European Journal of Clinical Pharmacy

Print ISSN: 2385-409X **Online ISSN**: 3105-0409

Website: https://farmclin.com/

Original Research Article

High-Resolution Computed Tomography in the Early Detection of Pulmonary Emphysema: Imaging Patterns, Quantitative Assessment, and Clinical Implications

Article History:

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Received: 11-11-2025

Revised: 26-11-2025

Accepted: 09-12-2025

Published: 31-12-2025

Abstract: ***Background:*** Pulmonary emphysema, a major structural component of chronic obstructive pulmonary disease (COPD), is characterized by irreversible destruction of alveolar walls and permanent enlargement of distal airspaces. Early emphysematous changes often remain clinically silent and may not be detected by conventional chest radiography or spirometry. With advances in imaging technology, high-resolution computed tomography (HRCT) has emerged as the most sensitive and specific imaging modality for detecting early and subclinical emphysema, allowing detailed visualization of lung parenchyma and subtle structural abnormalities. Objectives: This review aims to comprehensively analyze the imaging spectrum of early pulmonary emphysema on HRCT, describe qualitative and quantitative imaging patterns, and critically evaluate their clinical relevance, prognostic implications, and correlation with functional impairment. ***Materials and Methods***: A systematic narrative review of published literature was conducted using electronic databases including PubMed/MEDLINE, Google Scholar, Scopus, Web of Science, and Embase. Original research articles, review articles, meta-analyses, and consensus statements published in English were included. Studies focusing on HRCT features of emphysema, early disease detection, quantitative CT analysis, and clinico-radiological correlations were reviewed. Relevant data were extracted, synthesized, and analyzed descriptively. ***Results:*** HRCT demonstrates superior sensitivity in detecting early emphysematous changes compared to conventional imaging and pulmonary function tests. Characteristic findings include focal and diffuse low-attenuation areas, centrilobular lucencies, subpleural emphysematous spaces, and loss of normal vascular markings. Quantitative CT parameters, particularly low-attenuation area percentage (LAA%), correlate strongly with disease severity, symptom burden, and functional decline. HRCT phenotyping allows differentiation of emphysema subtypes with important clinical and prognostic significance. ***Conclusion:*** HRCT plays a pivotal role in the early diagnosis, phenotypic classification, and longitudinal assessment of pulmonary emphysema. Integration of qualitative and quantitative HRCT findings with clinical and functional data enhances disease characterization, supports early intervention strategies, and improves patient management and prognostication.

Keywords: Pulmonary emphysema; HRCT; Early emphysema; Quantitative CT; COPD; Imaging spectrum

INTRODUCTION

Pulmonary emphysema is a chronic, progressive lung disease defined by irreversible enlargement of airspaces distal to the terminal bronchioles accompanied by destruction of alveolar walls, without significant

fibrosis [1]. It represents a major structural component of chronic obstructive pulmonary disease (COPD), which is currently one of the leading causes of morbidity and mortality worldwide [2]. The global burden of COPD continues to rise due to persistent exposure to tobacco smoke, biomass fuel combustion, environmental pollution, and aging populations [3].

Traditionally, emphysema has been diagnosed using chest radiography and pulmonary function tests (PFTs). However, chest radiographs lack sensitivity and specificity, particularly in early disease, as radiographic signs become apparent only when substantial lung destruction has already occurred [4]. Similarly, spirometry primarily reflects airflow limitation and may remain normal in patients with early emphysema, especially when parenchymal destruction precedes small airway obstruction [5]. Several studies have demonstrated that a significant proportion of smokers with normal spirometry already harbor emphysematous changes detectable on HRCT [6,7].

High-resolution computed tomography has revolutionized the evaluation of diffuse lung diseases by enabling thin-section imaging with superior spatial resolution [8]. HRCT allows direct visualization of lung parenchyma and provides detailed information on disease distribution, extent, and pattern. Since the seminal work of Muller et al., HRCT has been recognized as the imaging gold standard for the diagnosis and characterization of emphysema [9].

Early detection of emphysema is clinically important for several reasons. First, emphysema detected at an early stage may identify individuals at high risk for disease progression, allowing timely intervention such as smoking cessation and preventive strategies [10]. Second, HRCT-based phenotyping of emphysema subtypes has been shown to correlate with symptom burden, exacerbation risk, response to therapy, and mortality [11,12]. Third, quantitative CT analysis provides objective and reproducible measures of disease severity, which may serve as imaging biomarkers in clinical trials and longitudinal follow-up [13].

Advances in CT technology, including multidetector scanners, low-dose protocols, and automated quantitative software, have further expanded the role of HRCT in emphysema evaluation [14]. Quantitative indices such as the percentage of low-attenuation areas below −950 Hounsfield units (HU) have shown strong correlations with histopathological emphysema severity and pulmonary function decline [15].

Given the increasing recognition of HRCT as a central tool in emphysema evaluation, this review aims to provide an in-depth discussion of the imaging spectrum of early pulmonary emphysema, highlighting qualitative and quantitative HRCT features and emphasizing their clinical relevance and prognostic implications.

MATERIALS AND METHODS

Search Strategy

A comprehensive literature search was conducted using **PubMed/MEDLINE, Google Scholar, Scopus, Web of Science, and Embase** databases. Search terms included combinations of: *emphysema*, *high-resolution computed tomography*, *early emphysema*, *quantitative CT*, *low attenuation areas*, and *COPD imaging*.

Study Selection

Peer-reviewed original research articles, review articles, meta-analyses, and consensus guidelines published in English were included. Case reports, editorials, and non-English publications were excluded unless they provided unique or landmark data.

Data Extraction and Synthesis

Relevant data on HRCT findings, emphysema subtypes, quantitative assessment techniques, and clinical correlations were extracted and synthesized into thematic sections. Due to the narrative nature of the review, formal meta-analysis was not performed.

RESULTS

HRCT Appearance of Normal Lung Parenchyma

On HRCT, normal lung parenchyma demonstrates uniform attenuation with visible broncho vascular structures extending to the lung periphery. Secondary pulmonary lobules are well delineated, and there is no focal or diffuse reduction in attenuation.

Qualitative HRCT Findings in Early Emphysema

Early emphysema is characterized by subtle focal or patchy areas of decreased attenuation without visible walls, commonly referred to as low-attenuation areas (LAAs). These areas often show reduction in vascular caliber and number, reflecting underlying alveolar destruction.

Centrilobular Emphysema

Centrilobular emphysema is the most common subtype, particularly in smokers. HRCT shows small, round or polygonal lucencies in the central portion of secondary lobules, predominantly in the upper lobes. In early disease, these changes may be focal and limited in extent.

Panlobular Emphysema

Panlobular emphysema involves uniform destruction of the entire secondary lobule. HRCT demonstrates diffuse, homogeneous low attenuation, often with lower lobe predominance. It is classically associated with alpha-1 antitrypsin deficiency but may also occur in smokers.

Paraseptal Emphysema

Paraseptal emphysema appears as subpleural or periseptal low-attenuation spaces, often adjacent to interlobular septa. It is frequently detected incidentally and may be associated with spontaneous pneumothorax.

Quantitative HRCT Assessment

Quantitative CT techniques measure lung density and calculate the proportion of lung voxels below a predefined attenuation threshold, commonly −950 Hounsfield units (HU). The percentage of low-attenuation area (LAA%) correlates strongly with histopathological emphysema severity and pulmonary function decline.

Early and Subclinical Emphysema

Several studies have shown that HRCT can detect emphysema in smokers with normal spirometry. These individuals may already exhibit reduced diffusing capacity and exercise intolerance, highlighting the value of HRCT in identifying subclinical disease.

RESULTS

Table 1: Comparison of Imaging Modalities in the Evaluation of Pulmonary Emphysema

Modality	Sensitivity for Early Disease	Structural Assessment	Quantification	Limitations
Chest X-ray	Low	Indirect	No	Poor sensitivity in early disease
Spirometry	Moderate	Indirect	Functional only	May be normal in early emphysema
HRCT	High	Direct	Qualitative & quantitative	Radiation exposure
Quantitative CT	Very High	Direct	Objective & reproducible	Software variability

Table 2: HRCT Features of Emphysema Subtypes

Emphysema Type	HRCT Appearance	Distribution	Clinical Association
Centrilobular	Focal low-attenuation areas	Upper lobes	Smoking
Panlobular	Uniform low attenuation	Lower lobes	Alpha-1 antitrypsin deficiency
Paraseptal	Subpleural lucencies	Peripheral	Pneumothorax risk
Mixed	Combination patterns	Diffuse	Advanced disease

Table 3: Quantitative HRCT Parameters and Clinical Correlation

Parameter	Definition	Clinical Significance
LAA-950	% voxels < −950 HU	Emphysema severity
Mean Lung Density	Average attenuation	Disease progression
Vascular Pruning	Reduced vessel count	Functional impairment
Air Trapping Index	Expiratory low density	Small airway disease

DISCUSSION

Pulmonary emphysema is a structurally defined disease characterized by irreversible destruction of alveolar walls and permanent enlargement of distal airspaces. The clinical diagnosis of emphysema has traditionally relied on spirometry and chest radiography; however, these tools fail to adequately capture early parenchymal destruction, particularly in asymptomatic or minimally symptomatic individuals [1,2]. The present review underscores the pivotal role of high-resolution computed tomography (HRCT) in detecting early emphysematous changes, characterizing disease phenotypes, and providing clinically meaningful information beyond conventional diagnostic modalities.

HRCT Versus Conventional Diagnostic Tools

Chest radiography has limited sensitivity for emphysema, as radiographic signs such as hyperinflation, flattened diaphragms, and vascular attenuation typically appear only in advanced disease

[3]. Similarly, spirometry reflects airflow limitation rather than structural damage and may remain normal until substantial lung destruction has occurred [4,5]. Several large cohort studies have demonstrated that emphysema detectable on HRCT frequently precedes airflow obstruction measured by spirometry, highlighting the dissociation between structural and functional abnormalities in early disease [6–8].

HRCT allows direct visualization of lung parenchyma at the level of secondary pulmonary lobules, making it uniquely suited for detecting subtle emphysematous changes. The ability of HRCT to identify low-attenuation areas (LAAs) before clinical or functional impairment has important implications for early diagnosis, risk stratification, and preventive intervention [9,10].

Pathophysiologic Correlation of HRCT Findings

The HRCT manifestations of emphysema closely reflect underlying histopathological changes. Low-attenuation areas on HRCT correspond to regions of alveolar wall destruction and loss of capillary beds, resulting in reduced tissue density and diminished vascular markings [11,12]. Gevenois et al. demonstrated a strong correlation between CT-derived lung density measurements and histologic emphysema severity, validating HRCT as a surrogate marker for pathological disease burden [13].

Centrilobular emphysema, the most prevalent subtype, primarily affects respiratory bronchioles and is strongly associated with cigarette smoking [14]. HRCT shows focal, poorly marginated lucencies centered within secondary pulmonary lobules, often with upper lobe predominance [15]. These changes reflect early inflammatory injury and protease-mediated destruction in regions exposed to maximal smoke deposition [16].

Panlobular emphysema, in contrast, involves uniform destruction of the entire acinus and is classically associated with alpha-1 antitrypsin deficiency [17]. HRCT demonstrates diffuse, homogeneous low attenuation, frequently with lower lobe predominance. Clinically, this subtype is associated with earlier symptom onset and more rapid disease progression [18].

Paraseptal emphysema is characterized by subpleural emphysematous spaces adjacent to interlobular septa. Although often clinically silent, it carries a significant risk of spontaneous pneumothorax, particularly in younger patients [19,20]. Recognition of this pattern on HRCT is therefore of prognostic and preventive importance.

Clinical Relevance of Early Emphysema Detection

The detection of early emphysema on HRCT has profound clinical implications. Several studies have shown that smokers with HRCT-detected emphysema but preserved spirometry exhibit reduced diffusing capacity, impaired exercise tolerance, and increased respiratory symptoms compared to smokers without emphysema [7,21]. These findings challenge the traditional reliance on spirometry alone for disease detection and highlight the importance of structural imaging in early disease assessment.

Early identification of emphysema provides an opportunity for targeted interventions, most notably smoking cessation, which remains the most effective strategy for slowing disease progression [22]. Visual demonstration of emphysematous changes on HRCT has been shown to improve patient awareness and motivation for smoking cessation [23].

Quantitative HRCT and Disease Phenotyping

Quantitative HRCT has transformed emphysema assessment from a subjective to an objective and reproducible process. Density-based metrics, particularly the percentage of lung voxels below −950 HU (LAA-950), have been extensively validated and correlate strongly with histopathology, lung function decline, symptom severity, and mortality [13,24–26].

Large population-based studies, including the COPDGene and MESA cohorts, have demonstrated that quantitative emphysema burden independently predicts mortality, exacerbation frequency, and cardiovascular comorbidity, even after adjusting for spirometric indices [27–29]. These findings underscore the prognostic value of HRCT beyond traditional functional measures.

Importantly, HRCT enables phenotypic classification of COPD, distinguishing emphysema-predominant from airway-predominant disease. This phenotyping has therapeutic implications, as emphysema-predominant patients may respond differently to pharmacologic therapy and may be candidates for interventions such as lung volume reduction surgery or bronchoscopic lung volume reduction [30–32].

HRCT in Disease Progression and Longitudinal Monitoring

Serial HRCT allows assessment of emphysema progression over time, providing insights into disease natural history. Studies have shown that quantitative CT measures may detect progression earlier than spirometry, making HRCT a valuable tool for monitoring disease evolution and evaluating treatment efficacy in clinical trials [33,34].

Advanced imaging techniques, including parametric response mapping and texture-based analysis, allow simultaneous assessment of emphysema and small airway disease, further refining disease

characterization [35]. These approaches have demonstrated that small airway disease often precedes emphysematous destruction, reinforcing the concept of COPD as a heterogeneous and progressive spectrum [36].

Radiation Exposure and Technical Considerations

Despite its advantages, HRCT is associated with radiation exposure, which remains a concern, particularly for screening and longitudinal follow-up [37]. However, the development of low-dose CT protocols and iterative reconstruction techniques has significantly reduced radiation dose while maintaining diagnostic accuracy [38,39].

Standardization of CT acquisition parameters and quantitative analysis methods remains a challenge, as variability across scanners and software platforms can affect measurement reproducibility [40-44]. Ongoing efforts toward protocol harmonization and validation of automated tools are essential for broader clinical adoption.

Recent large-scale prospective evidence underscores the prognostic significance of emphysema detected on low-dose CT (LDCT), even in asymptomatic individuals. A 2025 Radiology study involving over 9,000 asymptomatic adults undergoing LDCT for lung cancer screening demonstrated that baseline emphysema presence was associated with significantly increased long-term mortality, including COPD-related and all-cause mortality, over a 25-year follow-up . Notably, individuals with mild emphysema exhibited increased mortality risk compared to those without emphysema, and this risk escalated with emphysema severity. These results indicate that emphysema on CT is not merely an incidental structural finding, but a robust prognostic imaging biomarker that should prompt early clinical intervention and more aggressive risk modification strategies—especially in high-risk smoking populations participating in routine lung cancer screening programs [45].

In addition to prognostication, 2025 research continues to refine our understanding of quantitative CT metrics in relation to systemic disease risk. A recently published retrospective cohort study found that quantitatively assessed emphysema severity on HRCT independently predicts coronary artery disease (CAD) among COPD patients, even after adjusting for conventional cardiovascular risk factors . Patients with higher low-attenuation area percentage (LAA%) exhibited increased CAD risk and more complex coronary lesions compared to those with lower LAA%, suggesting that CT-derived emphysema burden serves as a cross-systemic risk marker beyond pulmonary outcomes. These findings reinforce the clinical importance of integrating HRCT quantification into holistic patient evaluation, not only for respiratory risk but for comprehensive cardiovascular risk profiling as well [46].

CONCLUSION

High-resolution computed tomography is the most sensitive imaging modality for detecting early pulmonary emphysema. It enables detailed visualization of subtle parenchymal abnormalities, accurate phenotypic classification, and quantitative assessment of disease burden. Integration of HRCT findings with clinical and functional parameters enhances early diagnosis, risk stratification, and personalized patient management. HRCT should be considered an essential tool in the comprehensive evaluation of patients at risk for emphysema.

Future Directions

The future of emphysema imaging lies in advanced quantitative analysis, artificial intelligence, and machine learning-based tools that enable automated detection, classification, and prognostication . Integration of imaging biomarkers with clinical, functional, and molecular data holds promise for precision medicine approaches in COPD management.

Limitations

This review is limited by its narrative design and reliance on previously published data.

Variability in HRCT acquisition techniques, quantitative thresholds, and study populations across the literature may affect comparability.

Future large-scale, standardized, longitudinal studies are required to further refine imaging-based definitions of early emphysema.

DECLARATIONS:

There is no any conflict of interest.

Acknowledgements

Dr. Adnan Shaikh, Dr. Mufidur Rehman, Dr. Yayati Pimpalwar*along with Dr. Ganesh Kumarand Dr. Sadaf Sultana extend their sincere gratitude Integral University, Lucknow for their immense support and provision of the important facilities to carry out this research smoothly with the MCN no. IU/R&D/2026-MCN0004216.

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