airway lumen diameter; it increases as the angle that the airway crosses the scanned plane increases; this phenomenon becomes worse in the case of airways that run parallel to the scanned plane because then the probability of a voxel to contain a mixture of airway wall and air is further increased.

Pitch: The distance in millimetres that the examination table travels during a single revolution of the X-ray tube in helical CT. When this distance is divided by the collimation thickness (in millimetres) the outcome is termed pitch ratio, which is usually referred to simply as pitch, and represents an important technical parameter that is selected (along with kilovoltage peak, current-time product, collimation and anatomical coverage) prior to the initiation of scanning. A lower pitch ratio provides a higher z-axis resolution and fewer artefacts. In single-detector CT scanners, the higher the pitch ratio, the lower the radiation dose due to the decrease in duration of exposure of the patient. However, this is not the case in MDCT, where the concept of pitch ratio is complex and is determined by beam collimation (a combination of all detector thicknesses) and table speed but is independent of gantry rotation time.

Pixel: Picture element, i.e. the voxel (square) surface that appears on the screen.

Postprocessing: Application of image reformattting techniques onto the raw CT data. These techniques include MPR (sagittal, coronal, oblique and curved), MIPVR, SSD, external VR and VB.

Reconstruction interval: Image reconstruction is the conversion of raw data to an axial image (via complex mathematical algorithms). However, it is often loosely used in the context of the various reformattting or 3-dimensional rendering techniques (e.g. MPR, MIPVR, external VR and VB). The reconstruction interval is derived by dividing the pitch by the number of reconstructed images per tube revolution; the wider the reconstruction interval, the fewer the reconstructed images. The reconstruction interval is an important independent variable of a CT scan examination. Although it is selected prior to scanning, it can be manipulated retrospectively, i.e. during postprocessing. Reduction of the reconstruction interval results in improved spatial resolution along the z-axis. In addition, overlapping ±50% of the reconstructed images results in reduced partial volume averaging and therefore improved density and volume measurement of small lesions as compared to contiguous slicing. Such postprocessing of scan data is accomplished without further irradiation to the patient.

Volumetric data: In helical CT, the spiral movement of the beam in reference to the patient's longitudinal axis (2-axis) allows
the result of the different ways that voxels are selected, and their relative contribution is weighted.

**Voxel Volume element**, i.e. the elemental oblong (ideally cube; isotropic imaging) that constitutes along with a multitude of other such cubes the irradiated (in MRI) slice of body tissues. In essence, a voxel is the 3-dimensional equivalent of a pixel that combines the pixel area (x- and y-axis) with the tomogram slice thickness (z-axis).

Terms such as MPR, MPVR, SSD, (external) VR and VB that are explained in the text are not included in the glossary.

### References


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