Radiology of Bronchiectasis

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- **Key Points** (3-5 bulleted sentences indicating the main takeaways/defining elements of the article)
  - On computed tomography imaging, bronchiectasis appearances and distribution within the lung can suggest the underlying disease aetiology
  - Visual scores of bronchiectasis-related damage are limited in their ability to simultaneously consider disease extent and severity
  - Computer analysis of computed tomography imaging may be a sensitive measure of disease burden and disease progression over time
  - Magnetic resonance imaging of the lung can provide functional and structural information and has an important role in the evaluation of young patients and the early detection of lung damage

- **Synopsis:** Bronchiectasis is a radiological diagnosis made using computed tomography (CT) imaging. Whilst visual CT assessment is necessary for the diagnosis of bronchiectasis, visual assessment of disease severity and progression is challenging. Computer tools offer the potential to improve the characterisation of lung damage in patients with bronchiectasis. Newer imaging techniques such as magnetic resonance imaging with hyperpolarised gas inhalation have the potential to identify early forms of disease and are without the constraints of requiring ionising radiation exposure.

Introduction

Within the lungs, the airways run alongside the pulmonary arteries within the peribronchovascular interstitium, the connective tissue envelope that runs through the centre of the secondary pulmonary lobule. On computed tomography (CT) imaging, bronchi and pulmonary arteries can be seen to divide at regular intervals within the lobes. The bronchi divide at bifurcations or trifurcations with the parent airway dilating before separating into its daughter branches. Each airway division gives rise to a new airway generation, and the length of the airway between divisions is termed an airway segment. In health, the airways gradually taper or narrow in cross-sectional area as they travel towards the lung periphery.

Bronchiectasis represents the sequelae of damage to the airways and is most commonly characterised by the presence of abnormal airway dilatation and a loss of airway tapering. Bronchiectasis is associated with a variety of lung diseases and visual scoring systems applied to CT imaging have been used alone or in combination with clinical variables and pulmonary function tests to assess a patients disease burden. Recent advances in computer analysis may help improve the precision and sensitivity with which disease burden and disease progression are identified on CT. Accordingly, computer tools may have an important role in evaluating drug treatment response in clinical trials as well as for real-world assessments of disease behaviour.

This review will describe the imaging characteristics of bronchiectasis on CT and magnetic resonance imaging (MRI). The utility of semi-quantitative visual CT scores in disease characterisation will be discussed. We will also provide an overview of recent studies that have

deployed objective computer-based quantitative image analysis in bronchiectasis patients and describe the potential benefits and challenges related to using such tools in the coming years.

Defining Bronchiectasis on Computed Tomography

Bronchiectasis was first described in the early 19th century by Rene Laennec in patients suffering from tuberculosis[1]. The existence of bronchiectasis was determined following careful auscultation of the lungs, and corroboration of clinical findings with observations at post-mortem examination. Today the ubiquity of volumetric CT imaging has simplified the identification of abnormal airways in the lungs. Yet the definition of bronchiectasis on CT imaging is not without its controversies. For the purposes of this review only free-standing bronchiectasis, representing airway dilatation on the background of low attenuation lung will be considered. Traction bronchiectasis which results from fibrosis in the lung interstitium pulling open peripheral airways will not be considered.

Pathologically bronchiectasis has been defined as "irreversible localized or diffuse bronchial dilatation, usually resulting from chronic infection, proximal airway obstruction, or congenital bronchial abnormality"[2]. On CT, three imaging features have been used to define bronchiectasis:

1. A pulmonary arterial diameter larger than the luminal diameter of the corresponding airway
2. A lack of tapering of airways as they extend towards the lung periphery
3. Visible airways within the most peripheral 1cm of the lung

Bronchial luminal diameter larger than pulmonary artery

Assessment of the bronchus size in relation to that of the corresponding generational pulmonary artery has been an important metric with which to determine the presence of

bronchiectasis[2]. However over recent years, the potential to overestimate or even underestimate the presence of bronchiectasis using this method has become apparent. It is increasingly recognised that physiological conditions such as is seen in people living at high altitude[3] and as a consequence of normal ageing[4] can result in non-pathological airway dilatation. Spurious bronchiectasis can also be seen on CT imaging when an artery divides before its accompanying airway divides. The size of the pulmonary artery may then be compared to an airway of an earlier generational branch. This is particularly seen in the airways in the right middle and lingula lobes.

In pathological states such as smoking-related lung damage or hypoxic vasoconstriction[5] occurring in areas of chronic lung disease, the pulmonary arteries can decrease in calibre, again giving the false impression of airway dilatation[6]. In cases where the airways are genuinely abnormally dilated, a suboptimal inspiratory effort during acquisition of the CT may underestimate the presence of bronchiectasis as the airways are not fully inflated. When considering all these imaging caveats, relying on an airway being enlarged relative to the adjacent artery is no longer sufficient on its own to diagnose bronchiectasis on CT imaging.

Airways within 1 cm of the pleural surface

In healthy individuals, the walls of peripheral airways are thinner than the resolution limits of CT imaging. As a result the “small airways”, those with airway luminal diameters of <2mm are imperceptible in health as the air lying within the airway lumen merges with the air surrounding the airway. Small airways that become bronchiectatic however, have thickened walls and widened lumens and become visible in the lung periphery. A problem with requiring airways to

be dilated in the lung periphery before diagnosing bronchiectasis occurs with diseases where central rather than peripheral bronchiectasis predominates (Table 1).

Table 1

Aetiology	Lobes with most severe disease	Number of patients considered
Idiopathic Bronchiectasis	RLL and LLL[7] Lower lobes[8]	476 43
Cystic Fibrosis	Upper and middle lung regions[9] Upper lobes[10] RUL, right lung[11]	28 38 62
Post-Tuberculosis	RUL[12] Upper lobes[13]	101 42
Allergic bronchopulmonary aspergillosis	Upper lobes[14] Upper lobes[15]	23 18
Nontuberculous mycobacterial disease	LML, RML and RUL[16] Upper lobes[17] RUL, RML and LML[13] RUL, RML and LML[18]	85 48 100 24
Primary ciliary dyskinesia	RML, middle and lower lobes [19] LML[20]	45 20
Post-infective/aspiration	Lower lobes[8]	52
Immune deficiency/hypogammaglobulinaemia	LLL, RLL and RML[7]	18

RUL=right upper lobe; RML=right middle lobe; RLL=right lower lobe; LUL=left upper lobe; LML=lingula lobe; LLL=left lower lobe.

A lack of airway tapering

The most specific description of bronchiectasis on CT imaging is the "lack of tapering of bronchi"[2] as the airways extend from the centre of the lung to the periphery (Figure 1). Identification of a lack of normal tapering can be challenging as it requires careful scrutiny of the CT, ideally by an expert. Non-tapering of airways is typically assessed over the entire length of an airway from the lobar bronchi to the most distal airways. It is also possible to compare adjacent airways segments for more focal evaluation of whether an airway is tapering appropriately.

Accessory signs on CT that are typically associated with bronchiectasis include bronchial wall thickening and a build-up of sputum within dilated airways (Figure 1). In the large airways, sputum and debris can occlude the airway lumen and is manifest on CT imaging as mucus-plugging. Tracing a plugged airway proximally towards the centre of the lung can help distinguish a blocked airway from a pulmonary vessel, a common source of confusion. In the small airways, occlusion of the airway lumen with debris or mucus, termed an exudative bronchiolitis pattern is manifest as tree-in-bud nodularity whereby a branching pattern of solid tubes (representing non-hollow airways) is visible.

An indirect sign of small airways disease on CT imaging is a mosaic attenuation pattern whereby lung parenchyma of decreased attenuation on inspiratory CT imaging represents air trapping (Figure 1) within the acini of the secondary pulmonary lobule[21]. Expiratory CT is routinely performed today to accentuate the density differences between areas of air-trapping

consequent to small airways disease from normal lung which increases in density as the air leaves the alveoli on expiration. It is important to note that when airway walls are thickened, comparison of the inner airway wall diameter with the pulmonary artery may result in underestimation of bronchiectasis burden[22].

The observation of at least two of the above three key imaging features of bronchiectasis, as well as accessory signs including bronchial wall thickening, mucus plugging, tree-in-bud nodularity and small airways disease on CT can help increase confidence when assigning a diagnosis of bronchiectasis.

Classical descriptive appearances

Traditionally bronchiectasis has been categorized into three patterns on CT imaging. Cylindrical bronchiectasis is the most common form and as its name implies, demonstrates smooth dilatation throughout the length of the airway. Varicose bronchiectasis demonstrates a ruffled, beaded contour to the airway and is typically seen in association with allergic broncho-pulmonary aspergillosis (ABPA) infection and in post-tuberculous airway damage. Cystic bronchiectasis where an airway is dilated into a rounded sphere is typically seen associated with cystic fibrosis and following tuberculous infection.

The location of bronchiectasis can also provide a clue as to the underlying disease aetiology. Central bronchiectasis is more commonly seen in ABPA, cystic fibrosis and congenital tracheobronchomegaly (Mournier Kuhn syndrome). For peripheral bronchiectasis, the lobar distribution of disease can provide clues to aetiology (Table 1).

Clinical CT Evaluation

The optimal CT acquisition for the evaluation of bronchiectasis is a volumetric scan where CT slices are a maximum of 1mm in thickness in the axial plane. Evaluation of sagittal and coronal image reconstructions can aid in the delineation of airway dilatation and any lack of airway tapering. When performing longitudinal CT imaging in a patient, it is essential to have each CT timepoint imaged using the same CT scanner and reconstruction kernels to keep scanner-related measurement noise to a minimum.

Whilst considerable effort has gone into understanding the measurement variability associated with pulmonary function tests, understanding CT-related measurement variability remains a nascent field. Yet understanding what degree of change in longitudinal CT measurements reflects genuine disease deterioration as opposed to change resulting from measurement variation is essential to the development of robust prognostic tools. In addition to scanner-related measurement variability, differing patient effort between timepoints can strongly impact the assessment of bronchiectasis severity. For the follow-up of a patient with bronchiectasis, CTs are not typically performed at regular time intervals according to standardised protocols. Instead, a repeat CT is usually requested when a patient has clinically deteriorated, often with accompanied breathlessness. An unintended consequence is that a CT performed at the time of an exacerbation of disease, will often be of inferior quality compared to a CT acquired when the patient was clinically well. The repeat CT may provide valuable information such as the presence of infection but will be compromised in its ability to describe the natural history or trajectory of the underlying disease.

When evaluating lung damage related to bronchiectasis, several visual scoring methods have been employed. These scores typically assess a variety of imaging patterns (Table 2) using categorical scales on a lobar basis. One important limitation when using these semi-quantitative visual scores relates to their consideration of bronchiectasis extent and severity as two variables that compete in prognostic models. Yet separating the impact of bronchiectasis extent from bronchiectasis severity appears rather simplistic. Visual analyses ask to choose whether subtle dilatation of the airways in three bronchopulmonary segments of the lower lobes (extensive disease) is more prognostically important than marked dilatation of an airway (severe bronchiectasis) in a single bronchopulmonary segment. There is no easy reproducible way for visual CT scores to simultaneously consider both bronchiectasis extent and severity, but this is an area where the application of computational analyses to CT imaging could add real value.

Detailed semi-quantitative visual CT scores including the Brody[20,23,24] and Bhalla[25,26] scores are often performed by specialists. These lobar scores are time-consuming and may demonstrate variable inter-observer agreement[27]. As a result, their clinical utility in the real-world evaluation of patient disease burden is limited. Yet such scores can delineate unique imaging phenotypes of bronchiectasis[28]. The assessment of disease progression on longitudinal CT imaging, can be challenging when using visual scores as some areas of a CT might appear improved (with reduced mucus plugging or tree-in-bud opacification), yet with disease having worsened in other regions (Figure 2). Visual scores of disease evolution on longitudinal CTs are typically analysed on a whole lung level, with the result that localised changes in disease extent/severity

are often lost. Developing robust methods with which to evaluate bronchiectasis-related disease progression using visual CT scores remains an open challenge.

An alternative to complex visual scoring systems lies with the use of multidimensional bronchiectasis disease scores which take clinical, imaging and functional measurements to estimate disease burden. Such scores often only consider limited numbers of imaging variables and are therefore easier to perform. CT variables used in multidimensional bronchiectasis scores include bronchiectasis extent used in the FACED score (forced expiratory volume in 1 second, age, chronic colonisation, extension and dyspnoea)[12,29,30] or in the Bronchiectasis Severity Index: bronchiectasis extent or the presence of cystic bronchiectasis[31,32]. The Bronchiectasis Radiologically Indexed CT Score (BRICS) considers bronchiectasis severity and the number of bronchopulmonary segments containing emphysema.

Computer Analysis of Bronchiectasis

Over the past 10 years, rapid advances in the processing power of computers has resulted in the development of the field of quantitative medical image analysis. The aim has been to use computers to identify structures in organs such as the lung at a voxel level. By measuring the number of voxels and the location of structures within the lung, it should be possible to provide precise objective measurements that reflect healthy and diseased tissue. The earliest and simplest methods used Hounsfield unit density thresholds to categorise tissue as emphysema[33].

With regard to evaluating bronchiectasis, the key challenge has been computational delineation and measurement of the airways in the lung. In theory identifying all the voxels that constitute airways on a CT could provide a detailed volume of the airways. Expressing this as a percentage of total lung volume would normalise the airway measurement for an individual and remove the influence of differences in patient size or gender. By measuring the difference in inner and outer airway wall diameters it would also be possible to derive an estimate of airway wall thickening.

Yet computational analysis of the airways is a challenging task. It primarily involves two processes. Firstly, the lumen of the airways needs to be identified, a process termed segmentation. The second stage incorporates the specific calculations used to characterise or quantify airway features that indicate damage, all of which rely on the airway segmentation.

Several factors can affect the ability to segment the airways on a CT[35]. Inherent quantum noise is present on a CT and is influenced by factors including radiation dose, detector size and patient size. Quantum noise is responsible for the graininess of CT images, and is noticeably

greater on low dose CT acquisitions. The reconstruction algorithm used for a CT acquisition has a major impact on image interpretation by computer algorithms. The axial plane slice thickness of a CT image influences the spatial resolution of the image and ideally should be <1.5mm. Modern iterative reconstruction algorithms have been designed with the aim of lower radiation dose aim to denoise the image but can appear different to a computer when compared to images acquired using traditional filtered back projection techniques. High-resolution reconstruction algorithms enhance image contrast or employ edge enhancement of linear structures which help visual interpretation of structures in the lung, but can computational image interpretation. There has been a call for standardised computer-friendly reconstruction kernels to be available on all CT machines, which would aid image interpretation by computers and allow robust comparisons across timepoints. Yet with many reconstruction algorithms remaining propriety to commercial scanner manufacturers, this goal is yet to be realised.

Other constraints to computer analysis of CTs are common to visual CT analysis, and include breathing artefacts on the image, intercurrent infection limiting the number of airways that are visible, the quality of inspiration by the patient at the time of the scan and the consistency of image acquisition across CT timepoints.

Quantitative CT Analysis

Quantitative CT metrics typically reflect one of three analytic approaches:

1. A representation of real physical properties, such as airway diameter, typically considered in visual CT scores.

2. Texture analysis where small regions/patches of the CT are classified by appearance, with descriptions of the patterns terms based on radiological terms.
3. Latent features that often do not have an easily interpretable visual equivalent.

Table 3

Study	Quantitative Method	Cohort studied	Study patient number	Age (years, range)	Findings
Wielpütz et al. 2013[34]	Outer airway diameter, wall thickness and lumen area of all segmented airways	CF adults compared to healthy adults. CF children compared to healthy children	37	4 - 68	Outer airway diameter and wall th than controls. Significant correlati quantitative measures and FEV1 i
DeBoer et al. 2014[35]	Automated count of identifiable airways on inspiratory CT slices. Air trapping percentage on expiratory slices	CF children compared to normal controls	35	6 - 15	Average airway count per slice an significantly higher in CF than con airway count correlated with both lung function (FEV1 and FVC). Air correlated with visual CT scores, b
Santos et al. 2016[36]	Number of airway segments, airway lumen size and wall thickness	CF patients split using baseline FEV1 percentage	34	7 - 43	Greater number of airway segmen group. Significant correlations in v 3rd to 8th generation airways wit stronger in lower FEV1 group.
Kuo et al. 2017[37]	Luminal AA ratio, outer wall AA ratio, wall thickness-artery ratio for all identifiable segment AA pairs	CF children compared to normal subjects at baseline and after 2 years	12	0.6 - 5.2	Outer AA ratio and wall thickness- different between CF and controls Inner and outer AA ratio significan longitudinally in CF
Kuo et al. 2017[22]	Lumen AA ratio, outer AA ratio and airway wall thickness for all identifiable segment AA pairs	CF adolescents compared to normal controls	11	8.7-15.0 (IQR)	Outer AA ratio and airway wall thi significant differences between CI independent of lung volume. Diffe distal segmental generation
Diaz et al. 2017[6]	Airway and artery lumen size, luminal AA ratio, PWA, wall thickness, wall area percentage for 4-6th generation airways	Compared smokers with BE to normal subjects	21	67.0±9.5 (mean±SD)	Inner AA ratio, wall thickness, wal in BE than controls. No difference artery diameters smaller in BE tha

Diaz et al. 2018[38]	Lung blood vessel volume	Smokers with and without BE.	155	45 - 80	BE patients had more vascular pru Those with vascular pruning had l
Bak et al. 2018[39]	Air trapping percent calculated using mean I/E lung density ratio	Different levels of severity of BE in COPD patients.	73	48 - 96	COPD with BE showed significantl density ratio than COPD patients ratio correlated with BE severity
Hoang-Thi 2018[40]	Fixed and adapted CT density threshold scores n PCD	Correlate automated lung density with lung function tests	62	39 ± 15 (mean$\pm$SD)	Mean lung density plus one stand better with FEV1 and FVC than vis
Kuo et al. 2020[41]	Tapering of airways and outer wall AA ratio	CF children compared to controls groups	12	5.5 - 15.0 (IQR)	Significantly reduced airway taper airways. Increased outer AA ratio compared to control groups
Robinson et al. 2020[42]	Air trapping percentage	CF children followed up at 3-months, 1-year and 2 years	36	7.3 - 17.5	Quantitative air trapping and visu scores increased at 1 and 2-year f
Xing et al. 2020[43]	CT features with Machine learning	Differentiate between NTM and PTB using 103 CT-derived features	116	30 - 76	Shape and tissue texture features bronchiectasis were found to be t NTM and PTB

CF=cystic fibrosis; I/E=inspiratory-expiratory; BE=bronchiectasis; AA=Airway-artery; IQR=Inter quartile range; SD=standard deviation; PCD=primary ciliary dyskinesia; FEV_1=Forced expiratory volume in 1 second; FVC=forced vital capacity; PWA=peak wall attenuation; COPD=chronic obstructive pulmonary disease; NTM=non-tuberculous mycobacteria; PTB=pulmonary tuberculosis

Quantitative metrics that have been applied to evaluate bronchiectasis include:

Number of Resolvable Airways

As described earlier, as bronchiectasis worsens, more airway segments become visible on the CT. Quantifying the number of visible airway segments on a CT, a task that could be rapidly performed by computational tools, could therefore be a powerful indicator of disease extent. Sampling of airway counts on interspaced CT imaging has been performed in patients with cystic fibrosis[35]. With volumetric imaging, more precise airway counts can be computed by calculating the number of airway segments between airway branching points using an airway segmentation [22,36]. Yet this method is heavily reliant on the particular CT acquisition protocol and reconstruction kernels used.

Airway Measurements

The most commonly used airway measurements consider either airway diameters or cross-sectional areas, with the measurement being acquired in a plane perpendicular to the airway's central axis[44]. Whilst the inner airway wall diameter is often visually compared to the pulmonary artery to detect bronchiectasis, airway wall inflammation can make an airway lumen size appear much smaller than it really is, disguising the presence of bronchiectasis. As a result, measurement of the airway diameter/cross-sectional area using the outer airway wall is more typically used with computational analysis. Several studies in cystic fibrosis (CF) and smokers with radiological bronchiectasis have shown that the airway lumen size is no different to that of that of control populations.. However when airways are measured using the outer airway wall,

both airway size and wall thickness have been shown to be significantly different in disease populations compared to healthy subjects[6,34,36].

Tapering of an airway can be identified using computational analysis by measuring cross-sectional areas or diameters of airways at regular intervals along the airway centreline[44]. A challenge lies in the transient dilatation seen at airway bifurcations that could suggest artefactual bronchiectasis. The only study to have considered tapering metrics demonstrated reduced airway tapering in paediatric CF patients when compared to healthy participants when using both inner and outer airway wall measurements[41]. Tapering metrics may work well in the assessment of cylindrical bronchiectasis, where dilatation is relatively constant through the length of the airway. However, tapering measurement of varicose and cystic bronchiectasis where dilatation and narrowing can co-exist in a single airway might be more challenging.

Air-Trapping

Airway inflammation with narrowing and loss of compliance can result in air trapping within the acinus. Though the blocked airway may not be resolvable on CT, its sequelae of dilated secondary pulmonary lobules is visible on inspiratory CTs and accentuated on expiratory scans. Air-trapping can therefore be quantified at a voxel level. Simple methods to quantify air trapping have utilised HU density thresholds (-850 HU) on expiratory CTs[35,42]. The parametric response map method compares Hounsfield unit (HU) threshold changes across registered inspiratory and expiratory CTs to classify emphysema and functional small airways disease. On the inspiratory CT, all voxels of <-950 HU are considered to represent emphysema. Following registration of the expiratory CT to the inspiratory CT, any non-emphysematous voxels with a HU density <-856 on the expiratory CT are considered regions of functional small airways

disease. Varying HU density thresholds have been used to categorise the severity of air trapping[29]. Yet a requirement of all these methods is an adequate quality inspiratory and expiratory CT acquisition. A way of optimising breath holds lies in real-time spirometric feedback to the patient during the CT acquisition so that they are aware when they should breathe in and breathe out[30].

Airway-Artery Ratio

Challenges in delineating bronchiectasis using visual evaluation of the airway-artery ratio have already been described. Yet quantitative measurements of the airway-artery ratio have demonstrated significant correlations with CF disease severity in adolescent patients[8,21,25]. In adult smokers diagnosed with radiological bronchiectasis however, where the airway-artery ratio was found to be greater than control subjects, it was shown that rather than differences in airway size between groups, it was the artery that was smaller in patients compared to the control group[6].

Other QCT measures

There are a number of quantification measures that have not been as frequently reported in the context of bronchiectasis:

Though artery size has been frequently analysed, the general quantification of vessel volume has rarely been reported in studies of patients with bronchiectasis. A reduction in the volume of small vessels (<5 mm^2 in cross-section) in the peripheral lung[38], termed vascular pruning, has been shown to occur in smokers with mild radiological bronchiectasis. In smokers with bronchiectasis,

the presence of peripheral vascular pruning was associated with reduced six-minute walk test distances and forced expiratory volume in 1 second.

Using methods analogous to characterising air trapping with CT density thresholds, automated CT density analysis has been used to group different HU values within the lung into several distinct thresholds. The thresholds can be fixed or adaptive based on the HU histogram for the whole lung CT range to account for individual variation in inspiration. A study in adults with CF using such an approach showed that density thresholds correlated better with longitudinal disease severity than visual CT scores[45]. Another study using adaptive thresholds in patients with primary ciliary dyskinesia demonstrated density thresholds correlating better with disease severity measures (FEV1 and FVC) at baseline than visual CT scores[40].

Xing et al. 2020 considered 103 computer-derived CT variables each of which represented a different latent CT feature[43]. Shapes and tissue features that represented bronchiectasis were shown to be the best discriminators for differentiating non-tuberculous mycobacterial infection from pulmonary tuberculosis infection.

Challenges in Bronchiectasis Quantification

The majority of quantitative studies considered in this review were performed in CF patients. The relative abundance of imaging data in CF makes it an easier disease process to study and to develop automated tools. Should the computer-based tools developed in CF populations be transferred to analyse non-CF populations they will need to be fine-tuned and optimised to learn the unique imaging characteristics of the new bronchiectasis disease populations.

Optimising computer algorithms ideally requires large datasets of cases where the imaging parameters and variety of patient included are diverse enough to ensure there is no bias in the training data.

The performance of computer algorithms is heavily influenced by the training data used to develop the algorithm. Should the training data not have sufficient representation of patients of different ages, or consider gender, ethnic, socioeconomic or geographic distribution of cases adequately, there is a risk of introducing bias into the computer model. To have a computer algorithm that is robust in performance and generalisable to new datasets it should be trained on large diverse datasets. In this regard collaboratives such as Bronch-UK[46] and EMBARC[47] will be valuable resources for the development of bronchiectasis specific computer algorithms.

Regarding newer deep learning computer methods, an algorithm may identify a patient as likely to have a poor clinical outcome, but it may not be able to demonstrate in visual terms what features on the CT are driving the decision that the outcome will be poor. The need to be able to see what a computer model is basing its prognostic prediction on is important to gain clinician and patient trust that the right decision is being made by the computer. Being able to interpret computer-derived imaging features can help ascribe a biological explanation as to why the imaging features link to reduced survival. This can in turn help in the delineation of disease pathophysiology and drug development.

It is clear that visual CT evaluation is sufficient for disease detection. The real advantage of computer analysis of CT imaging is likely to be in longitudinal analysis of disease severity and extent change (Figure 3). The development of quantitative CT metrics are likely to increasingly

focus on measuring longitudinal disease progression which a human observer cannot quantify with the same precision. To train such models adequately, large diverse longitudinal datasets will be imperative. The algorithms will also need to focus on improving automated airway segmentations to identify as many abnormal peripheral airways as possible and be able to detect and quantify mucus plugging in airways, a task for which deep learning may be well suited[43,48].

Quantitative MRI Analysis

As well as having a higher inherent signal to noise ratio, CT imaging has a much faster image acquisition time than MRI. A rapid image acquisition avoids motion artifacts as the whole CT study can be performed within a single breath hold. The greater spatial resolution with CT also allows the resolution of larger numbers of smaller airway branches. The main constraint with CT imaging is the exposure of patients to ionising radiation. In young populations undergoing repeated imaging such as patients with cystic fibrosis or primary ciliary dyskinesia this can result in a cumulative increased risk of developing cancer. MRI is therefore being increasingly used for the assessment of younger patients with airways disease and has the added advantage of providing insights into the functional impact of lung disease.

Studies utilising quantitative MRI focus primarily on lung ventilatory defects. Differences in non-contrast enhanced MR signal-intensity between inspiratory and expiratory MR scans has been found to correlate with lung-function measures in patients with CF[49]. The inhalation of inert

hyperpolarised noble gases such as ^{3}Helium during MRI acquisition has been shown to accentuate the MR spin magnetization of the noble **gas which increases the MR signal to noise ratio within the lungs**. When the hyperpolarised gas diffuses into the airspaces, it is possible to get a measure of lung ventilation by calculating the volume of lung that has a low ^{3}He MR signal. In patients with bronchiectasis, quantification of ventilatory defects have been shown to be increased in lobes showing bronchiectasis on CT, and in lobes with no bronchiectasis on CT when compared to healthy subjects[50]. Ventilatory improvements have also been demonstrated following airway clearance therapy in patients with non-CF bronchiectasis[51]. Detecting ventilatory defects using hyperpolarised gas MRI is likely to be a sensitive method by which to detect early lung damage, particularly in young patients thereby avoiding radiation exposure[50].

Summary

Bronchiectasis on CT imaging is best identified by considering together a lack of airway tapering, enlargement of an airway relative to its accompanying pulmonary artery and evidence of enlarged airways in the lung periphery. Bronchiectasis patterns and distribution on visual CT evaluation can point to underlying disease aetiologies. MR analysis of bronchiectasis is a rapidly advancing field that provides functional as well as structural information on lung disease and will play a key role in assessment of younger patients, and patients with early disease.

When characterising lung damage on CT imaging and particularly disease progression over time, visual scores are time consuming and do not easily consider disease extent and severity together. It is likely that automated computer tools will replace visual analysis in the coming

years, particularly when evaluating disease progression. For computer tools to perform at their best, training data needs to be diverse and large, thereby minimising inherent biases in the dataset. Bronchiectasis registries are likely to be an important resource to allow training of specific computer tools which may perform better than tools that have been trained on cystic fibrosis datasets but repurposed for bronchiectasis assessment. The easy deployment of such algorithms in hospital settings will be crucial to prevent computer tools from being instruments only used in research studies.

Clinics care points

- Visual CT assessment is necessary for the diagnosis of bronchiectasis.
- Bronchiectasis can be identified by non-tapering of an airway on CT.
- Visualisation of an airway within the outer 1cm of the lung parenchyma also indicates the presence of bronchiectasis.
- A bronchiole may appears larger than its accompanying pulmonary artery for reasons unrelated to airways disease. The pulmonary artery:airway ratio is therefore not an optimal way of assessing for the presence of bronchiectasis.

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Table Legends

Table 1 Lobar disease distribution on computed tomography imaging for various causes of bronchiectasis.

Table 2 Variables analysed using semi-quantitative visual analysis of computed tomography imaging.

Table 3 Studies that have deployed quantitative analysis of computed tomography imaging in patients with bronchiectasis over the last 10 years.

Figure Legends

Figure 1. Axial CT images demonstrating (a) free-standing bronchiectasis and mucus filled airways (arrow) and (b) functional small airways disease (star).

Figure 2. Progressive dilatation of peripheral airways (arrow) seen on two axial CT images performed over the course of 12 months in a patient with non-tuberculous mycobacterial infection. The extent of bronchiectasis as well as the severity of dilatation had increased in the lungs over time, but visual CT scores consider extent and severity of disease separately.

Figure 3. Airway segmentations of a patient with bronchiectasis (top row) derived from two chest computed tomography scans taken 8 months apart. Airway graph networks of the

airways in the lung (bottom row), where the airway segments are represented as branches. Branch thickness is proportionate to the average airway diameter computed by automated quantification of the computed tomography image. The separate lobes have been labelled by colour. The lingula has been considered as a separate lobe. LLL, left lower lobe; LML, lingula lobe; LUL, left upper lobe; RML, right middle lobe; RLL, right lower lobe; RUL, right upper lobe.

Table 2

CT Variable				
	0	1	2	3
Severity of bronchiectasis	Absent	Mild: luminal diameter slightly greater than vessel diameter	Moderate: luminal diameter x2–3 greater than vessel diameter	Severe: luminal diameter >3 times greater than vessel diameter
Extension of bronchiectasis (number of affected segments)	Absent	1–5	6–9	> 9
Bronchial Wall Thickening	Absent	Mild: wall thickness equal to vessel diameter	Moderate: wall thickness up to 2 times vessel diameter	Severe: wall thickness >2 times vessel diameter
Mucus plugging (number of affected segments)	Absent	1–5	6–9	> 9
Sacculations (number of affected segments)	Absent	1–5	6–9	> 9
Involvement of bronchial generations	Absent	> 4th generation	> 5th generation	> 6th generation
Bullae	Absent	Unilateral (< 4)	Bilateral (< 4)	> 4
Air trapping (low attenuation) (number of affected segments)	Absent	1–5	> 5	
Atelectasis	Absent	Subsegmental	Segmental/lobar	
Emphysema (number of affected segments)	None	1-5	>5	
Consolidation/Collapse	None	Subsegmental	Segmental/Lobar	

Figure 1

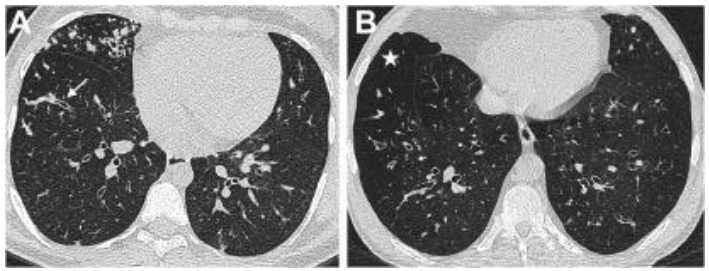

Figure 2

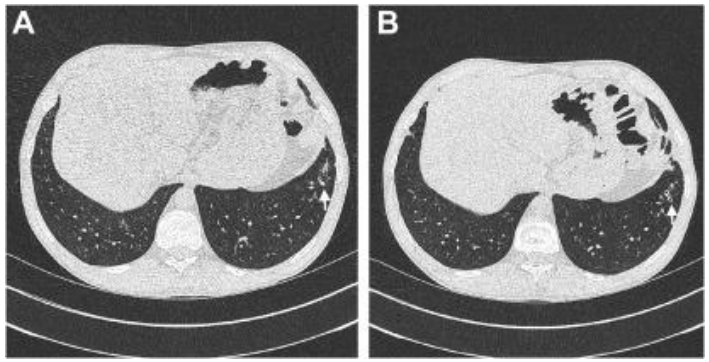

Figure 3