HRCT Findings in Pulmonary Tuberculosis: Predicting Disease Activity Through Radiological Assessment

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Article Info

ISSN (online): 2582-8940
Volume: 07
Issue: 01
Received: 01-12-2025
Accepted: 02-01-2025
Published: 04-02-2026
Page No: 157-164

Abstract
Pulmonary tuberculosis (TB) remains one of the most consequential infectious diseases globally, responsible for significant morbidity and mortality across all age groups, and continues to pose a formidable challenge to public health systems in both high-burden and resource-limited settings. A primary limitation in the timely clinical management of pulmonary TB has been the inherent delay associated with sputum culture confirmation, which may require several weeks and during which critical treatment decisions must be made on the basis of clinical and radiological evidence alone. High-resolution computed tomography (HRCT) of the chest offers a non-invasive and rapidly available imaging modality that can identify characteristic morphological features of active and inactive pulmonary TB, and has the potential to guide early therapeutic decisions when microbiological data are awaited. The present cross-sectional study was designed to compare HRCT findings with sputum positivity status in 40 patients with confirmed or clinically suspected pulmonary TB, thereby evaluating the utility of specific HRCT features in distinguishing active from inactive disease. Of 40 patients enrolled, 24 were classified as having active TB based on sputum smear positivity and 16 as having inactive disease. Statistical analysis using Fisher's exact test demonstrated that centrilobular nodules (p=0.0001), tree-in-bud pattern (p=0.003), consolidation (p=0.004), and cavitation (p=0.022) were significantly more prevalent in active disease, while fibrosis (p=0.008) and tractional bronchiectasis (p=0.023) showed a significantly higher prevalence in inactive cases. Ground glass opacity, lymphadenopathy, emphysema, pleural effusion, calcified granuloma, and pleural thickening did not demonstrate statistically significant differences between the two groups. These findings collectively affirm that HRCT can meaningfully contribute to the prediction of TB disease activity, supporting its role as a complementary diagnostic tool in clinical practice, particularly in settings where rapid microbiological confirmation is unavailable.

DOI: https://doi.org/10.54660/IJMBHR.2026.7.1.157-164

Keywords: High Resolution Computed Tomography, Pulmonary Tuberculosis, Centrilobular Nodules, Tree-in-Bud Pattern, Disease Activity, Sputum Positivity

Introduction

Tuberculosis is an infectious disease caused by Mycobacterium tuberculosis and remains one of the leading causes of death attributable to a single infectious agent worldwide [1, 5]. The global burden of tuberculosis continues to be disproportionately concentrated in low- and middle-income countries, where overcrowding, malnutrition, and inadequate access to healthcare facilitate transmission and delay diagnosis [5, 6]. Pulmonary tuberculosis, which accounts for the majority of TB cases, represents the primary form of the disease and is the chief driver of person-to-person transmission via aerosolized respiratory droplets [1, 5]. The co-epidemic of tuberculosis and human immunodeficiency virus infection has further amplified the global impact of TB, as HIV-positive individuals bear a substantially elevated lifetime risk of progression from latent to active TB [2, 3, 4].

The standard diagnostic pathway for pulmonary tuberculosis relies upon sputum smear microscopy and culture for Mycobacterium tuberculosis, with culture confirmation representing the definitive microbiological standard [8, 9]. However, conventional culture methods using solid media such as Lowenstein-Jensen medium may require four to eight weeks for definitive identification [8, 9]. Even radiometric liquid culture systems, which have significantly reduced turnaround times, may not provide timely guidance for clinical decision-making in all clinical scenarios [8]. This delay creates a diagnostic gap in which patients with clinically suspected active tuberculosis must either await culture confirmation before commencing treatment or be started on empirical antituberculous therapy based on clinical and radiological assessment alone [1, 10]. In resource-constrained settings, where sputum smear-negative TB is particularly prevalent and culture facilities may not be accessible, the ability to assess disease activity through imaging assumes particular clinical importance [33, 35].

Chest radiography has long served as the primary imaging tool for the detection and monitoring of pulmonary tuberculosis, offering a widely available, low-cost modality for initial assessment [11, 12, 13]. However, plain radiography has well-recognized limitations in terms of sensitivity and specificity for distinguishing active from inactive disease, and its spatial resolution is insufficient for the characterization of subtle parenchymal abnormalities [14, 15].

High-resolution computed tomography of the chest, using thin-section acquisition techniques with a high spatial frequency reconstruction algorithm, provides substantially superior anatomical detail of the pulmonary parenchyma, airways, and mediastinal structures, enabling the identification of HRCT patterns that correlate with specific pathophysiological stages of TB infection [10, 17, 25].

Among the HRCT findings that have been investigated as markers of active pulmonary tuberculosis, centrilobular nodules and the tree-in-bud pattern occupy a particularly prominent position. Centrilobular nodules represent foci of caseous necrosis and inflammatory infiltration within the peribronchovascular interstitium of the secondary pulmonary lobule, reflecting active airspace disease with involvement of small airways and peribronchiolar tissue [27, 30]. The tree-in-bud pattern, characterized on HRCT by small nodules of 2 to 4 millimeters connected to linear branching structures resembling a budding tree, corresponds pathologically to the filling of terminal and respiratory bronchioles with caseous or mucopurulent material, and is therefore a marker of endobronchial spread of active infection [29, 30]. Both centrilobular nodules and the tree-in-bud pattern have been consistently reported in the literature as robust radiological indicators of active, smear-positive pulmonary tuberculosis, and are considered among the most diagnostically useful HRCT features in this context [30, 31, 32].

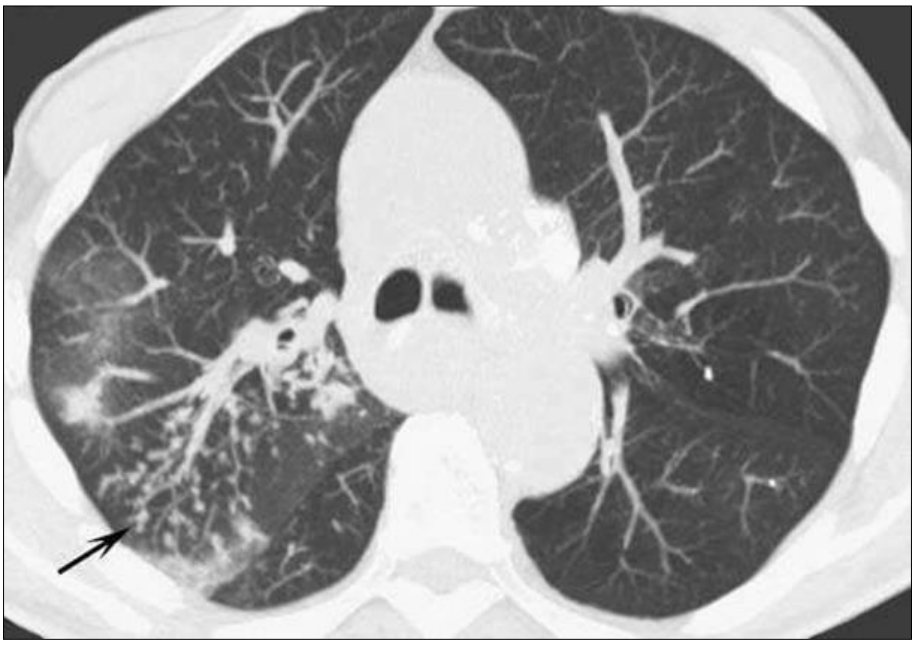

Fig 1: Centrilobular nodules with tree-in-bud pattern on HRCT imaging.

Consolidation on HRCT represents replacement of normal air-containing alveolar spaces by inflammatory exudate, caseous material, or fibrotic tissue, resulting in homogeneous or heterogeneous opacification of lung parenchyma within which air bronchograms may be visible [13, 15, 30]. In the context of active pulmonary TB, consolidation typically reflects coalescent areas of pneumonic infiltration or lobar involvement, and its presence on HRCT has been associated with sputum smear positivity and active bacteriological disease in multiple prior investigations [30, 31, 32]. Cavitation, another cardinal feature of active pulmonary TB, arises as a consequence of liquefactive necrosis within areas of caseous consolidation, with subsequent communication to the airway and expectoration of necrotic contents [1, 13, 30]. Cavities on HRCT may appear as thick-walled or thin-walled lucencies within areas of parenchymal opacity, and their presence correlates strongly with high mycobacterial burden, infectivity, and smear positivity [30, 31].

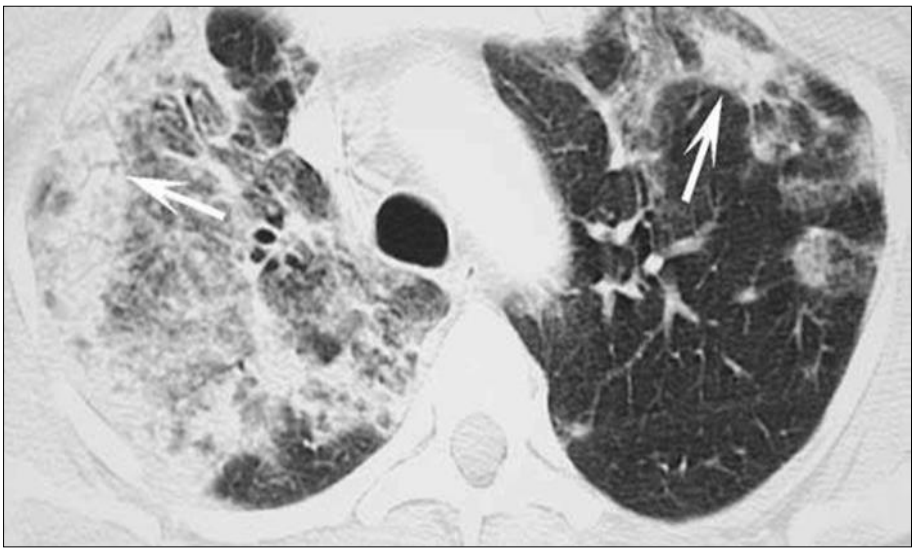

Fig 2: Consolidation on HRCT imaging (pointed by white arrows).

2. Aims and Objectives

The primary aim of this study was to systematically evaluate the HRCT findings in patients with pulmonary tuberculosis and to compare the frequency of specific radiological features between those with active disease, as defined by sputum smear positivity, and those with inactive disease, as defined by sputum smear negativity. The secondary objectives were to determine the statistical significance of the association between individual HRCT findings and disease activity status using Fisher's exact test, to identify HRCT features that may serve as reliable radiological predictors of active versus inactive pulmonary tuberculosis, and to assess the potential clinical utility of HRCT as an adjunct to microbiological confirmation in the assessment of TB disease activity. The findings of this study were intended to contribute to the evidence base supporting the role of HRCT in the management of pulmonary tuberculosis, with particular relevance to clinical scenarios in which prompt microbiological confirmation is unavailable or delayed.

3. Materials and Methods

3.1. Study Design and Setting

This study was conducted as a cross-sectional, observational investigation at a tertiary-level medical institution equipped with dedicated radiology and pulmonology services. The study was performed in accordance with the ethical principles of the Declaration of Helsinki, and appropriate institutional ethical clearance was obtained prior to patient enrollment. Written informed consent was obtained from all participating patients. HRCT examinations were performed on a multi-detector CT scanner using standardized high-resolution acquisition parameters, including thin-section collimation of 1 to 2 millimeters, high spatial frequency reconstruction algorithms, and targeted lung field imaging in full inspiration [17, 18, 19]. Images were reviewed and interpreted by experienced thoracic radiologists who were blinded to the microbiological results at the time of HRCT interpretation. Disease activity was classified on the basis of sputum smear microscopy results, with active tuberculosis defined as confirmed sputum smear positivity for acid-fast bacilli and inactive tuberculosis defined as smear negativity in the presence of clinical and radiological evidence of prior TB disease.

3.2. Inclusion and Exclusion Criteria

A total of 40 patients with pulmonary tuberculosis were enrolled consecutively over the study period. Patients were eligible for inclusion if they had a clinical diagnosis of pulmonary tuberculosis supported by one or more of the following: sputum smear examination results, compatible clinical symptoms including cough, hemoptysis, fever, and weight loss, and chest imaging findings consistent with pulmonary TB. Patients were excluded from the study if they had previously been treated with antituberculous therapy, if their clinical or radiological presentation was attributable to a confirmed alternative pulmonary pathology, if they were unable to cooperate with HRCT acquisition, or if contraindications to CT imaging were present. Of the 40 patients enrolled, 24 were classified as having active pulmonary tuberculosis based on sputum smear positivity, and 16 were classified as having inactive pulmonary tuberculosis based on sputum smear negativity with clinical and radiological features consistent with treated or quiescent prior TB disease.

3.3. Statistical Methods

Statistical analysis of the study data was performed using appropriate methods for categorical variables. The frequency and percentage distribution of each HRCT finding were calculated for the active and inactive TB groups separately. The Fisher's exact test was applied to assess the statistical significance of differences in the proportional distribution of each HRCT feature between the two groups, given the relatively small sample size and the presence of expected cell counts below five in several contingency tables. A p-value of less than 0.05 was considered statistically significant. All statistical computations were performed using standard statistical software.

4. Results

HRCT examinations were performed in all 40 patients and a total of twelve distinct HRCT features were systematically evaluated and compared between the active (n=24) and inactive (n=16) tuberculosis groups. The results for each feature are presented in the tables below. Statistical analysis revealed that six HRCT findings demonstrated statistically significant differences between the two groups, while the remaining six were statistically insignificant.

4.1. Centrilobular Nodules, Tree-in-Bud Pattern, and Consolidation

Centrilobular nodules were present in 20 of 24 active TB cases (83.33%) and in only 2 of 16 inactive cases (12.50%), a difference that was highly statistically significant (p=0.0001). The tree-in-bud pattern was identified in 17 active TB patients (70.84%) compared with 3 inactive cases (18.75%), yielding a statistically significant p-value of 0.003. Consolidation was present in 16 active TB patients (66.67%) and in 3 inactive patients (18.75%), with a statistically significant p-value of 0.004. These three findings collectively represent the most diagnostically discriminating HRCT features for active pulmonary tuberculosis identified in this study.

Table 1: Frequency Distribution of HRCT Findings in Active and Inactive Pulmonary Tuberculosis: Centrilobular Nodules, Tree-in-Bud, and Consolidation

HRCT Feature / Status	Active TB n	Active TB %	Inactive TB n	Inactive TB %	p-value (Fisher's)
Centrilobular Nodules					
Present	20	83.33%	2	12.50%	0.0001
Absent	4	16.67%	14	87.50%	
Total	24	100%	16	100%	
Tree-in-Bud Pattern					
Present	17	70.84%	3	18.75%	0.003
Absent	7	29.16%	13	81.25%	
Total	24	100%	16	100%	
Consolidation					
Present	16	66.67%	3	18.75%	0.004
Absent	8	33.33%	13	81.25%	
Total	24	100%	16	100%	

Note: The differences in the presence of centrilobular nodules, tree-in-bud pattern, and consolidation between active and inactive cases of pulmonary TB were all statistically significant (p less than 0.05).

4.2. Cavitation, Ground Glass Opacity, and Lymphadenopathy

Cavitation was detected in 16 active TB patients (66.67%) and in 4 inactive patients (25.00%), with a statistically significant p-value of 0.022. Ground glass opacity was present in 7 active cases (29.16%) and in 5 inactive cases (31.25%), yielding a p-value of 0.88, which was not statistically significant. Lymphadenopathy was identified in 10 active patients (41.67%) and in 5 inactive patients (31.25%), with a p-value of 0.739, which also did not reach statistical significance. These findings indicate that while cavitation is a meaningful marker of active disease, ground glass opacity and lymphadenopathy are distributed comparably across both disease activity states in this cohort.

Table 2: Frequency Distribution of Cavitation, Ground Glass Opacity, and Lymphadenopathy in Active and Inactive Pulmonary Tuberculosis

HRCT Feature / Status	Active TB n	Active TB %	Inactive TB n	Inactive TB %	p-value (Fisher's)
Cavitation					
Present	16	66.67%	4	25.00%	0.022
Absent	8	33.33%	12	75.00%	
Total	24	100%	16	100%	
Ground Glass Opacity					
Present	7	29.16%	5	31.25%	0.88
Absent	17	70.84%	11	68.75%	
Total	24	100%	16	100%	
Lymphadenopathy					
Present	10	41.67%	5	31.25%	0.739
Absent	14	58.33%	11	68.75%	
Total	24	100%	16	100%	

Note: Cavitation showed a statistically significant difference between active and inactive TB cases (p less than 0.05), whereas the differences in ground glass opacity and lymphadenopathy were statistically insignificant.

4.3. Fibrosis, Tractional Bronchiectasis, Emphysema, Pleural Effusion, Calcified Granuloma, and Pleural Thickening

Fibrosis was present in only 8 active TB patients (33.33%) but in 13 of 16 inactive patients (81.25%), a difference that was statistically significant (p=0.008), confirming its predominant association with chronic or treated disease. Tractional bronchiectasis similarly demonstrated a significantly higher prevalence in the inactive group, being present in 11 inactive patients (68.75%) compared with 7 active patients (29.16%), with a statistically significant p-value of 0.023. Emphysema was observed in 6 active (25.00%) and 9 inactive patients (56.25%), with a p-value of 0.093 that did not reach statistical significance. Pleural effusion was present in 9 active patients (37.50%) and 3 inactive patients (18.75%), with a non-significant p-value of 0.29. Calcified granuloma was identified in 5 active patients (20.83%) and 8 inactive patients (50.00%), with a p-value of 0.11. Pleural thickening was detected in 6 active (25.00%) and 9 inactive patients (56.25%), yielding a p-value of 0.13. The four features of emphysema, pleural effusion, calcified granuloma, and pleural thickening thus did not demonstrate statistically significant differences between the two groups.

Table 3: Frequency Distribution of Fibrosis, Tractional Bronchiectasis, Emphysema, Pleural Effusion, Calcified Granuloma, and Pleural Thickening in Active and Inactive Pulmonary Tuberculosis

HRCT Feature / Status	Active TB n	Active TB %	Inactive TB n	Inactive TB %	p-value (Fisher's)
Fibrosis					
Present	8	33.33%	13	81.25%	0.008
Absent	16	66.67%	3	18.75%	
Total	24	100%	16	100%	
Tractional Bronchiectasis					
Present	7	29.16%	11	68.75%	0.023
Absent	17	70.84%	5	31.25%	
Total	24	100%	16	100%	
Emphysema					
Present	6	25.00%	9	56.25%	0.093
Absent	18	75.00%	7	43.75%	
Total	24	100%	16	100%	
Pleural Effusion					
Present	9	37.50%	3	18.75%	0.29
Absent	15	62.50%	13	81.25%	
Total	24	100%	16	100%	
Calcified Granuloma					
Present	5	20.83%	8	50.00%	0.11
Absent	19	79.17%	8	50.00%	
Total	24	100%	16	100%	
Pleural Thickening					
Present	6	25.00%	9	56.25%	0.13
Absent	18	75.00%	7	43.75%	
Total	24	100%	16	100%	

Note: Fibrosis and tractional bronchiectasis showed statistically significant differences between active and inactive TB cases (p less than 0.05). Emphysema, pleural effusion, calcified granuloma, and pleural thickening were statistically insignificant and may be observed in both active and inactive disease.

5. Discussion

The findings of this study provide cross-sectional evidence supporting the utility of specific HRCT features in the radiological assessment of pulmonary TB disease activity, and broadly corroborate the results of several previously published investigations in this field [31-35]. The identification of a panel of HRCT findings — specifically centrilobular nodules, tree-in-bud pattern, consolidation, and cavitation — as statistically significant markers of active disease, combined with the recognition that fibrosis and tractional bronchiectasis are preferentially associated with inactive disease, offers a coherent radiological framework for the assessment of disease activity when microbiological data are unavailable or delayed.

The highly significant association between centrilobular nodules and active TB (p=0.0001) in this study is consistent with the observations of Hatipoglu *et al*., who reported centrilobular nodules in a high proportion of patients with active pulmonary TB and emphasized their value as a reliable indicator of active endobronchial disease [31]. Im *et al*. had earlier demonstrated that centrilobular nodules represent one of the earliest and most consistent HRCT changes in active pulmonary TB, corresponding to the pathological process of airway-centered caseous necrosis and peribronchiolar inflammation [30]. The present study's finding that centrilobular nodules were present in 83.33% of active cases but only 12.50% of inactive cases echoes these earlier reports and reinforces the diagnostic significance of this finding. Raniga *et al*. similarly identified centrilobular nodules as among the most frequent and diagnostically useful HRCT features in active pulmonary TB in their series [32], and the present data corroborate this position.

The tree-in-bud pattern demonstrated a statistically significant association with active TB in this study (p=0.003), with a prevalence of 70.84% in the active group compared with 18.75% in the inactive group. This finding aligns closely with prior reports. Im *et al*. described the tree-in-bud pattern as a characteristic HRCT manifestation of endobronchial spread in active pulmonary TB, representing the direct filling of small airways with infectious material and correlating with high mycobacterial burden [30]. Hatipoglu *et al*. similarly documented the tree-in-bud pattern as a feature predominantly observed in active disease [31]. Tozkoparan *et al*., in their study of HRCT parameters in suspected smear-negative pulmonary TB, identified the tree-in-bud pattern as one of the findings associated with microbiologically confirmed active disease, supporting its use as an activity indicator even in the challenging subset of smear-negative patients [33]. Nakanishi *et al*. likewise found the tree-in-bud pattern to be predictive of sputum smear positivity in their cohort, lending further support to its role as a marker of airway-centered active infection [35].

Consolidation was present in 66.67% of active TB patients and only 18.75% of inactive patients in this series (p=0.004), a finding consistent with the pathological basis of consolidation as representing ongoing airspace inflammation and pneumonic infiltration. Hatipoglu *et al*. reported consolidation as a frequent HRCT feature of active pulmonary TB [31], and the literature broadly supports consolidation as reflecting current disease activity, particularly when occurring in the typical upper lobe and apicoposterior distribution characteristic of post-primary tuberculosis [13, 15, 30]. Raniga *et al*. included consolidation among the HRCT features indicative of active disease in their

reliability study [32], and the present results reinforce this consensus. Majmudar and Rajput similarly identified consolidation as significantly associated with microbiologically confirmed active disease in their HRCT study, reporting prevalence figures broadly compatible with those observed in the present study [34].

Cavitation was detected in 66.67% of active and 25.00% of inactive TB patients (p=0.022), confirming a statistically significant association with active disease. The pathophysiological basis of cavitation in TB is well established, arising from liquefactive necrosis within consolidated lung tissue with communication to the bronchial tree and resulting in a highly infectious reservoir of mycobacteria [1, 13]. Hatipoglu *et al*. reported cavitation in a substantial proportion of their active TB cohort and recognized it as a major indicator of active bacteriological disease [31]. Tozkoparan *et al*. included cavitation among the HRCT features evaluated in their study of activity prediction in smear-negative TB and found it to contribute meaningfully to the diagnostic assessment [33]. The relatively high prevalence of cavitation even among inactive cases in the present series (25.00%) may reflect the persistence of healed or fibrotic cavities in patients with prior severe TB, which can be difficult to distinguish from active cavitation on the basis of morphology alone without serial imaging or clinical correlation.

Fibrosis demonstrated a markedly higher prevalence in the inactive TB group (81.25%) compared with the active group (33.33%) in this study (p=0.008). This finding is readily explicable on the basis of disease biology, as pulmonary fibrosis represents the end-stage sequela of granulomatous inflammation and tissue destruction following adequate treatment or spontaneous resolution of active TB [1, 13, 15]. The significant association of fibrosis with inactive disease in the present cohort is congruent with the observations of Raniga *et al*., who identified fibrosis as predominantly associated with inactive or treated TB in their HRCT reliability study [32]. Similarly, Majmudar and Rajput recognized fibrosis as a hallmark of treated or quiescent disease in their series [34]. Tractional bronchiectasis, which arises as a direct mechanical consequence of pulmonary fibrosis, was significantly more prevalent in the inactive group in the present study (68.75% versus 29.16%, p=0.023), a finding that parallels the distribution of fibrosis and reflects the shared pathological basis of both features as markers of longstanding parenchymal damage.

Ground glass opacity did not demonstrate a significant difference between active and inactive TB in this study (p=0.88), with nearly equal proportions of 29.16% and 31.25% in the respective groups. Ground glass opacity in pulmonary TB is generally considered to represent early inflammatory infiltration or hypersensitivity-mediated alveolar reaction, and its non-specific nature across multiple pulmonary pathologies likely accounts for its lack of discriminatory value between disease activity states in the present cohort [10, 30]. Hatipoglu *et al*. similarly noted that ground glass opacity did not reliably distinguish active from inactive TB in their series [31]. Lymphadenopathy was present in 41.67% of active and 31.25% of inactive patients, without statistical significance (p=0.739). While hilar and mediastinal lymphadenopathy is recognized as a common finding in primary and post-primary TB, and may reflect either active granulomatous inflammation or fibrocaseous healed nodes, the failure of lymphadenopathy in isolation to distinguish disease activity status is consistent with prior reports [15, 31, 32]. Emphysema, pleural effusion, calcified granuloma, and pleural thickening all showed statistically insignificant differences between the two groups. Emphysematous changes in TB-affected lungs may reflect airway destruction attributable to prior disease rather than ongoing active infection, explaining their occurrence in both groups [1, 10]. Calcified granulomas are recognized as markers of healed primary TB, and their higher prevalence in the inactive group (50.00% versus 20.83%), while not reaching statistical significance in this relatively small cohort, is consistent with their biological origin as residua of resolved disease [1, 13, 15]. Pleural effusion in pulmonary TB may occur in both active and reactive phases of the disease and is not reliably associated with current bacterial activity, as the effusion may in part represent a hypersensitivity immune response rather than direct pleural infection [1, 15]. Pleural thickening, similarly, may develop as a consequence of prior pleural disease irrespective of current parenchymal activity.

Taken together, the results of this study suggest that a combination of HRCT features, particularly the quartet of centrilobular nodules, tree-in-bud pattern, consolidation, and cavitation, provides a meaningful radiological basis for predicting active pulmonary TB, while fibrosis and tractional bronchiectasis preferentially indicate inactive or resolved disease. These findings are consistent with the emerging literature supporting HRCT as a clinically useful adjunct to microbiological confirmation in the assessment of TB disease activity [32, 33, 34, 35]. The limitations of this study include its cross-sectional design, the relatively small sample size of 40 patients, the use of sputum smear microscopy rather than mycobacterial culture as the reference standard for disease activity classification, and the restriction to a single center. Future studies with larger patient cohorts, culture-confirmed disease activity classification, and serial HRCT follow-up would strengthen the evidence base and enable more precise determination of the sensitivity and specificity of individual HRCT features as activity predictors.

6. Conclusion

This cross-sectional study demonstrates that several specific HRCT findings are significantly associated with active pulmonary tuberculosis as defined by sputum smear positivity, and that HRCT therefore has meaningful clinical utility as a complementary diagnostic modality in the assessment of TB disease activity. Centrilobular nodules, tree-in-bud pattern, consolidation, and cavitation were each significantly more prevalent in active disease, while fibrosis and tractional bronchiectasis were significantly more prevalent in inactive disease, consistent with their established pathophysiological correlates. Ground glass opacity, lymphadenopathy, emphysema, pleural effusion, calcified granuloma, and pleural thickening did not demonstrate statistically significant differences between active and inactive groups, limiting their individual discriminatory value. These results support the systematic interpretation of HRCT findings as a contribution to the clinical assessment of pulmonary TB disease activity, particularly in settings where microbiological confirmation is unavailable, delayed, or equivocal. The integration of HRCT into the diagnostic pathway for pulmonary TB has the potential to facilitate earlier treatment decisions, reduce the period of diagnostic uncertainty, and improve patient outcomes, and warrants further prospective evaluation in larger, multi-center studies

employing culture-based disease activity classification and long-term clinical follow-up.

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How to Cite This Article
Kalra S, Sylonia SC, Garga UC, Choudhary A. HRCT findings in pulmonary tuberculosis: predicting disease activity through radiological assessment. Int J Med All Body Health Res. 2026;7(1):157–164. doi:10.54660/IJMBHR.2026.7.1.157-164.