CT techniques for imaging the lung: recommendations for multislice and single slice computed tomography

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Abstract
The introduction of multislice computed tomography (MSCT) has provided the thoracic radiologist with a powerful tool with which to image the lungs. Enthusiasm for new protocols should be tempered with concerns over the potential increase in radiation dose, and before older protocols are abandoned there should be good evidence that newer protocols are objectively superior. Ultimately, the best protocol is one that provides the most relevant clinical information at the lowest dose possible.

Keywords: Multislice computed tomography; Single slice computed tomography; Lung; Protocols

1. Introduction
The main developments in computed tomography (CT) in thoracic imaging have been the introduction of HRCT, spiral/volumetric CT and more recently, multislice CT (MSCT). The introduction of each technique has brought different opportunities but also exposed some limitations. Undoubtedly, the most exciting development in CT technology has been the MSCT. MSCT permits shorter acquisition times, greater coverage and image resolution, and also provides a substrate to better exploit the potential of currently available three-dimensional (3D) techniques. However, the substantial increase in the number of images generated by certain protocols will continue to challenge both radiologists and those involved with image storage. The advent of MSCT technology has led to increasing choice in the selection of parameters for the examination of the lungs. Some areas such as the investigation of suspected pulmonary embolism have received considerable attention and in these situations there is good evidence to support the CT protocols that are currently used. However, in many other situations standard protocols do not yet exist. It is the aim of this article to review the literature for support, if not hard evidence, for specific CT lung protocols. Commonly encountered clinical conditions/situations are dealt with individually and each section starts with a summary of typical protocols (for single and four-channel multislice CT) described in the literature; additional refinements to the basic protocol are discussed separately in full. Two definitions of pitch are used with multislice CT, depending on whether a section, or the total collimation of the detector array is chosen as a reference [1]. In this review, the latter definition is used (table increment per 360° rotation divided by the total beam width) as this definition is applicable to both single and multislice CT systems. It also should be emphasised that protocols for MSCT are scanner-specific and therefore the type of scanner used is indicated where appropriate.

2. Diffuse infiltrative lung disease

2.1. Recommendations
Currently, it is not clear from the published literature what MSCT protocols are being used in everyday practice to evaluate diffuse lung disease. Protocols that have been used in recent studies are outlined below.
Technique [reference] | kV/mAs | Detector collimation (mm) | Section thickness (mm) | Reconstruction interval (mm) | Pitch | IV contrast
--- | --- | --- | --- | --- | --- | ---
MSCT a [2] | 40/140 | 4 × 1 | 1.25 | 1.25 mm sections at 10 mm increments and 5 mm contiguous sections | 1.5, scan time: 0.75 s/rotation | N/A
MSCT a [3] | Not specified | 4 × 1 | 1.25 | As above | 2, scan time: 0.5 s/rotation | N/A
Single slice CT (SSCT) [4,5] | 120–140/280–340 | 1 | 10 | N/A

Schoepf et al. [2], Mastora et al. [3], Mayo et al. [4], Murata et al. [5].

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2.2. Discussion

High resolution computed tomography plays a central role in the evaluation of interstitial lung disease with established advantages over plain chest radiography with regard to confidence and accuracy of diagnosis [6–8]. Nevertheless, what constitutes the optimal HRCT technique remains undecided. Historically, most authorities have recommended section widths of between 1 and 1.5 mm from the thoracic inlet to the lung bases, with sections spaced 10–20 mm apart and the patient breath-holding at near total lung capacity. Studies have shown that an accurate diagnosis can be achieved in patients with a wide spectrum of interstitial lung disease using a more limited technique [9,10]: with a more minimalist approach, images are typically obtained at the level of the arch, tracheal carina and 2 cm above the right hemidiaphragm. In reality however, even experienced radiologists need the reassurance that confirmatory or ancillary features are not being missed by keeping the interspace distance to less than 2 cm.

The patient with suspected combined focal and diffuse lung disease (e.g. the familiar scrambled questions on a request form: “haemoptysis, short of breath? nodule on CXR”) formerly posed a problem, as both contiguous volumetric CT as well as HRCT was required. Multislice CT offers the convenience of a single protocol for the evaluation of these patients. Schoepf et al. [2] acquired scans with 1 mm collimation with multislice CT and reconstructed 5 mm contiguous and 1.25 mm high-resolution CT sections from the original data. Image quality (assessed subjectively) of the 5 mm ‘fused’ images was significantly superior to the 5 mm single slice CT images, and the 1.25 mm images were of similar quality to conventional HRCT (1 mm sections acquired at 10 mm increments) using single detector CT. Mastora et al. [3] used a similar protocol for 86 patients being evaluated for diffuse lung disease. They found that the contiguous 5 mm thick reconstructed sections provided additional diagnostic information in 13% of cases, most often by detecting solitary lung nodules that were not evident on the HRCT study. For the occasional patient in whom such a comprehensive examination is required, this may be an appropriate and useful technique (Fig. 1). However, for the majority of patients being evaluated for suspected interstitial lung disease, conventional HRCT would still appear to be the most appropriate examination. An HRCT examination usually yields 30 images; a protocol involving the reconstruction of 5 mm contiguous sections and 1.25 mm sections at 10 mm increments (from a volumetric set acquired with 1 mm detector collimation) would yield approximately 90 images. In an attempt to reduce the number of images that need to be interrogated using this protocol, Remy-Jardin et al. [11] evaluated the diagnostic accuracy of coronal thin sections as an alternative to transverse HRCT scans. Reconstructions in the coronal plane result in fewer images (owing to the overall conformation of the thorax) and diagnostic accuracy was as precise when compared with transverse HRCT. Nevertheless, protocols that involve scanning the entire chest with 1 mm collimation are considerably more radiation intensive than a HRCT examination and the tendency to replace HRCT with a volumetric protocol should be resisted. The issue of dose with respect to MSCT is an important one. Volumetric imaging of the chest with 1 mm collimation (performed on a MSCT Somatom Plus 4 Volume Zoom scanner; Siemens, Erlangen, Germany) produces an effective dose of between 7.5 and 7.8 mSv even when a low 70 mAs is used [12]. This is considerably higher than the effective dose of a conventional (1.5 mm at 10 mm intervals) HRCT which is approximately 0.98 mSv (140 kVp and 175 mAs).

2.3. Technique refinements

2.3.1. Prone scans

Interspaced high-resolution CT sections in the supine position are usually sufficient for the diagnosis of diffuse lung disease. Additional scans obtained with the patient prone are occasionally necessary to detect or exclude subtle disease
Fig. 1. An example of a patient with known emphysema presenting with a cough and an incidental nodule at the right apex on chest radiography. Images were acquired using MSCT (4 mm x 1 mm detectors) with reconstructions at (a, b) 3/3 mm and (c) 1.25/10 mm. The 3 mm sections demonstrated a calcified nodule at the right apex (a) and revealed several smaller nodules (b) (arrowheads) not demonstrated on the interspaced 1.25 mm sections. However, thin sections showed mild cylindrical bronchiectasis within the lingula and left lower lobe.
in the posterior parts of the lung. Many centres only obtain prone scans when normal physiologic dependent opacification needs to be differentiated from a true pathologic abnormality [13], but this requires either close monitoring of the scans (not always practical) or recalling patients for additional scans.

Volpe et al. [14] found that prone scans were indicated when chest radiographs were normal, questionably abnormal or showed minimal abnormality. In patients with an obvious diffuse abnormality on chest radiography, supine HRCT was diagnostic in 44/46 (96%) and prone scans were only helpful in two cases. As chest radiographs are frequently reviewed prior to HRCT, patients in whom prone scanning is likely to be of benefit can be selected. The exception to this is in the investigation of patients with asbestos exposure and suspected (but not clinically obvious) asbestosis, where routine prone scanning is probably indicated (Fig. 2).

This disease has a typically basal distribution and early lung fibrosis may be missed without prone scans [15].

2.3.2. ECG gating
Some scanners are capable of prospective ECG-gating. Schoepf et al. [16] subjectively assessed image quality, diagnostic value and the presence of respiratory and cardiac motion artefacts on ECG-gated versus non-ECG-gated HRCT sections. ECG gating improved image quality and reduced cardiac artefacts (Fig. 3). ECG-gating has become routine in many institutions including our own. Nevertheless, it has not yet been determined whether ECG-gating actually improves the diagnostic accuracy of HRCT, but theoretically at least, it should be easier to detect subtle parenchymal and airway abnormalities on images with less motion artefact.

2.3.3. Low dose HRCT
To counteract the noise inherent in thin sections, high exposure factors (120–140 kVp and 240–300 mA) were originally recommended for HRCT but lower dose techniques have since been investigated. Lee et al. [9] compared low dose (80 mA s) and conventional dose (340 mA s) HRCT using single slice CT and found no difference in diagnostic accuracy in 50 patients with chronic diffuse infiltrative lung disease. However, Zwirewich et al. [17] comparing HRCT images acquired at 40 and 400 mA s found that although the low dose technique provided satisfactory visualization of the lung parenchyma in the majority of cases, it failed

Fig. 2. Patient with known asbestos exposure and suspected interstitial fibrosis. (a) HRCT acquired in the supine position. Fine subpleural line (arrows) and increased subpleural density particularly in the right lower lobe. Elsewhere there are changes of centrilobular emphysema. (b) HRCT acquired in the prone position. There is a persistent subpleural fine reticular pattern (arrows) representing early asbestosis.
Fig. 3. The effects of ECG-gating on HRCT image quality. (a) Non-ECG-gated and (b) ECG-gated thin-section HRCT in a 72-year-old man. The absence of ECG-gating may cause cardiac motion to distort pulmonary vessels in the lingula. The adjacent transradiancy (arrow) may be misinterpreted as a bronchiectatic airway[16]. The non-ECG gated image also has a blurred left ventricular border.

in some cases to demonstrate subtle ground glass opacity (20%) and emphysema (11%). A compromise might be to use 80–90 mA s for the initial HRCT and to use the lower dose (40–50 mA s) for subsequent follow up.

The mA s used in high-resolution protocols with MSCT varies with reported values ranging from 70[12] to 140 mA s [2]. At our institution, 90 mA s is used and this is reduced to between 50 and 70 mA s in our low dose protocol for young female patients (Fig. 4).

It has been established that increasing pitch proportionately reduces patient radiation dose on a single slice CT if all other parameters are kept constant, though this relationship does not apply to all multislice systems. Mahesh et al.[1] showed that on a Somatom Plus 4 Volume Zoom scanner (Siemens, Erlanger, Germany) the measured radiation dose was identical for all pitch selections. This CT system automatically produces a proportionate increase in tube current when the pitch selection is increased, presumably to maintain a similar level of noise. Caution should be exercised when extrapolating dose reduction strategies from single slice to multislice CT systems.

2.3.4. Maximum intensity projections

One of the early reported limitations of HRCT for the assessment of diffuse infiltrative lung disease was the perception that micronodules were more reliably distinguished from blood vessels on standard collimation sections [6,18], although the problem of making this distinction has probably been overstated in the past. Maximum intensity projection (MaxIP) images have been advocated as an additional tool in the evaluation of diffuse infiltrative lung diseases. Remy-Jardin et al.[19] compared conventional CT (1 mm and 8 mm collimation) with MaxIP images (sliding slabs of 3, 5 and 8 mm thickness generated from volumetric CT performed at the level of the region of interest (ROI)) in patients with a suspicion of micronodular infiltration. MIP images showed micronodular disease involving less than 25% of the lung when conventional CT was inconclusive and better defined the profusion and distribution of micronodules when they were identified on conventional images. However, in patients with normal 1 and 8 mm images, sliding-thin-slab MIPs did not reveal additional lung abnormalities. Bhalla et al.[20] used MaxIP reconstruction in 20 patients with known diffuse lung dis-
Fig. 4. HRCT of patient being evaluated for suspected interstitial lung disease. (a) HRCT image obtained with 90 mA s demonstrating posterior emphysema and subtle areas of ground glass (arrowhead) in the right upper lobe anteriorly. (b) HRCT image obtained with 40 mA s show no appreciable change in diagnostic quality, but there is an almost imperceptible increase in image noise.
ease and found two main advantages over thin-section CT: more precise identification of nodules and more accurate characterization of nodule distribution (perivascular versus centrilobular).

3. Staging of lung cancer

3.1. Recommendations

<table>
<thead>
<tr>
<th>Technique [reference]</th>
<th>kV/mA s</th>
<th>Detector collimation (mm)</th>
<th>Section thickness (mm)</th>
<th>Reconstruction interval (mm)</th>
<th>Pitch</th>
<th>IV contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSCT&lt;sup&gt;a&lt;/sup&gt; (protocol at our institution)</td>
<td>120/90 (chest)</td>
<td>4 × 2.5</td>
<td>3 and 5</td>
<td>3 and 5</td>
<td>1.5</td>
<td>90 mls 240 mg/ml</td>
</tr>
<tr>
<td></td>
<td>120/165 (abdo)</td>
<td>4 × 2.5</td>
<td>3 and 5</td>
<td>3 and 5</td>
<td>1.5</td>
<td>3 mls/s</td>
</tr>
<tr>
<td>SSCT [21–23]</td>
<td>140/140–200</td>
<td>4 × 2.5</td>
<td>3 and 5</td>
<td>3 and 5</td>
<td>1.5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Patz et al. [21], ATS/ERS guidelines [22], Zeman et al. [23].
<sup>a</sup> Somatom Volume Zoom; Siemens Erlangen, Germany.

3.2. Discussion

Computed Tomography is the standard imaging modality used to stage lung cancer, but a survey of 520 radiology departments in the U.S. revealed that there is no consistency in the CT protocol used, and the optimal and most cost effective imaging parameters have yet to be established [24]. Opinion remains divided over the use of intravenous (IV) contrast in this situation. Recent guidelines published by Silvestri et al. suggest that IV contrast is unnecessary for staging chest CT scans [25]. It is acknowledged that IV contrast can be helpful in distinguishing vascular structures from lymph nodes, but the limitations of CT as a tool for staging the mediastinum are well recognized and in practice, mediastinoscopy and tissue sampling are usually required. There is further support for abandoning the routine use of IV contrast from a study by Patz et al. [26] who showed that in only 2/84 patients was there any disagreement in nodal stage between non-enhanced and contrast-enhanced thoracic CT. Of note, histology from these 2 cases showed that contrast-enhanced CT understaged 1 case and overstaged the other.

The ATS/ERS statement [22] on the pre-treatment evaluation of non-small-cell lung cancer recommends contrast only for central tumours with probable mediastinal invasion, or if there is difficulty differentiating mediastinal vessels from enlarged lymph nodes. In practice, it appears that intravenous contrast is widely used in CT lung cancer examinations (86% of the respondents in the survey by Chen et al) [24]. It is anticipated that multislice CT using protocols with a detector collimation of 1 or 1.25 mm will substantially improve the evaluation of chest wall and mediastinal invasion although this has yet to be quantified in terms of sensitivity and specificity [27].

Despite some evidence to suggest that a routine search for extrathoracic metastases may not be necessary in asymptomatic patients with stage I or II disease [28,25], contrast enhanced scanning of the adrenals, liver and brain is commonly performed [24]. A typical protocol is to scan the thorax with intravenous contrast using 5 mm-section collimation, acquiring the images after a 25 s delay; the acquisition of abdominal images is started at 60 s for optimal liver enhancement. Unfortunately this phase of enhancement does not allow distinction between adrenal metastases and adenomas, and patients in whom adrenal masses are found will need either delayed contrast enhanced CT [29], MRI [30] or FDG-PET [31] for further characterisation.

4. Low dose screening for NSCLC

Investigators have recently used low dose computed tomography for screening asymptomatic high-risk individuals for lung cancer. Authors of these studies [32,33–35] have suggested that screening with CT can depict lung cancers that are of a smaller size (<2 cm in diameter) and earlier stage (85–93% at stage I) than those observed at chest radiography. Protocols used in some of the larger lung cancer screening trials and those recommended in a consensus statement of the Society of Thoracic Radiology are outlined below.

<table>
<thead>
<tr>
<th>Technique [ref.]</th>
<th>kV/mAs</th>
<th>Detector collimation (mm)</th>
<th>Section thickness (mm)</th>
<th>Reconstruction interval (mm)</th>
<th>Pitch</th>
<th>IV contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSCT&lt;sup&gt;b&lt;/sup&gt; [36]</td>
<td>120–140/20–60</td>
<td>4 × 1 or 4 × 2.5</td>
<td>1.25–3</td>
<td>1.25–3</td>
<td>1.5–3.75</td>
<td>N/A</td>
</tr>
<tr>
<td>MSCT&lt;sup&gt;b&lt;/sup&gt; [37]</td>
<td>120/40</td>
<td>4 × 3.75</td>
<td>2.5–5</td>
<td>3.75</td>
<td>1.5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Aberle et al. [36], Swensen et al. [37], Henschke et al. [32], Kaneko [33], Diedrich et al. [34].
<sup>a</sup> Not specified.
<sup>b</sup> LightSpeed Model QX/I; GE Medical Systems, Milwaukee, WI.
4.1. Recommendations

4.2. Discussion

Itoh et al. [38] have shown that images obtained at an effective tube current of 20 mA s are of equal diagnostic utility to those obtained at 50 mA s for the detection of 6 mm simulated nodules. Schoepf et al. [39] recommend a protocol that comprises acquisition of the entire chest using 1 mm collimation (MSCT) at 120 kVp and 10–40 mA s depending on the body type of the screened individual. At a tube current of 10 mA s, the effective radiation dose is 0.27 mSv which is approximately equivalent to two conventional chest radiographs. These studies have encouraged the acceptance of low dose CT as a screening tool. For most screening chest studies, the 1 mm images can be fused into 5–10 mm maximal intensity projections to limit the number of individual axial images that need to be interrogated. If detailed scrutiny of a lung nodule is required, 1 mm sections may be used [39].

The possibility that lung cancers may be missed by low dose CT has recently been raised by Li et al. [40] who compared the clinical, histopathological and imaging features of lung cancers missed at CT screening in a general population (which included non-smokers and women). Of 83 primary lung cancers (histopathologically confirmed) that were found during an annual low dose screening program, 32 had previously been missed on 39 CT scans. In 23 cases, this was due to detection error and in 16, due to interpretative error. In the detection error group, lesions were most frequently missed in non-smoking women, and nearly all these lesions were well-differentiated adenocarcinomas. Of the 23 cancers missed owing to detection error, the lesions generally appeared as faint nodules of ground glass density (91%). Most of these (83%) lesions were closely related to normal structures and were considered to be pulmonary vessels, or were obscured by adjacent hilar structures. Cancers missed owing to interpretative error either mimicked benign disease or were present against a background of other lung disease (for example emphysema, tuberculosis and lung fibrosis). While radiologists can be made aware of these potential pitfalls, ultimately, the interpretation made by human observers is limited by the information conveyed on the images. Attempts have been made to develop automated computerized systems to improve detection of lung nodules. Armato et al. [41] have shown that with an automated lung nodule detection method, 32 of 38 (84%) missed cancers in a database of low dose CT scans were subsequently correctly detected. An understanding of the radiological and histopathological characteristics of missed cancers and the incorporation of computerized detection methods has the potential to reduce the number of lung cancers missed by radiologists on CT images.

5. Suspected pulmonary embolism

5.1. Recommendations

5.2. Contrast-enhancement protocol

Options for scan delay:
1. Automated triggering – preset threshold in region of interest centred on pulmonary artery.
2. Test bolus of contrast and evaluation of resulting time-density curve.
3. Operator-selected “best guess” delay (usually 10–20 s).

Between 120 and 140 mls of 24–30% contrast is generally used and this is injected at a rate of 3–5 mls/s. The use of higher concentrations of contrast can result in streak artefacts originating from the superior vena cava, which can degrade image quality in the adjacent right pulmonary artery. Most scanners come equipped with programs that allow continuous monitoring of the attenuation within a region of interest. When a set level of contrast enhancement (increase in attenuation of usually >100 HU) is reached within the pulmonary artery, the diagnostic scan is automatically initiated. There have been proponents of determining the scan delay in each individual patient by using a test bolus of contrast and a time-density curve, [45] but this is at the cost of increased radiation dose and contrast. In a study comparing image quality (subjective assessment) of images obtained by individual contrast timing with a fixed scan delay of 20 s, no important differences were observed [46]. Recent studies have used a fixed delay ranging from 12 to 20 s [42,47]. Review of the literature suggests that standard
settings (window width 350–500 HU and window centre 50–80 HU) are most frequently employed in CT pulmonary angiogram studies, although the use of wider window settings (600–700 HU) is useful in identifying smaller emboli that may be obscured by high-density contrast material (Fig. 5).

5.3. Discussion

CT pulmonary angiography (CTPA) is now an established technique for investigating patients with suspected pulmonary embolism and its accuracy has steadily improved as advances have been made in CT technology. Initially performed with 5 mm collimation [48,49], CTPA provided accurate evaluation of central pulmonary arteries, but the detection of smaller filling defects was limited because of the effect of partial volume on small-sized vessels. A sizeable proportion (at least 10%) of segmental vessels are not adequately demonstrated with 5 mm collimation [50].

Subsecond gantry rotation was a significant breakthrough which enabled longer z-axis coverage for an exposure of equivalent duration, and more relevant to CTPA, an equivalent z-axis coverage with thinner (2–3 mm) collimation. The use of thinner collimation resulted in marked improvement in the demonstration of the segmental and subsegmental arteries, but limitations remained with respect to the smaller subsegmental arteries even with 2 mm collimation [44]. This inability to depict subsegmental clot has been a source of controversy, despite uncertainty over the clinical significance of small peripheral emboli. The significance of the missed small PE and the problem of whether patients with a negative CTPA can be safely left without long-term anticoagulation has been intensely investigated. Several recent studies [51–53] have looked at the frequency of venous thromboembolic episodes in a three month period subsequent to a negative CTPA and concluded that patients with a clinical suspicion of acute PE, stable vital signs and a negative CTPA could be safely left untreated. Of note, between 3 and 5 mm collimation was used in the studies. The value of a negative CTPA has, however, not been evaluated exclusively in patients with poor cardiopulmonary reserve where a small additional PE may be fatal. As long as the accuracy of CT for the detection of peripheral emboli is questioned, efforts to improve the quality of CT pulmonary angiography are likely to continue.

Several investigators have evaluated multislice CT [42,43,47]. The use of 1 mm detector collimation (1.25 section width) allows an increase in the rate of detection of subsegmental emboli and the shorter duration of data acquisition with MSCT results in optimal image quality even with a dyspnoeic patient.

Meticulous technique is needed in CTPA as the possibility of producing suboptimal or entirely non-diagnostic studies is very real. Particular attention should be paid to concentration of contrast, rate of injection, collimation and selection of the scan delay. When arterial opacification of part of the

Fig. 5. CTPA of a 45-year-old woman with symptoms suggestive of pulmonary embolism. (a) Representative image (1.25 mm section thickness) viewed at window width 400 HU and level 40 HU showing possible filling defects within segmental arteries of the left upper lobe (arrowheads). (b) Image viewed at window width 1000 HU and level 100 HU as described by Brink et al. [99]. The filling defects are better appreciated with a wider window setting.
pulmonary arterial tree is suboptimal, a second acquisition with more limited anatomical coverage can be undertaken after modification of the start delay.

5.4. Technique refinements

5.4.1. Multiplanar reconstructions

Multiplanar and curved multiplanar (MPR and CMPR) are two-dimensional (2D) techniques that provide alternative viewing perspectives usually with conventional window settings. Remy-Jardin et al. [54] demonstrated that combining both transverse and 2D reformatted images improved the accuracy of CT in depicting pulmonary embolism. The main indications for multiplanar 2D reformatted images are interpretative difficulties on transverse CT sections either due to partial volume averaging or the inability to differentiate periarterial from endoluminal abnormalities.

5.4.2. "Paddle-wheel display"

Simon et al. [55] have recently described a novel method of reconstructing images from an axial data set (acquired with MSCT using 2.5 mm collimation with a 1.25 mm reconstruction interval) called a “paddle-wheel” display which may be used to evaluate the pulmonary arteries. Each planar slab (of 5 mm thickness) passes through a central horizontal axis between the two lungs and hilum and consequently, the large hilar structures of interest appear on every image. Unlike the standard sagittal and coronal reconstructions that display only short segments of vessels and airways, the paddle-wheel reformations display branching structures in continuity from hilum to pleura. In a study by Chiang et al, the 5 mm paddle-wheel images had similar detection rates of pulmonary embolism when compared to conventional 2.5 mm axial images [56]. Importantly, the paddle-wheel technique reduces the number of images for review compared with standard axial images. Other advantages are an increase in reader confidence (vascular continuity is demonstrated to a greater degree) and a more accurate assessment of clot burden (the paddle-wheel images often display the cranio-caudal extent of clot on a single image). Large-scale studies comparing the paddle-wheel display method with more traditional imaging methods in the evaluation of pulmonary embolism are awaited. Currently, the authors suggest that the paddle-wheel method is used as a complement to, rather than a replacement for axial images in the diagnosis of pulmonary embolism [56].

6. Imaging of the patient with obstructive airways disease

6.1. Bronchiectasis

6.1.1. Recommendations

The standard HRCT protocol (1–1.5 mm collimation at 10 mm intervals in a supine position) has, over the years proved reliable (sensitivity of 96% and specificity of 93% using bronchography as the reference standard) for the diagnosis of bronchiectasis, with satisfactory interobserver variation [61]. Although there is no single optimal window for the depiction of abnormalities of the bronchi and lung parenchyma, most studies use a level of −500 to −700 HU with a window width of 1000–1500 HU [59,60]. A window width less than 1000 HU causes a spurious appearance of bronchial wall thickening [62].

Lack of tapering of the bronchial lumen has been suggested as the most reliable sign of cylindrical bronchiectasis [60], but this is difficult to perceive for vertically oriented bronchi on interspaced trans-axial thin-section CT. Several reports have suggested a role for volumetric data acquisition in the investigation of suspected bronchiectasis [63,64]. Lucidarme et al. [63] compared HRCT (1.5 mm sections at 10 mm intervals) with helical CT using 3 mm collimation, pitch of 1.6 and 2 mm reconstruction intervals. Perhaps unsurprisingly, the number of patients and segments considered to be affected by bronchiectasis were higher on the volumetrically acquired examination. Additionally, interobserver agreement was better with volumetric scans for the identification of segments that were positive for bronchiectasis, the extent of bronchiectasis in a given lobe and the distribution of disease in a given segment. However, the increased radiation dose required for volumetric acquisitions has so far prevented it from replacing conventional HRCT for the diagnosis of bronchiectasis.

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The role of MSCT in the diagnosis of bronchiectasis has recently been evaluated. Remy-Jardin et al. [57] demonstrated comparable accuracy of 3 and 1.25 mm images (reconstructed from a volumetric data set acquired with 1 mm detector collimation) in the detection and characterization of bronchiectasis. These results suggest a potential useful-
ness of 3 mm thick images generated from 4 mm × 2.5 mm acquisitions in the screening of bronchiectasis. This would allow a 20% reduction in radiation dose compared to 4 mm × 1 mm acquisitions. However not unexpectedly, the 3 mm images led to underrecognition of mild cylindrical bronchiectasis at the subsegmental level and consequently the authors recommend this section thickness for screening and the follow-up of bronchiectasis, with high-resolution CT remaining the imaging standard of reference prior to surgery for bronchiectasis.

7. Imaging of the patient with suspected small airways disease

7.1. Recommendations

There have been no studies evaluating MSCT in suspected small airways disease. The protocol used at our institution is outlined below.

<table>
<thead>
<tr>
<th>Technique [ref.]</th>
<th>kV/mAs</th>
<th>Detector collimation (mm)</th>
<th>Section thickness (mm)</th>
<th>Reconstruction interval (mm)</th>
<th>Pitch</th>
<th>IV contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSCT* (protocol at our institution)</td>
<td>120/90</td>
<td>2 × 0.5</td>
<td>1</td>
<td>10</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>SSCT [65,66]</td>
<td>120–140/200–350</td>
<td>1</td>
<td>10</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hansell et al. [65], Stern et al. [66].*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Somatom Volume Zoom unit (Siemens, Forchheim, Germany).

7.2. Discussion

HRCT is currently regarded as the imaging method of choice for the detection of small airways disease. Standard HRCT technique is satisfactory for demonstrating constrictive bronchiolitis and diffuse panbronchiolitis. The former requires attention to appropriate contrast resolution to demonstrate sometimes subtle regional attenuation differences caused by air-trapping (mosaic attenuation pattern) The latter is more dependent on adequate spatial resolution to depict the small branching structures that characterise panbronchiolitis (tree-in-bud pattern) [67]. A suggested HRCT protocol is 1–1.5 mm collimation sections every 10 mm from apices to costophrenic angles with the patient breath-holding at full inspiration [68,69]. Care should be exercised when choosing window widths as minor differences in lung attenuation may only be visible when narrow (<1000) window widths are used [66].

7.3. Technique refinements

7.3.1. Expiratory scans: end-expiratory

The necessity of expiratory CT sections is somewhat controversial with conflicting results from several studies [75–77]. In a study by Leung et al. [75], air-trapping on expiratory CT was the most sensitive sign (sensitivity 91%) of constrictive bronchiolitis in 11 patients with transbronchial biopsy confirmation. In a recent prospective study that included 111 expiratory scans in 38 heart-lung transplant recipients, the presence of air-trapping occupying more than 32% of lung parenchyma had a sensitivity of 83% and a specificity of 89% for the diagnosis of bronchiolitis syndrome (BOS), and in some patients this preceded the spirometric criteria for BOS [77]. However, Lee et al. [76] have questioned the sensitivity and specificity of expiratory CT. In their study, the air-trapping score in patients with biopsy proven bronchiolitis obliterans was not significantly different to biopsy-negative patients with air-flow limitation.

Nevertheless, expiratory thin-section CT may depict air-trapping in some patients with constrictive bronchiolitis who have false-negative transbronchial biopsy results owing to the patchy distribution of this disease; furthermore expiratory scans obtained prior to biopsy may allow the biopsy to be targeted to the most abnormal lung regions. It is likely that expiratory CT will at least for now continue to play a role in the evaluation of complications related to, and the surveillance of, graft function in lung transplants.
7.3.2. Dynamic expiratory computed tomography

Dynamic studies where sections are obtained in rapid succession at a given level during forced expiration may improve the conspicuity and apparent extent of air-trapping [78]. A recent study that compared low dose (40 mA) dynamic expiratory CT with the more conventional end-expiratory CT technique demonstrated that the density changes were significantly greater with the dynamic technique [79]. The authors routinely use dynamic expiratory low dose thin-section CT in evaluating lung transplant patients in conjunction with scans obtained at full inspiration. Each dynamic sequence (acquired at the level of the arch, carina and 2 cm above the right hemidiaphragm) is obtained as a 6 s cine-acquisition without table incrementation, and reconstructed at 1 s intervals. Window level/width settings of \(-700/1000\) HU are recommended.

7.3.3. Minimum intensity projections (MinIP)

The contrast differences between normal and low attenuation lung parenchyma in patients with constrictive obliterator bronchiolitis may be extremely subtle on inspiratory HRCT images and image processing techniques such as minimum intensity projections (MinIPs) can improve the conspicuity of subtle changes in density of the lung parenchyma [80,20]. In a study by Fotheringham et al. [80], MinIP images showed good correlation with pulmonary function tests and had the lowest observer variation when compared with inspiratory and expiratory images. The acquisition of thin contiguous images (1–1.5 mm) is a pre-requisite for producing MinIP images and for centres without MSCT, the data set can be acquired through areas thought to be indeterminate on the initial HRCT examination [20]. Window settings for the interpretation of MinIP slabs have not been standardized; window widths of 350–500 HU and a window level of \(-750\) to \(-900\) HU have been used in previous studies.

8. Focal pulmonary disease

The investigation of the solitary pulmonary nodule will not be reviewed in any detail given the comprehensive reviews which address this subject [81,82].

8.1. Recommendations

<table>
<thead>
<tr>
<th>Technique [ref.]</th>
<th>kV/mAs</th>
<th>Detector collimation (mm)</th>
<th>Section thickness (mm)</th>
<th>Reconstruction interval (mm)</th>
<th>Pitch</th>
<th>IV contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSCT* (protocol at our institution)</td>
<td>120–140/90–120</td>
<td>4 × 2.5</td>
<td>3 or 5</td>
<td>3 or 5</td>
<td>1.5</td>
<td>Dependant on nature of suspected abnormality</td>
</tr>
<tr>
<td>SSCT [83]</td>
<td>140/140–280</td>
<td>5 or 7–8</td>
<td>5 or 7–8</td>
<td>1.6 or 1.5</td>
<td>As above</td>
<td></td>
</tr>
</tbody>
</table>

Leung et al. [83].

* Somatom Volume Zoom unit (Siemens, Erlangen, Germany).

8.2. Discussion

The type of CT protocol employed to investigate a suspected focal pulmonary radiographic abnormality depends to some extent on the nature of the abnormality and the clinical setting. In most cases, the entire lung is usually imaged, with or without intravenous contrast, to exclude other lung abnormalities and to assess the hilar and mediastinal structures [84]. Variables such as section thickness, table speed and the reconstruction interval should be tailored to the individual case, and with single slice CT, if review of the examination demonstrates pathology requiring further characterization then a limited volumetric acquisition through the area of interest may be acquired with thin-section (1 mm) collimation [83]. With multislice computed tomography contiguous 5 mm sections are usually adequate for a “general lung CT examination”, and if the images are acquired using 2.5 mm collimation, then retrospective reconstructions at 3 mm can be viewed for further characterization.

The frequency with which CT is now used to further evaluate a suspected focal abnormality seen on a chest radiograph has prompted efforts to investigate low dose techniques. Takahashi et al. [85] using low dose (50 mA) CT demonstrated diminished low-contrast resolution and increased noise levels when compared with standard dose (250 mA) CT, but focal pulmonary abnormalities were visualized equally well with the low dose technique, apart from subtle ground glass opacity. There was no difference for the detection mediastinal abnormalities, although only a few cases were included in this study. Wildberger et al. [86] using a MSCT (Somatom Volume Zoom; Siemens, Forchheim, Germany) have derived a mathematical relationship between X-ray attenuation and patient weight. They found that adaptation of the mAs based on the (body weight of a patient (kg) – 10), produced an examination with image quality comparable to the standard dose (120 mAs), the latter being the manufacturer’s recommendation. Such a manoeuvre resulted in approximately a 45% reduction in radiation dose. In the face of existing evidence, it is surprising that more centres have not adopted such a simple radiation reducing strategy.
9. Imaging of patient with central airway abnormalities

9.1. Recommendations

<table>
<thead>
<tr>
<th>Technique [ref.]</th>
<th>kV/mA s</th>
<th>Detector collimation (mm)</th>
<th>Section thickness (mm)</th>
<th>Reconstruction Interval (mm)</th>
<th>Pitch IV contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSCT a [87]</td>
<td>Not specified</td>
<td>4 × 2.5</td>
<td>3</td>
<td>1.25</td>
<td>1.5 N/A</td>
</tr>
<tr>
<td>MSCT b [88]</td>
<td>140/100</td>
<td>4 × 1 (2.5 mm detectors may be selected for faster coverage and less noisy images)</td>
<td>1.25</td>
<td>1</td>
<td>1.5 N/A</td>
</tr>
<tr>
<td>SSCT [89–91]</td>
<td>120–140/140–280</td>
<td>2–3</td>
<td>30–50% overlap index</td>
<td>1.5–2</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Boiselle et al. [87], Lawler et al. [88], Naidich et al. [89], Ferretti et al. [90], Grenier et al. [91].

a Light Speed QX/I; General Electric Medical Systems, Milwaukee, WI.
b Siemens Plus 4 Volume Zoom (Siemens Medical Systems, Iselin, NJ).

9.2. Discussion

The high quality volume data sets that can be rapidly acquired with current multislice CT coupled with the latest advances in volume rendering software has made routine three-dimensional airway imaging a reality. Although axial imaging currently remains the standard for evaluating the central airways, several limitations are associated with axial images: difficulty in detecting subtle airway stenoses, underestimation of the craniocaudal extent of disease, difficulty displaying the complex 3D relationships of the airways and inadequate representation of the airways that are oriented obliquely to the axial plane [89,92–94]. Two-dimensional multiplanar and three-dimensional reconstruction images have the potential to facilitate the assessment of a wide variety of airway diseases [87] (Fig. 6).

9.2.1. Multiplanar reconstructions

Quint et al. [95] evaluated CT images from 27 patients following lung transplantation using 3 mm collimation, pitch of 1, and a 1.5 mm reconstruction interval and found axial images were 91% accurate in the detection of bronchial stenoses. By comparison, viewing the axial images with multiplanar reconstructions (sagittal and coronal) improved accuracy, albeit marginally to 94%. However, observers found it easier to visualize mild stenoses (<25% narrowing) on the multiplanar images; reflecting the perceptual difficulty of accurately assessing luminal calibre on sequential axial images (Fig. 7). Multiplanar reconstructions also depict the lengths of stenotic segments more clearly due to the orientation of these images along the long axis of the airway.

9.2.2. Surface shaded display

Three-dimensional surface shaded display (3D SSD) has also been used as an additional technique to identify bronchial stenoses. This technique displays a subset of the volumetric data by including voxels in a range of attenuation values to determine surfaces. A large amount of data is lost in the final reconstruction, limiting the overall utility of the technique. Kauczor et al. [96] assessed the benefits of using 3D SSD compared with bronchoscopy in patients with suspected stenoses. Advantages of 3D SSD images included the more accurate evaluation of both the presence and the length of central stenoses as well as depicting the spatial orientation, branching angles and patency of distal air-filled bronchi; features not accessible bronchoscopically. However, two out of three segmental stenoses were missed using 3D SSD, a problem not usually encountered with the simpler multiplanar reconstruction technique.

9.2.3. Volume rendering

Improvements in the computational speed of computers have led to the replacement of shaded surface display renditions with 3D-volume rendering. Volume rendering converts the volume of information acquired by MSCT into a simulated three-dimensional form that surpasses the previous technique of surface-shaded display which is limited by threshold voxel selection. The volume-rendered 3D image is the computed sum of voxels along a ray projected through the data set in a specific orientation thus using all the MSCT data to form the final image. The volume rendering technique assigns a continuous range of values to a voxel allowing the percentage of different tissue types to be reflected in the final image while maintaining three-dimensional spatial relationships. Remy-Jardin et al. [93] compared overlapping axial CT images with volume-rendered bronchographic images for the detection of airway abnormalities and identification of lesion morphology. Findings on the volume-rendered images were concordant but added no complementary value to those on the transverse CT images in half of the cases. However, volume-rendered images provided supplemental information in a third and could correct potential interpretative errors from viewing only transverse CT images in 5%. The most recent technique to be applied to airway imaging is ‘virtual bronchoscopy’. These images are obtained using volume rendering techniques that allow internal rendering of the tracheo-bronchial tree producing appearance similar to that seen by a bronchoscopist (Fig. 8). Despite these ex-
Fig. 6. A 22-year-old patient being evaluated for stridor post-tracheostomy. (a) Axial and (b) 2D coronal reformation. The narrowing of the subglottic trachea is seen on the axial image. The coronal reformatted image enables the longitudinal extent and severity of the stenosis to be appreciated more easily on a single section.

Fig. 7. A 54-year-old woman with a tracheal carcinoid tumour. Axial CT (a) and virtual bronchoscopy simulation (b) demonstrate a lobulated soft tissue mass protruding into the lumen of the distal trachea just above the level of the carina. The VB image more clearly shows the mass extending into and narrowing the left main bronchus.

citing possibilities, virtual bronchoscopy remains just that, and despite software advances, the technique has not found widespread acceptance in airway imaging. Studies using this technique have revealed several limitations. Summers et al. [97] used virtual bronchoscopy to assess 14 patients with a variety of airway abnormalities. They found that overall, 90% of segmental bronchi that were measurable at CT could be measured at VB. However, of the total bronchi expected to be visible, only 82% could be evaluated at VB and only 76% of segmental bronchi were demonstrated compared...
with 91 and 85% respectively for multiplanar CT images. Axial CT and the ‘virtual’ images were of similar accuracy in estimating the maximal luminal diameter and cross-sectional area of the central airways. These authors used 3 mm sections, pitch of 2, a field of view of 26 cm or less and 1 mm-reconstruction intervals. Virtual bronchoscopy demonstrates stenoses of the central airways (proved with fibreoptic bronchoscopy) in most cases [90,98], but in the former study [90], all the stenoses demonstrated by VB were also shown on the axial CT images. In addition, evaluation of the length of the stenoses and surrounding tissues required simultaneous display of multiplanar reformations.

Naidich et al. [89] have suggested that endoluminal imaging may be of potential benefit in the follow up of patients with known malignant airway obstruction after laser or radiation therapy and in cases in which axial images are inconclusive regarding the presence or absence of endobronchial disease. However, this is a very specific and limited application of the technique.

The use of airway stents for benign and malignant stenotic disease provides another potential, but limited use for volume rendering techniques. As stents require frequent follow-up, 3DCT of the airway offers an easier way to monitor cases until adjustment requires direct intervention [88]. From a clinical perspective it is fair to say that for many lesions 3DCT does not have a greater sensitivity than conventional axial images, but it does confer advantage in describing spatial relationships of airway disease and importantly, communicating this to the clinicians [89].

10. Conclusion

There have been exciting advances in thoracic CT imaging, and while this has undoubtedly produced a proliferation of new protocols, these protocols should be validated against established ones. Ultimately, the ‘best’ protocol is one that makes a measurable difference to patient outcome by providing the most clinically relevant information at the lowest possible dose.

The large number of images generated by multislice CT is a major issue for workstation performance, film display and PACS archiving and ideally all images need to be reviewed in a cine-paging format at the workstation for diagnostic purposes. The hundreds of thin sections acquired using MSCT are incompatible with traditional viewing practice; thus MSCT may in the next few years force a rapid transition from two-dimensional to volumetric imaging. Although two-dimensional axial interpretation will remain fundamental in practice for some time, the concept of both volume acquisition and interpretation will undoubtedly play an increasing role.

References


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