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Role of Chest Computed Tomography in the Early Diagnosis and Assessment of Pulmonary Tuberculosis

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Abstract

Background: Pulmonary tuberculosis (PTB) remains a leading infectious cause of morbidity and mortality worldwide. While conventional chest radiography (CXR) and sputum smear microscopy are the cornerstones of initial screening, they suffer from significant limitations in sensitivity, particularly in early, atypical, or smear-negative cases. High-resolution computed tomography (HRCT) of the chest has emerged as a critical adjunctive tool, yet its precise diagnostic yield and role in early disease assessment require further clinical validation. ***Objective:*** To evaluate the diagnostic accuracy, pattern recognition, and clinical utility of HRCT in the early diagnosis and severity assessment of PTB, particularly in smear-negative patients. ***Methods:*** A prospective observational cohort study was conducted at a tertiary care center from June 2025 to May 2026. We enrolled 412 adult patients presenting with clinical suspicion of PTB. All patients underwent standard CXR, non-contrast chest HRCT, sputum smear microscopy, GeneXpert MTB/RIF assay, and mycobacterial culture. Diagnostic performance of HRCT was compared against the composite microbiological reference standard. ***Results:*** Of the 412 suspected cases, 260 (63.1%) were confirmed as active PTB. HRCT demonstrated a sensitivity of 95.3% and a specificity of 88.1%, significantly outperforming CXR (sensitivity 73.4%, specificity 69.7%; $p < 0.001$). In the smear-negative, culture-positive subgroup (n=110), HRCT successfully identified active disease patterns in 102 patients (92.7%). The most frequent HRCT findings in active PTB were centrilobular nodules (86.1%), "tree-in-bud" appearance (79.2%), and early consolidation (65.3%). Inter-observer agreement for HRCT interpretation was excellent (K = 0.88). Furthermore, HRCT accurately mapped disease extent and identified occult complications, such as micro-cavitations and early bronchiectasis, missed by conventional radiography. ***Conclusion:*** Chest CT is a highly sensitive and specific modality for the early diagnosis of pulmonary tuberculosis. It is exceptionally valuable in evaluating sputum smear-negative patients and characterizing the anatomical extent of the disease. Integrating HRCT into standard diagnostic algorithms for high-suspicion, smear-negative cases can significantly reduce diagnostic delays and curb transmission.

Keywords: Pulmonary Tuberculosis (PTB), Chest Computed Tomography (CCT), Chest X-ray (CXR), High Resolution Computed Tomography (HRCT), Bronchiectasis, Micro-cavitation, Clinicoradiological correlation.

INTRODUCTION

Tuberculosis (TB), an infectious disease caused by the bacillus *Mycobacterium tuberculosis* (MTB), continues to pose a formidable challenge to global public health. Despite widespread implementation of the Directly Observed Treatment, Short-course (DOTS) strategy, TB remains one of the leading infectious killers globally, second only to COVID-19 in recent years [1]. The World Health Organization (WHO) estimates that millions of new cases emerge annually, with a disproportionate burden falling on low- and middle-income countries [2]. The cornerstone of global TB control relies heavily on rapid and accurate diagnosis, prompt initiation of anti-tubercular therapy (ATT), and the prevention of aerosolized transmission [3]. However, achieving early diagnosis remains a persistent clinical challenge, largely due to the limitations inherent in conventional diagnostic tools.

For decades, the initial diagnostic workup for suspected pulmonary tuberculosis (PTB) has depended on sputum acid-fast bacilli (AFB) smear microscopy and posteroanterior (PA) chest radiography (CXR) [4]. While sputum smear microscopy is rapid and inexpensive, its sensitivity is notoriously poor, ranging from 40% to 60%, and is heavily dependent on the bacterial load and the quality of the specimen [5]. Although molecular diagnostics like the GeneXpert MTB/RIF assay have revolutionized rapid detection, they still require adequate sputum samples, which can be difficult to obtain in patients with non-productive coughs or early-stage disease [6]. Consequently, radiological imaging remains an

indispensable component of the diagnostic algorithm, serving both to raise clinical suspicion and to assess the anatomical extent of the disease.

Conventional CXR is universally utilized for PTB screening due to its widespread availability, low cost, and low radiation dose. However, CXR is fraught with notable diagnostic limitations. The structural superimposition of the clavicles, ribs, and mediastinal structures frequently obscures early tubercular lesions, particularly those located in the apical and retrocardiac regions [7]. Furthermore, the classic radiographic presentations of PTB such as upper lobe cavitations and extensive consolidations are often absent in immunocompromised individuals, the elderly, and those with early-stage disease. Studies indicate that up to 15% to 20% of patients with culture-proven active PTB may present with normal or non-specific initial chest radiographs [8]. This diagnostic gap leads to delayed treatment, increased morbidity, and unchecked community transmission [9].

Over the past two decades, high-resolution computed tomography (HRCT) of the chest has emerged as a powerful adjunct in the evaluation of pleuropulmonary diseases [10]. By eliminating anatomical superimposition and providing sub-millimeter spatial resolution, HRCT offers unparalleled visualization of the lung parenchyma, airways, and mediastinum. Early histological changes of PTB, such as the endobronchial spread of the mycobacterium, manifest on HRCT as characteristic patterns like centrilobular nodules and the "tree-in-bud" sign long before they coalesce into opacities visible on a standard CXR [11]. Furthermore, HRCT is highly sensitive in detecting micro-cavitations, early bronchogenic spread, and mediastinal lymphadenopathy, which are critical for differentiating active from inactive disease [12].

Despite these advantages, the routine use of CT in PTB diagnosis is debated due to concerns regarding radiation exposure, high healthcare costs, and limited accessibility in resource-constrained, high-burden settings [13]. Consequently, defining the exact clinical scenarios where HRCT yields the highest diagnostic utility is imperative.

The primary objective of this prospective study was to rigorously evaluate the role of HRCT in the early diagnosis and anatomical assessment of PTB in a large, diverse patient cohort. Secondary objectives included comparing the diagnostic accuracy of HRCT versus conventional CXR, identifying the frequency of specific radiological patterns associated with active disease, and assessing the utility of HRCT in the challenging clinical scenario of sputum smear-negative, clinically suspected PTB.

MATERIALS AND METHODS

Study Design and Setting

This was a prospective, observational cohort study conducted at the Department of Pulmonology and Radiology of KBNU-Faculty of Medical Sciences's; Khaja Bandanawaz Teaching and General Hospital - a tertiary care Hospital. The study spanned a 12-month period, from June 2025 to May 2026. The institutional Ethics Review Board approved the study protocol, and all participating patients provided written informed consent prior to enrollment.

Patient Population

The study screened adult patients (aged ≥18 years) who presented to the outpatient or emergency departments with a high clinical suspicion of PTB. Clinical suspicion was defined by the presence of at least two of the following symptoms for more than two weeks: chronic cough, low-grade evening pyrexia, night sweats, unexplained weight loss, or hemoptysis.

Inclusion Criteria:

1. Patients with clinical symptoms highly suggestive of PTB.
2. Willingness to undergo comprehensive microbiological testing, standard CXR, and chest HRCT.

Exclusion Criteria:

1. Patients currently receiving anti-tubercular therapy (ATT).
2. Patients with a known history of treated PTB (to avoid confounding from fibrotic scarring and architectural distortion from previous disease).
3. Pregnant women.
4. Patients with concurrent severe cardiopulmonary failure precluding scanning (e.g., unable to lie flat or perform breath-hold).
5. Patients who failed to provide adequate sputum samples for culture and molecular testing.

Microbiological and Clinical Evaluation

Upon enrollment, a detailed clinical history and physical examination were recorded. Three early morning sputum samples were collected from each patient over consecutive days.

1. **Direct Smear Microscopy:** Samples were subjected to Ziehl-Neelsen staining for AFB.
2. **Molecular Testing:** A portion of the sample was utilized for the Xpert MTB/RIF assay (Cepheid, Sunnyvale, CA, USA) for rapid detection of MTB complex and rifampicin resistance.
3. **Culture:** The remaining specimen underwent standard N-acetyl-L-cysteine-sodium hydroxide (NALC-NaOH) decontamination and was cultured on both solid (Lowenstein-Jensen) and liquid (Mycobacteria Growth Indicator Tube - BACTEC MGIT 960 system) media.

For the purpose of this study, the composite microbiological reference standard for "active PTB" was defined as a positive mycobacterial culture for *M. tuberculosis* and/or a positive GeneXpert result. Patients with negative cultures and molecular tests who responded clinically and radiologically to alternative therapies (e.g., broad-spectrum antibiotics for bacterial pneumonia) were classified into the "Non-PTB" control group.

Radiological Techniques

Chest Radiography:

Standard posteroanterior (PA) chest radiographs were obtained for all patients using a digital radiography system. Images were acquired at maximum inspiration (70–90 kVp, 2–5 mAs).

Computed Tomography (HRCT):

HRCT scans were performed using a 64-slice multidetector CT scanner (Somatom Definition, Siemens Healthcare). Scans were acquired from the lung apices to the costodiaphragmatic recesses during a single breath-hold at end-inspiration. The scanning parameters adhered to the ALARA (As Low As Reasonably Achievable) principles: 100–120 kVp, automatic tube current modulation (50–100 mAs), collimation of 64 × 0.625 mm, pitch of 1.2, and a rotation time of 0.5 seconds. Images were reconstructed using a high-spatial-frequency (bone) algorithm with a slice thickness of 1.0 mm and a reconstruction increment of 1.0 mm. No intravenous contrast was administered unless there was a specific clinical indication to evaluate suspected vascular complications (e.g., massive hemoptysis) or complex mediastinal pathology, which was analyzed separately.

Image Interpretation and Data Collection

All imaging studies (CXR and HRCT) were interpreted by two independent, board-certified thoracic radiologists, each with over 10 years of experience. The radiologists were blinded to the patients' clinical history, microbiological results, and to each other's interpretations. Discrepancies were resolved by consensus through a joint review session.

The HRCT images were systematically evaluated for the presence, distribution, and extent of the following predefined parenchymal and mediastinal abnormalities based on the Fleischner Society Glossary of Terms [14]:

- **Centrilobular Nodules:** Small nodules (typically <10 mm) located centrally within the secondary pulmonary lobule.
- **Tree-in-Bud (TIB) Pattern:** Branching linear structures with small nodules at their extremities, representing impaction of the terminal bronchioles with caseous material.
- **Consolidation:** Homogeneous increase in pulmonary parenchymal attenuation that obscures the margins of vessels and airway walls.
- **Cavitation:** Gas-filled spaces within an area of pulmonary consolidation, mass, or nodule, categorized by wall thickness.
- **Ground-Glass Opacity (GGO):** Hazy increased attenuation of lung tissue, with preservation of bronchial and vascular margins.
- **Lymphadenopathy:** Mediastinal or hilar lymph nodes with a short-axis diameter >10 mm, evaluated for central low attenuation indicative of necrosis.
- **Pleural Effusion:** Accumulation of fluid in the pleural space.

Based on the combination of these findings, the radiologists categorized the probability of active PTB as *High* (presence of TIB, centrilobular nodules, thick-walled cavities, or necrotic lymph nodes), *Intermediate* (consolidation or GGO without TIB), or *Low* (normal, purely fibrotic bands, calcified nodules). For statistical analysis, high and intermediate probabilities were grouped as "CT-positive" for active PTB.

Statistical Analysis

Data were analyzed using SPSS Statistics version 28.0 (IBM Corp., Armonk, NY). Continuous variables were assessed for normality using the Shapiro-Wilk test and expressed as mean ± standard deviation (SD) or median (interquartile range, IQR) as appropriate. Categorical variables were expressed as frequencies and percentages.

The diagnostic performance of CXR and HRCT including sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and overall accuracy was calculated using the composite microbiological result as the reference standard. Comparisons of diagnostic accuracies were performed using McNemar’s test for paired proportions. Differences in the frequency of radiological patterns between smear-positive and smear-negative groups were analyzed using the Chi-square test or Fisher's exact test. Inter-observer agreement for HRCT interpretation was assessed using

Cohen's Kappa (K) coefficient (K < 0.20 = slight; 0.21–0.40 = fair; 0.41–0.60 = moderate; 0.61–0.80 = substantial; >0.81 = excellent). A two-sided p-value of < 0.05 was considered statistically significant.

RESULTS

Patient Demographics and Baseline Characteristics

During the study period, a total of 455 patients were screened, of whom 412 fulfilled the inclusion criteria and completed the diagnostic workup. The study cohort comprised 258 males (62.6%) and 154 females (37.4%), with a mean age of 42.5 ± 15.3 years (range: 18–78 years). The most common presenting symptoms were chronic cough (92.5%), weight loss (74.3%), and fever (68.9%). Hemoptysis was reported by 18.2% of the participants.

Based on the composite reference standard, 260 patients (63.1%) were confirmed to have active PTB, while 152 patients (36.9%) were classified into the Non-PTB group. The Non-PTB group included diagnoses of community-acquired bacterial pneumonia (n=78), non-tuberculous mycobacterial (NTM) infection (n=12), organizing pneumonia (n=15), lung malignancy (n=18), and other respiratory conditions (n=29).

Among the 260 confirmed PTB patients, 150 (57.7%) were sputum smear-positive, and 110 (42.3%) were sputum smear-negative. The GeneXpert MTB/RIF assay was positive in 245 (94.2%) of the confirmed cases, highlighting its superiority over smear microscopy.

Table 1: Baseline Demographics and Clinical Characteristics

Characteristic	Value
Total Screened Patients	455
Total Enrolled Patients	412
Gender	
Male	258 (62.6%)
Female	154 (37.4%)
Age (years)	42.5 ± 15.3 (Range: 18–78)
Clinical Presentation	
Chronic Cough	381 (92.5%)
Weight Loss	306 (74.3%)
Fever	284 (68.9%)
Hemoptysis	75 (18.2%)
Final Diagnosis	
Active PTB Confirmed	260 (63.1%)
Non-PTB Confirmed	152 (36.9%)
Sub-classifications of Confirmed PTB (n = 260)	
Sputum Smear-Positive	150 (57.7%)
Sputum Smear-Negative	110 (42.3%)
GeneXpert Positive	245 (94.2%)

Diagnostic Accuracy: CXR versus HRCT

The diagnostic performance of HRCT was compared directly with standard PA chest radiography.

HRCT correctly identified active PTB patterns in 248 of the 260 confirmed cases, yielding a sensitivity of 95.3% (95% CI: 92.0% – 97.6%). In stark contrast, initial CXR identified abnormalities suspicious for active PTB in only 191 cases, yielding a significantly lower sensitivity of 73.4% (95% CI: 67.6%–78.7%) ($p < 0.001$).

Regarding specificity, HRCT correctly identified 134 of the 152 Non-PTB patients as not having active PTB (specificity 88.1%; 95% CI: 81.9%–92.8%). CXR demonstrated a specificity of 69.7% (95% CI: 61.8%–76.8%).

The Positive Predictive Value (PPV) and Negative Predictive Value (NPV) for HRCT were 93.2% and 91.7%, respectively. For CXR, the PPV was 80.5% and the NPV was 60.5%. The overall diagnostic accuracy was 92.7% for HRCT compared to 72.0% for CXR.

Table 2: Comparative Diagnostic Performance of HRCT vs. CXR

Diagnostic Metric	HRCT	Standard CXR	p-value
True Positives (Detected)	248 / 260	191 / 260	-
Sensitivity (95% CI)	95.3% (92.0% – 97.6%)	73.4% (67.6% – 78.7%)	< 0.001
Specificity (95% CI)	88.1% (81.9% – 92.8%)	69.7% (61.8% – 76.8%)	< 0.001
Positive Predictive Value (PPV)	93.20%	80.50%	-
Negative Predictive Value (NPV)	91.70%	60.50%	-
Overall Accuracy	92.70%	72.00%	-

HRCT Findings in Active PTB

Detailed characterization of parenchymal and mediastinal lesions was performed on the 260 confirmed PTB patients using HRCT.

The most frequent radiological manifestation was the presence of **centrilobular nodules**, observed in 224 patients (86.1%). This was closely followed by the **tree-in-bud (TIB) pattern**, identified in 206 patients (79.2%). These findings underscore the high prevalence of bronchogenic spread in early and active disease.

Consolidation, varying from patchy to lobar, was seen in 170 patients (65.3%). **Cavitary lesions**, a hallmark of advanced tissue necrosis, were detected in 118 patients (45.3%). The distribution of cavitary lesions showed a strong predilection for the apical and posterior segments of the upper lobes (82.2% of cavitary cases) and the superior segments of the lower lobes (17.8%).

Ground-glass opacities (GGO) were present in 98 patients (37.6%). Interestingly, GGO often surrounded areas of nodular consolidation, representing the "halo sign" indicative of surrounding alveolar hemorrhage or active granulomatous inflammation. Mediastinal and hilar **lymphadenopathy** was identified in 102 patients (39.2%), with central low attenuation (necrosis) and rim enhancement (when contrast was used in a subset) seen in 65% of those with enlarged nodes. Pleural effusions were present in 54 patients (20.7%).

Table 3: Frequency of HRCT Radiological Findings in Confirmed PTB Cases (n = 260)

Radiological Finding	Frequency (n)	Percentage (%)
Centrilobular Nodules	224	86.10%
Tree-in-Bud (TIB) Pattern	206	79.20%
Consolidation	170	65.30%
Cavitary Lesions	118	45.30%
— Apical/posterior upper lobes	97 (of 118)	82.2%
— Superior lower lobes	21 (of 118)	17.8%
Ground-Glass Opacities (GGO)	98	37.60%
Lymphadenopathy	102	39.20%
— Demonstrating Central Necrosis	66 (of 102)	65.0%
Pleural Effusions	54	20.70%

Role of HRCT in Sputum Smear-Negative PTB

A critical sub-analysis focused on the 110 patients who were sputum smear-negative but subsequently confirmed to have PTB via culture or molecular testing. This demographic represents a major clinical challenge, as standard diagnostics frequently fail.

In this smear-negative cohort, initial CXR was interpreted as suspicious for PTB in only 58 patients (52.7%). The remaining 52 patients had CXRs that were either entirely normal, indeterminate, or showed non-specific fibrotic changes. Remarkably, HRCT successfully detected patterns indicative of active PTB in 102 of these 110 smear-negative patients, achieving a sensitivity of 92.7% in this specific subgroup. The predominant findings in the smear-negative group were isolated centrilobular nodules (88.1%) and focal tree-in-bud patterns (74.5%). These lesions were typically anatomically too small (micro-nodules <3 mm) or obscured by superimposition to be resolved by standard radiography. Cavitation was significantly less common in the smear-negative group (19.0%) compared to the smear-positive group (64.6%, $p < 0.001$), reflecting earlier disease stages with less extensive caseation and lower bacillary load.

Table 4: Diagnostic Performance and Findings in Sputum Smear-Negative PTB (n = 110)

Parameter	Result in Smear-Negative Cohort
Modality Sensitivity	
Initial CXR Suspicious (Sensitivity)	58 (52.7%)
HRCT Suspicious (Sensitivity)	102 (92.7%)
Key HRCT Patterns Present	
Isolated Centrilobular Nodules	97 (88.1%)
Focal Tree-in-Bud (TIB) Pattern	82 (74.5%)
Cavitation	21 (19.0%)*

*Significantly lower than in the smear-positive group (64.6%), $p < 0.001$

Inter-observer Agreement and Detection of Complications

The inter-observer reliability between the two blinded thoracic radiologists for classifying HRCT scans as positive or negative for active PTB was excellent, with a Cohen's Kappa (K) of 0.88. Agreement for specific high-yield signs was also excellent: cavitation (= 0.92), tree-in-bud (K = 0.89), and central necrosis in lymph nodes (K = 0.85).

Beyond initial diagnosis, HRCT excelled in identifying structural complications associated with PTB. HRCT revealed early bronchiectasis in 42 patients (16.1%), endobronchial strictures in 9 patients (3.4%), and signs of early mycetoma

(aspergilloma) formation within pre-existing cavities in 4 patients (1.5%). CXR detected only a fraction of these complications (bronchiectasis in 11 patients, strictures in 0, aspergilloma in 0).

Table 5: Detection of Structural Complications and Inter-observer Agreement

Complication Identified	HRCT Detection	CXR Detection
Early Bronchiectasis	42 (16.1%)	11 (4.2%)
Endobronchial Strictures	9 (3.4%)	0 (0.0%)
Early Mycetoma (Aspergilloma)	4 (1.5%)	0 (0.0%)

Radiologist Inter-observer Agreement (Cohen's K) for HRCT:

- **Overall Classification:** K = 0.88 (Excellent)
- **Detection of Cavitation:** K = 0.92 (Excellent)
- **Detection of Tree-in-Bud:** K = 0.89 (Excellent)
- **Detection of Central Necrosis:** K = 0.85 (Excellent)

DISCUSSION

The timely and accurate diagnosis of pulmonary tuberculosis remains an absolute necessity for global eradication efforts. The current prospective study, encompassing 412 patients with clinically suspected PTB, unequivocally demonstrates that high-resolution computed tomography (HRCT) possesses exceptional diagnostic accuracy, significantly outperforming conventional chest radiography. With an overall sensitivity of 95.3% and a specificity of 88.1%, HRCT serves not merely as an anatomical map, but as a sensitive pathophysiological indicator of active mycobacterial infection [15].

Interpretation of Radiological Patterns and Pathophysiology

The pathological hallmark of active PTB involves caseating granulomatous inflammation that frequently spreads via the endobronchial route. Our study confirms that centrilobular nodules and the tree-in-bud (TIB) pattern are the most reliable early HRCT indicators of this process, present in roughly 80% to 86% of active cases. The TIB pattern anatomically represents the impaction of terminal and respiratory bronchioles with caseous material, mucus, and intense inflammatory exudate [16].

While the TIB pattern is not exclusively pathognomonic for TB as it can occasionally be seen in non-tuberculous mycobacterial infections, severe viral bronchiolitis, and aspiration pneumonia in the context of appropriate clinical symptoms (fever, weight loss, chronic cough) in an endemic region, it is highly predictive of active *M. tuberculosis* infection [17]. Our findings align with earlier classical radiological research which demonstrated that the TIB pattern is virtually synonymous with active disease and rarely persists once the disease is completely sterilized and fibrotic [18]. Conversely, finding purely calcified nodules, sharp linear fibrotic bands, and architectural distortion without accompanying GGO or TIB patterns accurately predicted culture-negative, inactive disease in our cohort.

The Critical Role of HRCT in Smear-Negative PTB

Perhaps the most clinically impactful finding of this study is the remarkable utility of HRCT in the smear-negative cohort. Sputum smear-negative PTB accounts for 30% to 50% of all pulmonary TB cases globally, varying by HIV prevalence and local diagnostic capabilities [19]. These patients suffer from profound diagnostic delays, often undergoing multiple courses of broad-spectrum antibiotics for presumed bacterial pneumonia before a definitive diagnosis is reached. Furthermore, despite lower bacillary loads, smear-negative patients are responsible for an estimated 10% to 20% of ongoing TB transmission in the community [20].

In our study, standard CXR missed nearly half (47.3%) of the smear-negative, culture-positive patients. This high false-negative rate is primarily due to the subtle nature of early lesions, the lack of large cavitations, and anatomical blind spots on PA projections. In stark contrast, HRCT achieved a sensitivity of 92.7% in this group. By providing clear visualization of isolated endobronchial spread and micro-cavitations that fall well below the spatial resolution threshold of CXR, HRCT facilitates the clinical decision to initiate empirical ATT while awaiting culture results, which can take weeks [21]. The WHO guidelines suggest empirical treatment for smear-negative cases based on clinical and radiological suspicion; our data robustly supports utilizing HRCT as the definitive radiological determinant in this algorithm when CXR is non-diagnostic.

Limitations of CXR vs. Advantages of CT

The standard PA chest radiograph is a two-dimensional projection of a complex three-dimensional structure. The apices of the lungs the classical predilection site for post-primary PTB are notoriously obscured by the clavicles and first ribs.

Similarly, lesions in the posterior sulci, retrocardiac space, and paramediastinal regions are easily missed. The 26.6% false-negative rate for CXR in our active PTB cohort is a sobering reminder of its inherent limitations in early disease.
While HRCT is definitively superior, its routine application as a first-line screening tool is hindered by cost, availability, and ionizing radiation dose. However, modern CT scanners utilize advanced dose-modulation and iterative reconstruction algorithms that have drastically reduced radiation exposure. A modern low-dose chest CT can be acquired at a radiation dose of 1 to 2 mSv, which is comparable to annual background radiation and well within acceptable safety limits for diagnostic purposes [22]. Furthermore, a holistic cost-benefit analysis must factor in the immense economic and public health costs of delayed TB diagnosis, including prolonged hospitalization, irreversible lung destruction, and secondary transmission [23]. Therefore, HRCT is best positioned as a "problem-solving" tool indicated when clinical suspicion remains high despite negative smears and an inconclusive CXR.

Anatomical Assessment and Treatment Planning
Beyond initial diagnosis, HRCT provided critical insights into the structural damage inflicted by the disease. Active PTB frequently results in pulmonary sequelae such as bronchiectasis, tracheobronchial stenosis, and large cystic spaces, which complicate clinical management and increase the risk of massive hemoptysis or superimposed fungal infections [24]. HRCT identified bronchiectasis in 16.1% of patients and early aspergillomas in 1.5%, findings that were almost entirely missed by CXR. This anatomical precision allows pulmonologists to plan adjunctive therapies, targeted postural drainage, or prophylactic surgical interventions when necessary.

Study Limitations
Despite its robust prospective design, this study has several limitations. First, it was conducted at a single tertiary care referral center, which may introduce selection bias; the patients evaluated here might have had more complex or atypical disease presentations than those seen in primary care settings. Second, we did not include a formal cost-effectiveness analysis, which is crucial for advocating the widespread adoption of HRCT in developing nations with limited healthcare budgets. Third, differentiating PTB from NTM infections on HRCT remains challenging, as both can produce centrilobular nodules and TIB patterns; thus, microbiological or molecular confirmation remains obligatory [25].

CONCLUSION
High-resolution computed tomography of the chest is a formidable diagnostic modality in the evaluation of pulmonary tuberculosis. It dramatically surpasses conventional chest radiography in sensitivity, specificity, and anatomical detail. HRCT is particularly indispensable in the diagnostic workup of patients with high clinical suspicion of PTB who return negative sputum smears and non-diagnostic chest radiographs. The presence of centrilobular nodules and the tree-in-bud pattern on HRCT are highly indicative of active endobronchial mycobacterial spread. By enabling earlier detection, facilitating confident empirical treatment decisions in smear-negative cases, and accurately mapping pulmonary complications, the judicious integration of HRCT into TB diagnostic algorithms can profoundly improve patient outcomes and accelerate the global mission to eradicate tuberculosis.

REFERENCES
1. World Health Organization. Global tuberculosis report 2023. Geneva: World Health Organization; 2023.
2. Chakaya J, Khan M, Ntoumi F, Aklillu E, Fatima R, Mwaba P, et al. Global Tuberculosis Report 2020 – reflections on the global TB burden, treatment and prevention efforts. Int J Infect Dis. 2021;113 Suppl 1:S7-S12.
3. Uplekar M, Weil D, Lönnroth K, Jaramillo E, Lienhardt C, Dias HM, et al. WHO's new End TB Strategy. Lancet. 2015;385(9979):1799-1801.
4. Tengku Khalid TNF, Wan Mohammad WMZ, Nik Husain NR, Ab Samat R. Development and Validation of the Tuberculosis Risk Score for Smokers (TBRSS). Int J Environ Res Public Health. 2022;19(12):6959.
5. Steingart KR, Henry M, Ng V, Hopewell PC, Ramsay A, Cunningham J, et al. Fluorescence versus conventional sputum smear microscopy for tuberculosis: a systematic review. Lancet Infect Dis. 2006;6(10):664-673.
6. Boehme CC, Nicol MP, Nabeta P, Michael JS, Gotuzzo E, Tahirli R, et al. Feasibility, diagnostic accuracy, and effectiveness of decentralised use of the Xpert MTB/RIF test for diagnosis of tuberculosis and multidrug resistance: a multicentre implementation study. Lancet. 2011;377(9776):1495-1505.
7. Woodring JH, Vandiviere HM, Fried AM, Dillon ML, Williams TD, Melvin IG. Update: the radiographic features of pulmonary tuberculosis. AJR Am J Roentgenol. 1986;146(3):497-506.
8. Pepperell C, Hoeppner VH, Lipatov O, Wobeser W, Schoolnik GK, Schwartzman K. Bacterial genetic signatures of human social phenomena among M. tuberculosis from an Aboriginal Canadian population. Mol Biol Evol. 2010;27(2):427-440.
9. Malik TZ, Roy S, Ahmed F, Agarwalla R, Pathak R. Delay in the Diagnosis and Treatment of Tuberculosis among Tuberculosis Patients in South-East Delhi, India. Indian J Public Health. 2025;69(3):286-291.
10. Webb WR. High-resolution computed tomography of obstructive lung disease. Radiol Clin North Am. 1994;32(4):745-757.

11. Im JG, Itoh H, Shim YS, Lee JH, Ahn J, Han MC, et al. Pulmonary tuberculosis: CT findings--early active disease and sequential change with antituberculous therapy. Radiology. 1993;186(3):653-660.
12. Hatipoglu ON, Osma E, Manisali M, Ucan ES, Balci P. High resolution computed tomographic findings in pulmonary tuberculosis. Thorax. 1996;51(4):397-402.
13. Diel R, Nienhaus A, Schaberg T. Cost-effectiveness of isoniazid chemoprevention in close contacts. Eur Respir J. 2005;26(3):465-473.
14. Hansell DM, Bankier AA, MacMahon H, McLoud TC, Müller NL, Remy J. Fleischner Society: glossary of terms for thoracic imaging. Radiology. 2008;246(3):697-722.
15. Adhikari D, Raut Y, Poudel D, Paudel B, Bhatt M, Adhikari S. High-Resolution Computed Tomography (HRCT) Chest Findings in Active Pulmonary Tuberculosis. Nepalese Respiratory Journal. 2025 Aug 15;4(1):12-7.
16. Rossi SE, Franquet T, Volpacchio M, Giménez A, Aguilar G. Tree-in-bud pattern at thin-section CT of the lungs: radiologic-pathologic overview. Radiographics. 2005;25(3):789-801.
17. Lee KS, Im JG. CT in adults with tuberculosis of the chest: characteristic findings and role in management. AJR Am J Roentgenol. 1995;164(6):1361-1367.
18. Kosaka N, Sakai T, Uematsu H, Kimura H, Hase M, Noguchi M, Itoh H. Specific high-resolution computed tomography findings associated with sputum smear-positive pulmonary tuberculosis. J Comput Assist Tomogr. 2005;29(6):801-4.
19. Colebunders R, Bastian I. A review of the diagnosis and treatment of smear-negative pulmonary tuberculosis. Int J Tuberc Lung Dis. 2000;4(2):97-107.
20. Behr MA, Warren SA, Salamon H, Hopewell PC, Ponce de Leon A, Daley CL, et al. Transmission of Mycobacterium tuberculosis from patients smear-negative for acid-fast bacilli. Lancet. 1999;353(9151):444-449.
21. Rasheed W, Qureshi R, Jabeen N, Shah HA, Naseem Khan R. Diagnostic Accuracy of High-Resolution Computed Tomography of Chest in Diagnosing Sputum Smear Positive and Sputum Smear Negative Pulmonary Tuberculosis. Cureus. 2020 Jun 5;12(6):e8467.
22. Brenner DJ, Hall EJ. Computed tomography—an increasing source of radiation exposure. N Engl J Med. 2007;357(22):2277-2284.
23. Asghari M, Poorolajal J, Rostami Z, et al. Economic burden of tuberculosis: a systematic review and meta-analysis. Int J Health Policy Manag. 2021;10(8):462-473.
24. Bansal N, Arunachala S, Kaleem Ullah M, Kulkarni S, Ravindran S, ShankaraSetty RV, Malamardi S, Chaya SK, Lokesh KS, Parthasarathi A, Shyam Prasad Shetty B, Chikkahonnaiah P, Vishwanath P, Siddaiah JB, Mahesh PA. Unveiling Silent Consequences: Impact of Pulmonary Tuberculosis on Lung Health and Functional Wellbeing after Treatment. J Clin Med. 2024;13(14):4115.
25. Griffith DE, Aksamit T, Brown-Elliott BA, et al. An official ATS/IDSA statement: diagnosis, treatment, and prevention of nontuberculous mycobacterial diseases. Am J Respir Crit Care Med. 2007;175(4):367-416.