Tuberculosis Aerosol Transmission and Control: A Survey

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Abstract

This survey provides a comprehensive analysis of tuberculosis (TB) research and public health strategies, focusing on the transmission dynamics of Mycobacterium tuberculosis (Mtb) through aerosols, early-stage TB characteristics, diagnostic advancements, and public health interventions. TB remains a significant global health challenge, exacerbated by factors such as drug resistance and co-infections with diseases like HIV/AIDS. The survey underscores the critical role of understanding aerosol transmission in TB control, particularly in healthcare settings, and highlights recent technological advancements in aerosol sampling and detection, which are pivotal for improving diagnostic accuracy and reducing transmission. Furthermore, the survey explores the influence of lung morphology on TB outcomes, emphasizing the need for targeted interventions to address age-related changes in lung function. Public health strategies, including infection control practices, educational and policy interventions, and socio-economic measures, are thoroughly reviewed, with a focus on enhancing TB management and prevention. The integration of omics technologies offers new insights into TB pathogenesis and transmission dynamics, facilitating the development of targeted therapies. The survey concludes by advocating for a multifaceted approach to TB control, combining diagnostic innovations, therapeutic advancements, and effective public health policies to mitigate TB transmission and improve global health outcomes.

1 Introduction

1.1 Public Health Impact of Tuberculosis

Tuberculosis (TB) remains a significant global public health challenge, with approximately one-quarter of the world's population infected with Mycobacterium tuberculosis (Mtb) [1]. Transmission primarily occurs through inhalation of infectious aerosols from individuals with active TB, which can persist in overcrowded and poorly ventilated environments [2]. This situation necessitates stringent infection control measures, particularly in high-incidence regions.

Several factors exacerbate the global TB burden, including inadequate diagnostic capabilities that often overlook cases in high-burden areas [1]. The rise of drug-resistant TB (DR-TB) complicates management strategies [3], while cavitary TB, linked to poor treatment outcomes and increased transmission, further complicates control efforts [4].

Healthcare workers (HCWs) are at heightened risk of TB transmission due to occupational exposure, necessitating enhanced infection control practices in healthcare settings [5]. The prevalence of latent TB infection (LTBI) among HCWs is significantly higher than in the general population, underscoring the need for targeted interventions [5].

The interplay between TB and other severe health conditions, such as HIV/AIDS and acute leukemia, complicates the public health landscape. TB is the leading cause of HIV/AIDS-related mortality globally, particularly affecting HIV-positive individuals in sub-Saharan Africa [6]. Additionally, TB

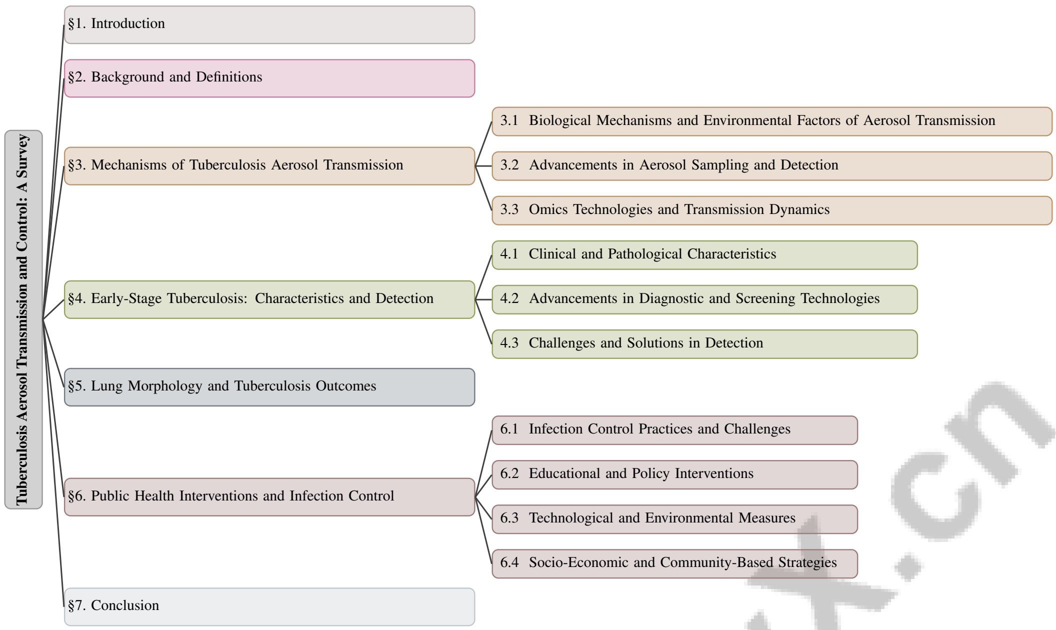

Figure 1: chapter structure

contributes significantly to childhood morbidity and mortality, with young children being particularly vulnerable to progression to active TB following exposure [7].

Addressing these challenges requires concerted efforts to enhance healthcare infrastructure, advance diagnostic and therapeutic strategies, and develop effective vaccines. Furthermore, understanding the immune mechanisms leading to lung parenchymal damage in TB and exploring host-directed therapies (HDT) could mitigate damage and improve outcomes [8].

1.2 Importance of Understanding Aerosol Transmission

Understanding aerosol transmission is crucial for TB control and prevention, given its significant role in spreading Mtb [9]. This mode of transmission is particularly concerning in healthcare settings, where healthcare workers, including nurses, face elevated risks of nosocomial TB infections [2]. The persistence of viable Mycobacterium tuberculosis complex (MTBC) in treated and untreated wastewater further emphasizes the infection risks associated with aerosol generation during treatment processes, potentially impacting exposed populations [10].

The emergence of multidrug-resistant TB (MDR-TB) and complexities from co-infections necessitate comprehensive strategies that incorporate an understanding of aerosol transmission to enhance TB care. Global migration trends have also influenced TB prevalence, highlighting the need for robust control measures informed by aerosol transmission dynamics [11].

Current diagnostic methods often inadequately address the urgency of TB diagnosis and treatment, exacerbating transmission dynamics. Thus, rapid and sensitive molecular tests, informed by aerosol transmission insights, are essential for reducing diagnosis time and improving treatment outcomes, particularly for high-risk populations, such as those co-infected with HIV, who are more susceptible to developing active TB [8].

1.3 Scope and Structure of the Survey

This survey explores the multifaceted aspects of TB research and public health, focusing on aerosol transmission dynamics and control measures. It addresses vital aspects of TB, including its public health impact, the importance of understanding aerosol transmission in prevention, and the challenges in early detection and management, particularly in high-risk environments such as crowded public spaces and among vulnerable populations [12, 13, 4, 14, 15]. The survey examines biological and environmental mechanisms facilitating TB aerosol transmission, reviewing recent studies on the physicochemical properties of aerosols and their role in TB spread. It also discusses advancements in aerosol sampling and detection technologies, alongside the application of omics technologies to study TB transmission dynamics.

The section on early-stage TB highlights its clinical and pathological characteristics, emphasizing recent advancements in diagnostic and screening technologies while identifying challenges in early detection and proposing potential solutions. It analyzes lung morphology's role in TB outcomes, discussing age-related changes in lung function, experimental approaches to modulate lung morphology, and the impact of lung structure on lesion segmentation and treatment planning.

Public health interventions and infection control strategies are thoroughly reviewed, evaluating the effectiveness of various measures such as vaccination, isolation, and ventilation improvements. The survey assesses a range of TB control strategies, including educational initiatives to enhance awareness among healthcare workers, policy interventions to strengthen TB management frameworks, technological innovations for improved detection and treatment, environmental measures to mitigate transmission risks in public spaces, and community-based approaches to engage affected populations in the fight against TB [12, 16, 17]. The conclusion synthesizes key findings, reflecting on their implications for future research and public health policy, and underscores the importance of integrated approaches to TB control.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Early-Stage Tuberculosis: Definitions and Challenges

Early-stage tuberculosis (TB) represents the initial immune response to Mycobacterium tuberculosis (Mtb) infection, crucial for determining disease outcomes [18]. This phase is often asymptomatic, incorporating latent TB infection (LTBI), which complicates detection and management efforts. Diagnostic challenges are particularly pronounced in high-burden regions, where existing methods frequently fail to identify cases, hindering timely intervention [11].

Traditional sputum microscopy often misses Mtb in sputum-negative individuals, necessitating innovative bioaerosol sampling protocols to improve detection in these populations. However, limited research on the environmental survival and transmission dynamics of the Mycobacterium tuberculosis complex (MTBC), such as in wastewater, further complicates detection strategies [10].

The rise of multidrug-resistant (MDR) and extensively drug-resistant (XDR) TB, coupled with the complexities of co-infections, underscores the need for rapid and precise diagnostics [6]. The interaction between Mtb and the host immune system, particularly granuloma formation, plays a pivotal role in disease progression and treatment outcomes [8]. Granulomas serve as bacterial containment sites and potential proliferation reservoirs, complicating early-stage TB diagnosis and treatment.

In healthcare settings, inadequate implementation of tuberculosis infection control (TBIC) measures and insufficient training on TBIC protocols impede early-stage TB management. The high LTBI prevalence among healthcare workers necessitates targeted interventions to mitigate transmission risks [7]. Accurate sampling methods are vital for predicting TB infection risk among individuals exposed to infectious aerosols, enhancing transmission dynamics understanding and early detection strategies.

Addressing TB's multifaceted challenges requires integrated strategies leveraging advances in diagnostic technologies—such as rapid, cost-effective screening tests and molecular diagnostics—while expanding our understanding of TB pathophysiology. This approach should focus on bridging detection gaps, particularly among vulnerable groups like children and HIV-positive individuals, and strengthening healthcare systems for effective early-stage TB management. Such efforts aim to improve case detection, reduce mortality, and contribute to global TB control and eradication goals [1, 6].

In exploring the complexities of tuberculosis (TB) transmission, it is essential to consider the multifaceted interactions between various biological and environmental factors. Figure 2 illustrates the hierarchical structure of key concepts in tuberculosis aerosol transmission, highlighting not only the biological mechanisms involved but also the environmental factors that influence these processes. Furthermore, the figure emphasizes advancements in aerosol sampling and detection techniques, as well as the pivotal role of omics technologies in enhancing our understanding of transmission dynamics. Each category within the figure is meticulously subdivided to underscore specific elements that contribute to TB transmission and inform effective control strategies. This comprehensive overview serves to contextualize the intricate web of factors that must be addressed in any effort to mitigate the spread of TB.

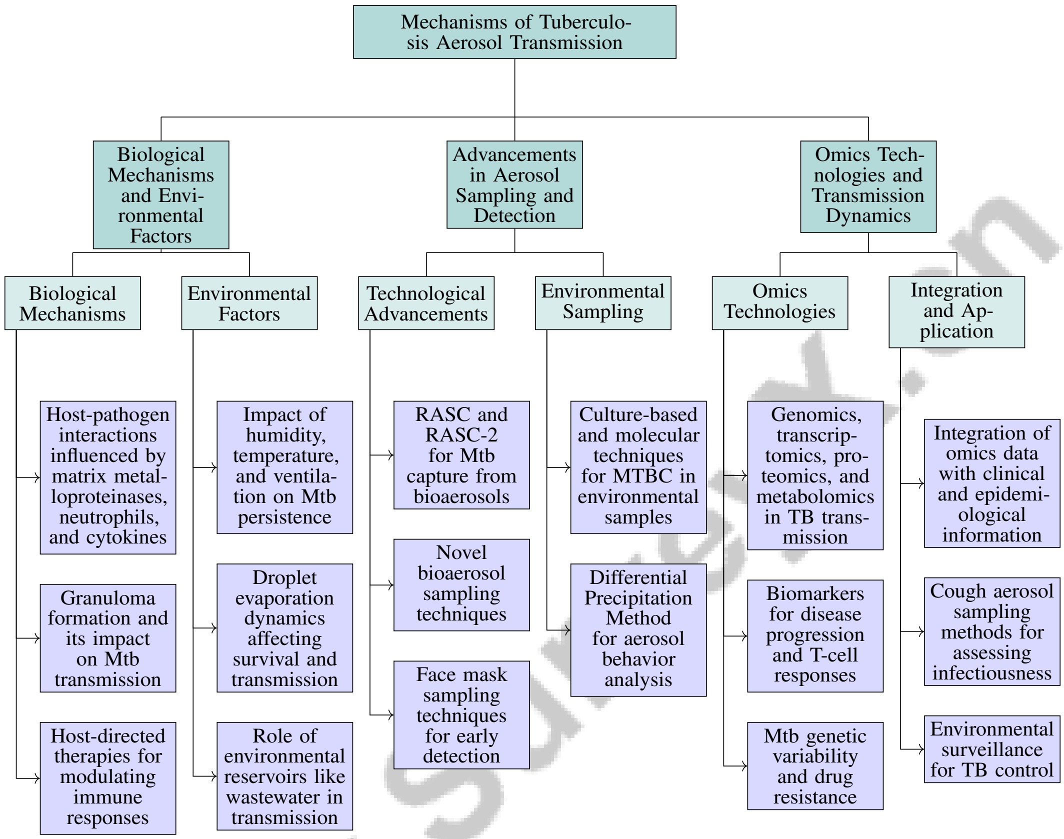

Figure 2: This figure illustrates the hierarchical structure of key concepts in tuberculosis aerosol transmission, highlighting biological mechanisms, environmental factors, advancements in aerosol sampling and detection, and the role of omics technologies in understanding transmission dynamics. Each category is further subdivided to emphasize specific elements contributing to TB transmission and control strategies.

3 Mechanisms of Tuberculosis Aerosol Transmission

3.1 Biological Mechanisms and Environmental Factors of Aerosol Transmission

The transmission of Mycobacterium tuberculosis (Mtb) via aerosols is governed by intricate biological mechanisms and environmental conditions. Host-pathogen interactions within lung tissues, influenced by matrix metalloproteinases, neutrophils, and cytokines, are crucial for determining infection outcomes and transmission dynamics [18, 8]. As illustrated in Figure 3, which depicts the key biological mechanisms, environmental factors, and detection methods related to the aerosol transmission of Mtb, the interplay of these elements is essential for a comprehensive understanding of transmission dynamics. The figure highlights the role of host-pathogen interactions, environmental conditions, and innovative detection techniques that enhance our insight into this complex process.

The Respiratory Aerosol Sampling Chamber (RASC) enhances Mtb detection from air samples by reducing dilution and contamination [19]. The multiplicity of pathogen copies in aerosols further informs transmission likelihood [9]. Environmental factors such as humidity, temperature, and ventilation significantly affect Mtb's persistence in aerosols, with droplet evaporation dynamics playing a pivotal role in its survival and transmission [20]. The presence of the Mycobacterium tuberculosis complex (MTBC) in wastewater suggests environmental reservoirs' potential role in transmission [10]. Advanced sequencing techniques reveal immune response spatial organization within lung tissues, providing insights into granuloma formation and its impact on Mtb transmission [21]. Host-directed therapies targeting these immune pathways offer promising strategies for modulating immune responses and reducing transmission risk [22].

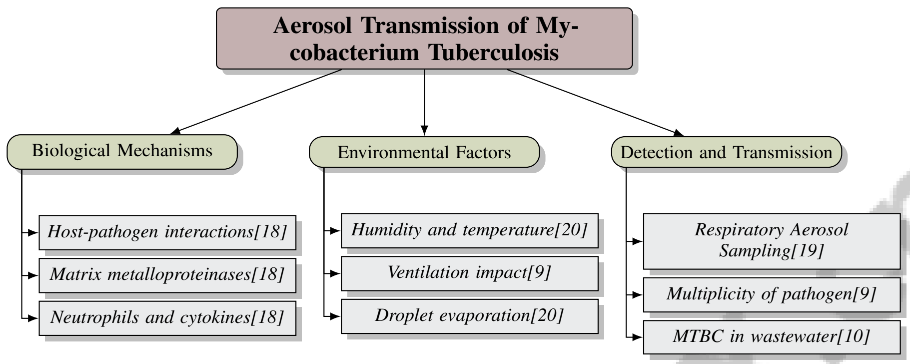

Figure 3: This figure illustrates the key biological mechanisms, environmental factors, and detection methods related to the aerosol transmission of Mycobacterium tuberculosis. It highlights the role of host-pathogen interactions, environmental conditions, and innovative detection techniques in understanding transmission dynamics.

3.2 Advancements in Aerosol Sampling and Detection

Recent technological advancements have revolutionized the sampling and detection of tuberculosis (TB) aerosols, crucial for understanding transmission dynamics and enhancing diagnostic capabilities. The RASC, employing high-efficiency filtration and sampling methods, captures live Mtb from bioaerosols, indicating a higher transmission potential than previously assumed [13, 19, 23]. RASC-2, with its high-flow wet-walled cyclone collector, improves viable Mtb recovery compared to its predecessor.

In addition to RASC, novel bioaerosol sampling techniques, including direct and indirect methods, represent significant advancements in aerosol sampling technology [15]. The Differential Precipitation Method enhances understanding of aerosol behavior under various environmental conditions [20]. Face mask sampling techniques demonstrate superior sensitivity and predictive capability for TB transmission, highlighting their potential for early detection and public health interventions [24]. Culture-based and molecular techniques identifying MTBC in environmental samples like wastewater underscore the importance of environmental reservoirs in TB transmission [10].

3.3 Omics Technologies and Transmission Dynamics

Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, have significantly advanced the understanding of tuberculosis (TB) transmission dynamics. These technologies identify biomarkers reflecting disease progression, assess T-cell responses, and evaluate Mtb metabolic profiles in bioaerosols, thereby enhancing diagnostic accuracy and informing transmission interruption strategies [13, 1]. They also provide insights into Mtb genetic variability, host immune responses, and molecular mechanisms of drug resistance, contributing to TB pathogenesis understanding.

Recent genomic and transcriptomic advancements illuminate Mtb-host interaction complexities, particularly concerning drug resistance, enabling the identification of genetic determinants and potential therapeutic targets [25]. Integrating omics data with clinical and epidemiological information is essential for effective public health strategies to control TB transmission. Innovative cough aerosol sampling methods assess TB patient infectiousness by linking bacterial load in aerosols to disease spread potential [26]. The RASC exemplifies integrating high-efficiency aerosol capture technology with fluorescent viability probes for detecting live Mtb in complex bioaerosol samples [13].

Understanding airborne transmission requires diverse methodologies and environmental factor consideration, influencing Mtb persistence and spread. Employing various approaches enhances transmission dynamics understanding and informs effective epidemic control measures [27]. The presence of MTBC in environmental reservoirs such as wastewater presents health risks, emphasizing environmental surveillance's importance in TB control efforts [10].

4 Early-Stage Tuberculosis: Characteristics and Detection

4.1 Clinical and Pathological Characteristics

Early-stage tuberculosis (TB) is characterized by the intricate interplay between Mycobacterium tuberculosis (Mtb) and the host immune system, with macrophages playing a central role [28]. The initial immune response, involving various pulmonary cells, determines the clinical and pathological features of early-stage TB [18]. Asymptomatic pulmonary TB (PTB) often resembles lung cancer in imaging, complicating diagnosis and necessitating comprehensive clinical assessment [29].

Age-related changes in alveolar lining fluid (ALF) may increase susceptibility to respiratory infections, influencing TB vulnerability [30]. Immune responses are crucial for disease progression, with key mediators contributing to lung damage, highlighting potential therapeutic targets [8]. Experimental models, such as Mauritian cynomolgus macaques, show disease patterns similar to other macaque populations, emphasizing variability in host responses to Mtb [31]. Quantitative FDG PET-CT analysis aids in understanding early-stage pathological changes and treatment outcomes [32].

The complexities of early-stage TB are further illustrated in Figure 4, which emphasizes the clinical and pathological characteristics of the disease. This figure delineates the roles of immune responses, diagnostic challenges, and the intricacies of transmission and treatment. In particular, the immune response section highlights the significance of macrophages, age-related changes in alveolar lining fluid, and the involvement of immune mediators. The diagnostic challenges section focuses on asymptomatic pulmonary TB, the use of FDG PET-CT analysis, and the relevance of cough aerosol cultures. Additionally, the transmission and treatment section addresses the correlation between aerosol colony-forming units (CFU) and transmission, the impact of bacterial burden in cavities, and the variability in host responses.

Higher aerosol colony-forming units (CFU) correlate with increased tuberculin skin test (TST) and interferon-gamma release assay (IGRA) results among contacts, indicating clinical implications for early-stage TB detection [33]. Cough aerosol culture positivity reveals critical clinical and microbiological characteristics for understanding transmission and managing early-stage TB. The significant bacterial burden in TB cavities complicates treatment, increasing transmission rates and failures, underscoring the need for early detection and intervention [4].

4.2 Advancements in Diagnostic and Screening Technologies

Method Name	Technological Innovations	Sensitivity and Accuracy	Clinical Applications
RASC[19]	Ddpcr, Rasc	More Sensitive Detection	Understanding TB Transmission
HLTEM[18]	Luminex Technology	Accurate Representation	Early Immune Responses
DAPL[29]	Pet-Ct Imaging	Diagnostic Accuracy	Differentiating Ptb

Table 1: Comparison of diagnostic methods for tuberculosis, highlighting technological innovations, sensitivity and accuracy, and clinical applications. The table presents a detailed examination of the Respiratory Aerosol Sampling Chamber (RASC), Human Lung Tissue Explant Model (HLTEM), and PET/CT imaging in the context of tuberculosis detection and diagnosis.

Recent advancements in diagnostic and screening technologies have significantly improved early-stage tuberculosis (TB) detection. The Respiratory Aerosol Sampling Chamber (RASC) effectively detects Mycobacterium tuberculosis (Mtb) in bio-aerosols, offering greater sensitivity than traditional culture methods when combined with droplet digital PCR (ddPCR) [19]. Molecular diagnostics, including nucleic acid amplification tests (NAATs) like Xpert MTB/RIF Ultra and Loop-Mediated Isothermal Amplification (LAMP), provide enhanced sensitivity and rapid results, especially for multidrug-resistant TB (MDR-TB) [11, 7]. Table 1 provides a comparative analysis of recent technological advancements in tuberculosis diagnostics, emphasizing the innovations, sensitivity, accuracy, and clinical applications of each method.

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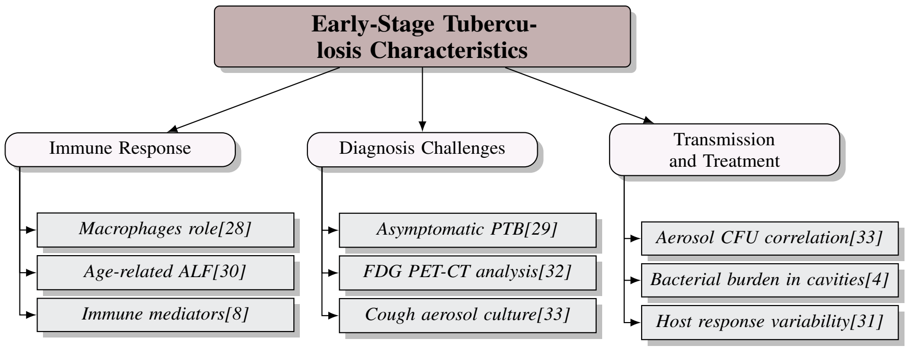

Figure 4: This figure illustrates the clinical and pathological characteristics of early-stage tuberculosis, emphasizing the roles of immune responses, diagnostic challenges, and transmission and treatment complexities. The immune response section highlights the significance of macrophages, age-related changes in alveolar lining fluid, and the involvement of immune mediators. The diagnosis challenges section focuses on asymptomatic pulmonary TB, the use of FDG PET-CT analysis, and the relevance of cough aerosol cultures. The transmission and treatment section addresses the correlation between aerosol colony-forming units and transmission, the impact of bacterial burden in cavities, and the variability in host responses.

The Human Lung Tissue Explant Model (HLTEM) allows for the study of initial immune responses in human lung tissue, improving understanding of TB pathogenesis and facilitating targeted diagnostics [18]. Imaging technologies, such as PET/CT scans, differentiate pulmonary TB from lung cancer, enhancing diagnostic accuracy through clinical and imaging data [29]. Biomarker research continues to advance TB diagnostics, with promising candidates identified to improve screening strategies [34].

These advancements represent significant progress in combating TB, offering new opportunities for early detection and improved patient outcomes. Addressing diagnostic gaps, particularly in the underreporting of TB cases and detection of drug-resistant strains, is vital for enhancing global TB control efforts. Innovative approaches, including non-sputum-based detection methods and automated digital radiography, are being explored to improve screening and triaging [1, 35].

4.3 Challenges and Solutions in Detection

Early-stage tuberculosis (TB) detection faces challenges due to limitations in current diagnostics and the disease's complexity. Existing tests struggle to distinguish between latent TB infection (LTBI) and active TB (aTB), leading to potential mismanagement [36]. Nonspecific symptoms and radiological features of asymptomatic PTB may mimic other conditions, risking unnecessary interventions [29].

Manual segmentation of TB lesions in imaging studies is hindered by inter- and intra-operator variability, affecting accurate disease burden quantification [37]. Automated models like CDC$_N$$etarelimitedbytrainingdataquality, impactingperformanceindiverseconditions$[38].$Inadequatecomparisonso$ $rayfindingsbetweenMDR - TBanddrug - sensitiveTB(DS - TB)increasemisdiagnosisrisk$[39].$ForpeoplelivingwithHIV(PLHIV), theWHOsymptomscreen'shighsensitivity$

Solutions include the RASC-2 method, which improves sensitivity and detection yield of viable Mtb [23]. Advanced imaging techniques and computational models can enhance detection accuracy and quantification [40]. Leveraging differential evaporation dynamics of respiratory droplets may inform new diagnostic approaches, affecting detection sensitivity [20]. Improving patient adherence to treatment through strategies like collapsing bandits applications can mitigate challenges associated with prolonged treatment durations [41].

Advancing biomarker study designs and validating promising biomarkers are crucial for enhancing diagnostic sensitivity and specificity [34]. These strategies, along with advancements in point-of-care diagnostics and personalized medicine, hold promise for overcoming existing limitations in early-stage TB detection and management.

5 Lung Morphology and Tuberculosis Outcomes

5.1 Influence of Age-Related Changes in Lung Function

Age-induced alterations in lung function substantially impact tuberculosis (TB) outcomes, particularly among the elderly. Changes in alveolar lining fluid (ALF) composition weaken innate immune responses against Mycobacterium tuberculosis (Mtb), increasing susceptibility to infections [30]. These alterations impair pathogen clearance and immune cell efficacy, leading to a higher infection risk and severe disease progression in older adults. The decline in lung elasticity and altered respiratory mechanics further exacerbate their vulnerability. The prevalence of latent tuberculosis infection (LTBI) is notably higher in older adults, elevating the risk of progression to active TB due to diminished immune control, especially in those with immune senescence [42, 36, 43]. Such individuals act as reservoirs for active TB cases, with reactivation risks heightened in immunocompromised individuals, underscoring the need for effective detection and management strategies in global TB control efforts.

Understanding the impact of aging on lung function and immune responses is vital for developing targeted interventions to improve TB treatment outcomes in the elderly. The lung mucosal environment in older adults exacerbates susceptibility to Mtb infection and lung pathology [30, 8]. This is further illustrated in Figure 5, which highlights the influence of age-related changes in lung function on tuberculosis outcomes, emphasizing the impact on TB susceptibility, alterations in immune responses, and potential intervention strategies. Strategies aimed at enhancing pulmonary immune defenses, such as optimizing ALF composition or boosting innate immune responses, could mitigate the increased TB risk in this demographic. Tailored screening and diagnostic approaches that consider age-related physiological changes may facilitate early TB detection and management, thus reducing morbidity and mortality.

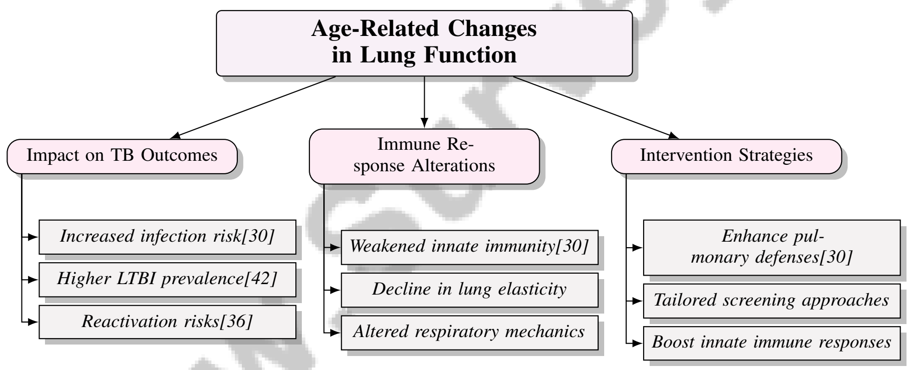

Figure 5: This figure illustrates the influence of age-related changes in lung function on tuberculosis outcomes, highlighting the impact on TB susceptibility, alterations in immune responses, and potential intervention strategies.

5.2 Experimental Approaches to Modulate Lung Morphology

Experimental strategies to modulate lung morphology are gaining attention for their potential to improve tuberculosis (TB) treatment outcomes. Alterations in lung structure significantly influence Mtb infection progression and therapeutic efficacy. Advanced imaging techniques and computational models are employed to segment and analyze TB-affected lung tissues accurately. The development of an automatic pipeline for robust segmentation of Mtb-infected lungs marks a significant advancement, effectively identifying fuzzy boundaries and incorporating lesions into analyses [40].

These technologies enable detailed examination of lung morphology, providing insights into how structural changes affect disease progression and treatment responses. Precise characterization of lung lesions through advanced imaging enhances understanding of how variations in lung morphology influence TB pathogenesis, informing more effective diagnostic and therapeutic strategies [44, 45, 8, 40, 29]. This knowledge is crucial for developing targeted therapies addressing specific morphological alterations associated with TB.

Therapeutic interventions, including pharmacological agents and physical therapies aimed at modulating lung morphology, show promise for enhancing TB treatment outcomes. Recent studies exploring host-directed therapies and the regulation of pulmonary inflammation by platelets highlight the potential of these interventions to address immune mechanisms underlying lung parenchymal damage. By improving lung structure and function, these strategies may lead to more effective TB management, reducing morbidity and interrupting disease transmission [46, 8]. Enhancing lung function and optimizing the pulmonary environment could facilitate more effective Mtb clearance and diminish disease progression risks.

Investigating experimental methods for modifying lung morphology represents a crucial research frontier that could yield substantial advancements in TB treatment strategies. This area of study enhances our understanding of immune mechanisms involved in lung damage and the role of host-directed therapies, as evidenced by recent findings on inflammatory mediators and the potential of targeted therapies to improve patient outcomes [40, 8]. By integrating advanced imaging and computational techniques with therapeutic interventions, researchers can develop more effective approaches to manage TB and enhance patient outcomes.

5.3 Impact of Lung Morphology on Lesion Segmentation and Treatment

Lung morphology significantly affects lesion segmentation and tuberculosis (TB) treatment planning, as structural variations impact the identification and characterization of pathological areas. Advanced imaging techniques, such as Z-score standardization, have proven instrumental in differentiating pathological from normal tissue, enhancing understanding of how lung morphology impacts TB outcomes [37]. These methods enable precise quantification of disease burden by accurately delineating lung boundaries while retaining critical pathological features, essential for effective treatment planning [40].

Proteomic analyses reveal a decrease in functional innate immune proteins in elderly alveolar lining fluid (E-ALF) compared to adult alveolar lining fluid (A-ALF), correlating with impaired macrophage control of Mtb [30]. This reduction in immune function may influence TB lesion progression and therapeutic efficacy, underscoring the importance of considering lung morphology and immune status in treatment strategies.

Incorporating advanced imaging techniques, such as 18F-FDG PET-CT, alongside proteomic analyses into clinical practice has the potential to significantly enhance lesion identification precision and optimize TB treatment planning. Improved correlations between scan metrics and clinical outcomes, including treatment response and recurrence risk, have been observed [44, 37, 32]. By accounting for variations in lung morphology and immune function, healthcare providers can tailor interventions to optimize patient outcomes, ultimately enhancing TB management.

6 Public Health Interventions and Infection Control

6.1 Infection Control Practices and Challenges

Benchmark	Size	Domain	Task Format	Metric
TB-XRAY[39]	366	Radiology	Comparative Analysis	Lesion Size, Morphology
CASS[33]	230	Infectious Diseases	Prediction OF Infection Risk	CFU, TST
iNKT-TB[47]	1,000	Immunology	Cell Profiling	iNKT frequency, CD4/CD8 ratio
LTBI-HCW[5]	708	Occupational Health	Prevalence Assessment	Prevalence Rate, Odds Ratio

Table 2: This table presents a detailed comparison of selected benchmarks relevant to tuberculosis infection control. It includes information on the size, domain, task format, and metrics utilized in each benchmark, highlighting the diversity and scope of studies in radiology, infectious diseases, immunology, and occupational health.

Tuberculosis (TB) infection control is fraught with challenges that impede effective disease management and prevention. In low-resource settings, the lack of rapid diagnostic tests delays diagnosis and treatment, adversely affecting TB control [3]. The complexity of immune responses and patient variability further complicates the implementation of effective interventions during TB treatment [8]. Retrospective data collection and clinical diagnosis often result in gaps in understanding the side effects of anti-tuberculosis therapy (ATT) [48].

The Respiratory Aerosol Sampling Chamber (RASC) offers a promising advancement in detecting Mycobacterium tuberculosis (Mtb) in aerosols, enhancing our understanding of TB transmission [19]. However, inadequate training on tuberculosis infection control (TBIC) protocols, coupled with socio-demographic factors, undermines healthcare workers' knowledge and practices [2]. Only a minority of healthcare workers demonstrate satisfactory infection control practices, indicating significant gaps that need addressing [17].

Moreover, the lack of comprehensive studies on the survival of Mycobacterium tuberculosis complex (MTBC) in environmental reservoirs like wastewater hinders the development of effective detection methods [10]. Innovative sampling methods assessing multiple pathogens can enhance public health responses by providing more accurate risk assessments [9].

As illustrated in Figure 6, the challenges in tuberculosis infection control encompass diagnostic issues, healthcare worker practices, and environmental and treatment gaps. This figure emphasizes the lack of rapid diagnostic tests, inadequate training, and the presence of Mycobacterium tuberculosis complex in wastewater, among other barriers. Despite advances in drug development and diagnostics, significant gaps remain in treatment guidelines, particularly for co-infected individuals [6]. A multifaceted approach incorporating technological advancements, improved diagnostics, and continuous education for healthcare workers is essential to enhance TB control efforts. Refining existing practices and implementing innovative solutions can significantly improve TB management. Table 2 provides a comprehensive overview of various benchmarks used in tuberculosis infection control research, illustrating the different domains and methodologies implemented to address the complexities of TB management.

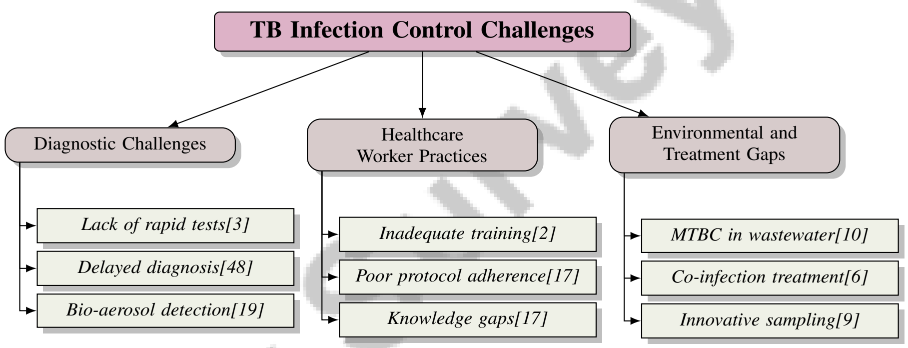

Figure 6: This figure illustrates the challenges in tuberculosis infection control, emphasizing diagnostic issues, healthcare worker practices, and environmental and treatment gaps. It highlights the lack of rapid diagnostic tests, inadequate training, and the presence of Mycobacterium tuberculosis complex in wastewater, among other barriers.

6.2 Educational and Policy Interventions

Educational and policy interventions are crucial for improving TB control by enhancing diagnostic capabilities, infection prevention, and control (IPC) measures, and addressing TB and co-infections' complexities. Education significantly influences TB infection control practices among healthcare workers, necessitating tailored training programs to rectify knowledge, attitudes, and practices (KAP) deficiencies [17, 2]. Evaluating these programs can substantially enhance TBIC practices [49].

Policy interventions should incorporate lessons from TB control to strengthen public health systems for future pandemics. The effectiveness of WHO standards in improving TB care delivery underscores the importance of community engagement and involving all care providers [50]. Understanding latent TB infection (LTBI) prevalence among healthcare workers is critical for informing public health interventions and improving occupational safety [5].

Integrating molecular diagnostics with clinical data and traditional methods is essential for a holistic TB management approach [51]. Future research should prioritize innovative diagnostics, new therapeutic agents, and integrated treatment approaches considering TB and co-infections' complexities to bolster global TB control efforts [6]. The TB-LAM test exemplifies advancements in diagnostics, offering high specificity and ease of use for rapid diagnosis without complex laboratory facilities [52].

Additionally, research should focus on developing child-friendly treatment options and coordinated public health efforts to address the TB epidemic among children [7].

Innovative methods like Collapsing Bandits, which maximize patient adherence to medications within budget constraints, are crucial for successful TB treatment [41]. Understanding the immune microenvironment in TB is vital for vaccine development, which could significantly enhance TB control efforts [53].

6.3 Technological and Environmental Measures

Technological and environmental strategies are vital for mitigating TB transmission by addressing biological and physical disease spread aspects. Preventive measures like physical distancing, face masks, and improved ventilation effectively reduce transmission risks, highlighting environmental controls' importance in TB management [54]. Real-time monitoring technologies and enhanced ventilation strategies are essential for minimizing biological agent transmission in healthcare and community settings [55].

Experimental studies involving aerosol exposure of macaques to Mycobacterium tuberculosis have provided valuable insights into clinical signs and disease features, enhancing our understanding of TB transmission dynamics [31]. The RASC offers a non-invasive method for capturing and analyzing the physiological state of aerosolized Mtb bacilli, facilitating real-time transmission dynamics assessment [13]. This technology emphasizes the importance of droplet evaporation modes in pathogen viability [20].

Despite these advancements, gaps remain in assessing the long-term effectiveness of IPC measures across diverse healthcare settings. Socio-economic factors influence these measures' implementation and success, necessitating further research to optimize IPC strategies [56]. Integrating environmental factors like ventilation and filtration into risk assessment frameworks is critical for understanding TB transmission in real-world contexts [9].

Organizing current methods into four main fields—managerial activities, administrative controls, environmental controls, and personal protective equipment—highlights the multifaceted approach required for effective TB control [57]. The development of algorithms like the Threshold Whittle algorithm has demonstrated effectiveness in improving TB medication adherence, showcasing the potential of technological interventions in enhancing treatment outcomes [41].

6.4 Socio-Economic and Community-Based Strategies

Socio-economic and community-based strategies are pivotal in TB control, addressing multifaceted factors influencing TB transmission and treatment adherence. Socio-economic determinants such as poverty, overcrowding, and limited healthcare access significantly affect TB susceptibility and outcomes, necessitating targeted interventions [51]. Community engagement is critical in these strategies, fostering tailored treatment approaches that consider individual patient needs and reducing the burden of long-term therapy while maintaining efficacy [5].

The COVID-19 pandemic has underscored the importance of maintaining continuity in TB services, including IPC measures during public health emergencies. Integrating TB care with broader public health initiatives and leveraging community-based resources are recommended to ensure the resilience of TB services [56]. Ongoing training and retraining programs are essential for reinforcing TBIC practices and integrating new educational technologies to enhance awareness and compliance among healthcare workers and communities [16].

Understanding the role of alveolar lining fluid (ALF) in TB susceptibility, particularly among the elderly, is crucial for developing community-based strategies tailored to vulnerable populations. Addressing specific immune dysfunctions in ALF can inform targeted interventions [30]. Additionally, preventive treatment strategies based on aerosol colony-forming unit (CFU) measurements can enhance socio-economic and community-based TB control efforts by identifying high-risk individuals for tailored interventions [15].

Collaboration among global institutions is vital for advancing TB vaccine research, with initiatives like the TBVAC2020 project emphasizing international partnerships in developing effective vaccines. These collaborative efforts, alongside socio-economic and community-based strategies, are essential for improving patient adherence to TB treatment regimens and ultimately reducing TB transmission [48].

To enhance community-based interventions for TB control, addressing deficiencies in TB infection control policies, providing adequate training for non-medical staff, and increasing awareness of infection control measures among healthcare workers are essential. Studies indicate that nearly half of healthcare workers in Nepal exhibit poor knowledge of TB infection control, particularly among administrative and lower-level staff. Regular skill-based training and orientation are necessary to improve infection control practices and mitigate the risk of nosocomial TB transmission [49, 16]. By fostering interdisciplinary research and integrating socio-economic considerations into TB control strategies, more effective approaches can be developed to manage TB and improve public health outcomes.

7 Conclusion

This survey provides a comprehensive examination of tuberculosis (TB), emphasizing the critical role of aerosol transmission in the spread of Mycobacterium tuberculosis (Mtb) and the necessity for improved diagnostic and infection control strategies. The increasing prevalence of drug-resistant TB underscores the need for precise and cost-effective molecular diagnostic tools. The distinction between chest X-ray findings in multidrug-resistant TB (MDR-TB) and drug-sensitive TB (DS-TB) highlights the need for prompt and accurate diagnosis to enhance public health outcomes. Moreover, the association between TB and lung cancer offers significant insights for future research and policy development. Understanding immune mechanisms is crucial for advancing host-directed therapies that reduce lung damage and improve patient care.

The integration of advanced omics technologies is pivotal in uncovering TB's biochemical pathways, facilitating the development of targeted treatments. Future research should focus on refining detection methods and exploring the persistence of MTBC in environmental settings to effectively minimize risks for susceptible populations. Developing accurate, child-friendly diagnostics and effective vaccines is imperative, given the specific epidemiological challenges of pediatric TB.

Addressing drug-resistant TB necessitates strategic interventions, as a considerable number of affected individuals continue to harbor culturable Mtb in aerosols, challenging current treatment paradigms. While computer-aided detection (CAD) systems hold potential for TB diagnosis, enhanced study designs are essential for their transition from development to clinical application. To bolster TB control initiatives, identifying viable vaccine candidates and ensuring robust collaboration and funding are vital for advancing vaccine research. Future investigations should delve into genetic factors affecting TB susceptibility and the complexities of granuloma formation, aiming to create targeted therapies that consider TB's inherent diversity. Enhanced understanding of host immune responses can lead to more effective interventions, particularly against resistant strains.

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