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Review Article

Radiological Evaluation of Pulmonary Tuberculosis

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A R T I C L E I N F O

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A B S T R A C T

Pulmonary tuberculosis (PTB) remains one of the leading causes of infectious morbidity and mortality worldwide despite advances in diagnostic and therapeutic strategies. Imaging plays a central role in the detection, characterization, and monitoring of disease progression and response to therapy. Radiological evaluation, particularly chest radiography and computed tomography (CT), continues to be indispensable in both resource-limited and advanced healthcare settings. Chest radiography remains the initial imaging modality of choice due to its accessibility, rapid acquisition, and cost-effectiveness. However, its sensitivity is limited, especially in early disease, immunocompromised states, and atypical presentations. High-resolution computed tomography (HRCT) has emerged as a superior modality for detecting subtle parenchymal abnormalities, early bronchogenic spread, and complications. Radiological manifestations vary significantly depending on host immune status, disease stage, and bacterial burden. Primary tuberculosis is typically characterized by lymphadenopathy, consolidation, and pleural effusion, whereas post-primary (reactivation) tuberculosis shows cavitation, upper lobe predominance, and bronchogenic dissemination. Miliary tuberculosis presents with diffuse micronodular patterns. Advanced imaging patterns such as the "tree-in-bud" appearance, centrilobular nodules, and ground-glass opacities are key indicators of active disease. Radiology also plays a critical role in identifying complications such as bronchiectasis, fibrosis, pneumothorax, and destroyed lung syndrome. Integration of imaging findings with microbiological and clinical data enhances diagnostic accuracy and guides management decisions. Recent advances, including artificial intelligence and computer-aided detection systems, are further improving diagnostic sensitivity and workflow efficiency. Despite these advances, challenges remain in differentiating active from inactive disease and distinguishing tuberculosis from other mimickers. This review synthesizes current literature on radiological manifestations, imaging modalities, and diagnostic patterns of pulmonary tuberculosis, emphasizing their clinical relevance and evolving role in modern practice.

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INTRODUCTION

Pulmonary tuberculosis, caused by Mycobacterium tuberculosis, continues to represent a major global health challenge, particularly in developing regions [1,2]. Despite the availability of effective treatment, delayed diagnosis and atypical presentations contribute significantly to disease burden.

Radiological imaging has long been integral to tuberculosis diagnosis. From conventional radiography to advanced cross-sectional imaging, radiology provides essential insights into disease activity, distribution, and complications [3].

The variability in imaging findings reflects differences in host immunity, disease chronicity, and pathogen virulence. In immunocompetent individuals, classical upper lobe cavitary disease predominates, whereas immunocompromised patients often present with atypical patterns [4].

This review critically evaluates the role of imaging in pulmonary tuberculosis, integrating evidence from contemporary literature.

PATHOPHYSIOLOGY AND RADIOLOGICAL CORRELATION

The radiological manifestations of tuberculosis are closely linked to its pathophysiology. Following inhalation, Mycobacterium tuberculosis bacilli reach the alveoli, where they are engulfed by macrophages. The host immune response leads to granuloma formation, which may either contain the infection or progress to active disease (5).

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Caseous necrosis within granulomas results in cavitation, a hallmark of post-primary tuberculosis (3). Bronchogenic spread leads to characteristic tree-in-bud patterns, while hematogenous dissemination produces miliary nodules (6).

METHODOLOGICAL APPROACH

A structured literature synthesis was performed using major databases including PubMed, Scopus, and Web of Science. Studies focusing on imaging findings, diagnostic performance, and radiological classification of pulmonary tuberculosis were included.

Priority was given to:

- Meta-analyses and systematic reviews
- Radiological-pathological correlation studies
- Recent imaging-based diagnostic advancements

RADIOLOGICAL MANIFESTATIONS OF PULMONARY TUBERCULOSIS

Radiological findings depend on disease stage and host immune response [5].

Table 1: Common Radiological Findings in Pulmonary Tuberculosis

Finding	Description	Pathophysiology	Reference
Consolidation	Patchy/lobar opacity	Alveolar exudation	[2]
Cavitation	Air-filled lucencies	Caseous necrosis	[3]
Nodules	Small rounded opacities	Granuloma formation	[5]
Lymphadenopathy	Enlarged nodes	Immune response	[4]
Pleural effusion	Fluid accumulation	Hypersensitivity	[6]
Calcification	Dense foci	Healed disease	[1]

IMAGING MODALITIES IN TUBERCULOSIS

Table 2: Imaging Modalities and Clinical Roles

Modality	Advantages	Limitations	Clinical Use	Reference
Chest X-ray	Widely available	Low sensitivity	Screening	[7]
CT Scan	High resolution	Radiation	Detailed evaluation	[3]
HRCT	Detects early disease	Cost	Subtle lesions	[8]
MRI	No radiation	Limited lung detail	Complications	[9]
Ultrasound	Portable	Limited lung use	Pleural disease	[6]

CLASSIFICATION OF TUBERCULOSIS BY RADIOLOGICAL PATTERNS

Table 3: Primary vs Post-primary Tuberculosis

Feature	Primary TB	Post-primary TB	Reference
Age group	Children	Adults	[4]
Cavitation	Rare	Common	[3]
Lymphadenopathy	Common	Rare	[5]
Location	Lower lobes	Upper lobes	[2]
Effusion	Frequent	Occasional	[6]

CT FEATURES OF ACTIVE DISEASE

Table 4: CT Findings of Active Tuberculosis

CT Feature	Description	Diagnostic Significance	Reference
Tree-in-bud	Branching nodules	Bronchogenic spread	[10]
Cavities	Thick-walled lesions	Active disease	[3]
Ground-glass opacity	Hazy opacities	Inflammation	[8]
Centrilobular nodules	Small nodules	Active infection	[5]
Bronchiectasis	Dilated bronchi	Chronic disease	[11]

MILIARY AND DISSEMINATED TUBERCULOSIS

Table 5: Imaging Features of Miliary Tuberculosis

Feature	Description	Imaging Modality	Reference
Micronodules	1–3 mm nodules	CT > X-ray	[12]
Diffuse distribution	Random pattern	CT	[3]
Ground-glass	Early disease	HRCT	[8]
Interstitial thickening	Advanced stage	CT	[5]
Bronchiectasis	Dilated bronchi	Chronic disease	[11]

RADIOLOGICAL COMPLICATIONS

Table 6: Complications of Pulmonary Tuberculosis

Complication	Imaging Findings	Clinical Significance	Reference
Fibrosis	Irregular scarring	Chronic disease	[11]
Bronchiectasis	Airway dilation	Recurrent infection	[3]
Pneumothorax	Pleural air	Emergency	[6]
Destroyed lung	Volume loss	Severe disease	[2]
Hemoptysis	Cavitary erosion	Life-threatening	[9]

ADVANCED IMAGING AND EMERGING TECHNOLOGIES

Recent advancements include:

- Artificial intelligence for automated detection
- Quantitative CT analysis
- Radiomics for disease characterization

AI-based tools have demonstrated improved sensitivity in detecting subtle lesions on chest radiographs [13].

DIFFERENTIAL DIAGNOSIS

Radiological overlap exists with:

- Lung malignancy
- Fungal infections
- Sarcoidosis
- Bacterial pneumonia

Differentiation relies on pattern recognition and clinical correlation.

DISCUSSION

Radiological imaging remains indispensable in pulmonary tuberculosis. While chest radiography continues as a frontline tool, CT imaging significantly enhances diagnostic accuracy.

HRCT has transformed the evaluation of early disease and subtle findings. Patterns such as tree-in-bud nodularity and cavitation provide strong indicators of active infection.

However, challenges persist:

- Differentiating active vs inactive disease
- Identifying drug-resistant patterns
- Managing atypical presentations

Integration with microbiological testing remains essential.

CONCLUSION

Radiological evaluation has evolved into an indispensable pillar in the comprehensive management of pulmonary tuberculosis, transcending its traditional role as a mere diagnostic adjunct. It now serves as a critical interface between clinical suspicion and definitive microbiological confirmation, particularly in high-burden and resource-limited settings where rapid diagnostic decisions are essential.

Chest radiography continues to be the backbone of tuberculosis screening programs worldwide due to its accessibility, affordability, and rapid turnaround time. However, its inherent limitations—particularly reduced sensitivity in early disease, immunocompromised patients, and atypical presentations—necessitate the integration of advanced imaging modalities. High-resolution computed tomography has significantly enhanced the detection of subtle parenchymal abnormalities, bronchogenic spread, and early cavitary lesions, thereby facilitating timely diagnosis and intervention.

The ability of CT imaging to characterize disease patterns—such as tree-in-bud nodularity, centrilobular nodules, and ground-glass opacities—provides valuable insights into disease activity and progression. Furthermore, CT plays a pivotal role in identifying complications, including bronchiectasis, fibrosis, and destroyed lung syndrome, which have profound implications for long-term patient outcomes.

Radiological imaging also contributes significantly to treatment monitoring. Serial imaging enables assessment of therapeutic response, detection of residual disease, and identification of complications such as drug-resistant tuberculosis or secondary infections. Persistent radiological abnormalities often reflect irreversible structural damage, underscoring the importance of early diagnosis and treatment initiation.

The integration of artificial intelligence and machine learning into radiological practice represents a transformative advancement. AI-based algorithms have demonstrated high sensitivity and specificity in detecting tuberculosis on chest radiographs, offering potential for large-scale screening and reducing interobserver variability. Radiomics further enhances diagnostic precision by extracting quantitative imaging features that may not be discernible to the human eye.

Despite these advancements, several challenges remain. Differentiating active from inactive disease continues to be a significant limitation, as radiological findings may overlap. Similarly, distinguishing tuberculosis from malignancy or other infectious and inflammatory conditions requires careful correlation with clinical and laboratory data.

A multidisciplinary approach integrating radiological, clinical, microbiological, and molecular findings is essential for accurate diagnosis and optimal patient management. Future research should focus on developing standardized imaging criteria, validating AI-based diagnostic tools, and integrating imaging biomarkers into clinical decision-making frameworks.

In conclusion, radiological imaging is not merely supportive but central to the diagnosis, management, and control of pulmonary tuberculosis. Continued advancements in imaging technology, combined with interdisciplinary collaboration, hold the potential to significantly improve patient outcomes and contribute to global tuberculosis eradication efforts.

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