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The Role of Digital Health Technologies in Combating MDR-TB: Promising Innovations and Future Strategies

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Abstract

Tuberculosis remains one of the most challenging public health problems, and multidrug-resistant TB (MDR-TB) in particular adds to the challenge we face. In 2023, about 400,000 people were diagnosed with MDR-TB, and Approximately 150,000 people died from MDR-TB, highlighting the ongoing global challenge in its prevention and treatment. This review aims to explore how current digital health technologies such as smartphone applications, tele-monitoring systems, and biometric tracking tools, which may support early case detection, enhance treatment adherence, and improve outcomes for patients with MDR-TB. Particular attention is given to vulnerable groups, including people living with HIV, mobile populations, and caregivers of young children. Recent studies highlight the growing effectiveness of digital health interventions in MDR-TB management**.** simple SMS prompts and video check-ins can enhance treatment completion rates by 20–30% compared to traditional directly observed therapy. Moreover, early trials of mobile health (mHealth) applications, including platforms like TOMO, indicate these tools can effectively monitor side effects and maintain patient engagement with healthcare providers, supporting the feasibility of broader, long-term implementation.
Summary: To ensure all patient populations benefit, digital health innovations must be supported by robust trials, clear implementation plans, and equitable access. AI-powered diagnostics and adherence technologies present promising opportunities in managing MDR-TB.

Keywords: MDR-TB, digital health, tele-monitoring, smartphone app, biometric tracking.

INTRODUCTION

Drug-resistant tuberculosis can arise through primary resistance, which occurs when drug-resistant TB bacteria are transmitted directly from one person to another, or through secondary (acquired) resistance, which develops during treatment due to factors like inappropriate treatment regimens, poor adherence, poor drug absorption, or drug interactions. There are several forms of drug-resistant TB: mono-resistant TB (resistant to one drug), poly-resistant TB (resistant to at least two drugs but not both isoniazid and rifampin), multidrug-resistant TB (MDR-TB) (resistant to at least isoniazid and rifampin), pre-extensively drug-resistant TB (pre-XDR TB) (MDR-TB plus resistance to either a fluoroquinolone or a second line injectable), and extensively drug-resistant TB (XDR TB), which involves resistance to isoniazid, rifampin, a fluoroquinolone, and either a second line injectable or newer drugs like bedaquiline or linezolid (CDC, 2025).

Although tuberculosis control has been effective in some regions of the world, these gains are threatened by the increasing burden of multidrug resistant (MDR) and extensively drug resistant (XDR) tuberculosis. XDR tuberculosis has evolved in several tuberculosis-endemic countries to drug-incurable or programmatically incurable tuberculosis (totally drug-resistant tuberculosis). This poses several challenges similar to those encountered in the pre-chemotherapy era, including the inability to cure tuberculosis, high mortality, and the need for alternative methods to prevent disease transmission (Dheda et al., 2017).

In 2012, there were approximately 450,000 new cases of MDR-TB and 170,000 deaths. Globally, MDR-TB is present in 3.8% of new TB patients and

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20% of patients who have a history of previous treatment. The highest MDR rates are found in countries of Eastern Europe and Central Asia, where MDR strains threaten to become as common as pan susceptible strains. In some countries, MDR strains account for up to 20% of new TB cases and well over 50% of patients with a history of previous TB treatment (Seung et al., 2015).

Indonesia is among the top three countries globally with the highest burden of MDR-TB. In 2022, over 700,000 TB cases were reported, marking a record in detection since TB became a national priority. The country also had an estimated 969,000 TB cases and 93,000 TB-related deaths, equating to approximately 11 deaths per hour. TB predominantly affects the productive age group, with individuals aged 45 to 54 years being most impacted. The treatment success rate for drug-resistant TB (DR-TB) was around 55% in 2022, below the global average, due to persistent challenges in diagnosis, treatment adherence, and healthcare infrastructure (Factsheet-Country-Profile-Indonesia-2022.Pdf,2019).

Pediatric tuberculosis also remains a significant global health concern, particularly in regions with high TB prevalence and limited healthcare resources. Children, especially those under the age of five, more susceptible to TB due to their immature immune systems, which are less capable of containing the infection. The disease often results from close contact with adults who have active pulmonary TB, making household exposure a primary risk factor. In many cases, pediatric TB is underdiagnosed because children are more likely to present with non-specific symptoms and are less likely to produce sputum samples for testing. This underdiagnosis contributes to the underreporting of pediatric TB cases, masking the true burden of the disease (Maphalle et al., 2022).

A report from the Ministry of Health of Indonesia underscores the importance of a robust healthcare infrastructure in managing MDR-TB. The report highlights that healthcare systems in regions with limited resources often face significant challenges, including insufficient diagnostic capacity and delayed treatment initiation, all of which facilitate the spread of resistant strains. Non-adherence to prescribed TB treatment is the key risk factor for MDR-TB (CM, 2018; Chasanah et al., 2022).

METHODS

A) This study is a narrative literature review design to explore current knowledge and prevention strategies related to (MDR-TB). b) Population Description: The initial population consisted of approximately 220 scientific articles related to MDR-TB, published between 2012 and 2024, retrieved from international databases. c) Sample Size After screening titles, abstracts, and full texts, 43 articles were included in the final analysis based on their relevance to MDR-TB prevention, treatment strategies, and risk factors. Inclusion criteria included English-language, peer-reviewed articles with full text availability and a publication date between 2017 and 2025. d) Research Variables: Keywords used in the search included: "multidrug-resistant tuberculosis", "MDR-TB", "drug resistance", "TB prevention", "BCG vaccine", "pediatric TB", and "digital health in TB management".
e) Source Databases: The literature search was conducted through PubMed, Scopus, and Google Scholar.

Research Procedure: Identifying the topic and research questions focusing on MDR-TB prevention and control. Developing a search strategy using selected keywords. Searching databases (PubMed, Scopus, Google Scholar) with filters for publication year (2012–2024) and language (English). Screening titles and abstracts to identify potentially relevant studies. Reviewing full texts of selected articles to assess eligibility. Extracting key data related to MDR-TB types, prevention strategies, global burden, and challenges in treatment and diagnosis, Synthesizing findings narratively according to themes.

DISSCUSION

Mechanisms and routes of drug resistance in tb

Drug resistance in Mycobacterium tuberculosis (MTB) mainly results from random genetic mutations that reduce the bacteria's response to specific drugs. These changes can affect drug targets, activate efflux pumps, or even inactivate the drugs themselves (Khan et al., 2019). Although the mutation rate is low about 1 in 100,000 for isoniazid and 1 in 10 million for rifampicin resistance still emerges, especially in poorly managed treatment settings. Resistance can develop primarily (through direct infection with

resistant strains) or secondarily (due to poor treatment adherence, malabsorption, or incorrect regimens). While secondary resistance has traditionally been seen as the major cause, newer studies show that in many high-burden areas, transmission of resistant TB strains is now a leading factor (Jang & Chung, 2020).

Environmental and systemic risk factors

The spread of MDR-TB is not just a medical issue it's deeply tied to living conditions, social structures, and healthcare quality. Overcrowded, poorly ventilated environments like slums or refugee camps provide ideal settings for TB transmission. Delays in diagnosis and lack of patient isolation make it worse. Other known risk factors include a history of incomplete TB treatment, HIV co-infection, and weak health systems (Desissa et al., 2018). In low-resource settings, even when patients want to comply, system failures like drug stockouts, lack of patient education, and poor follow-up can undermine treatment success. Individuals who have been previously treated for TB, especially those who did not complete their regimens, are at the highest risk for MDR-TB (CM, 2018).

Advances in mdr-tb pharmacotherapy

In 2018, the WHO reclassified anti-TB drugs based on safety and effectiveness. Group A drugs including fluoroquinolones, bedaquiline, and linezolid are now the backbone of MDR-TB treatment. Fluoroquinolones like levofloxacin and moxifloxacin block DNA replication. They're widely used and generally well tolerated but may cause QT prolongation or mild GI/CNS effects. Linezolid interferes with protein synthesis and has shown high efficacy in MDR-TB, though long-term use can cause neuropathy or blood disorders. WHO recommends a 600 mg dose to balance efficacy and safety. Bedaquiline, a newer agent that blocks ATP synthase, significantly improves outcomes when taken with food. It's generally safe but requires monitoring for QT interval changes.

prevention

In an effort to overcome the longstanding barriers to rapid and accurate diagnosis of tuberculosis, particularly in cases involving HIV co-infection and multidrug resistance, a large multicenter study evaluated the Xpert MTB/RIF assay across five high-burden countries like Peru, Azerbaijan, South Africa, and India. Conducted between July 2008 and March 2009, the study enrolled over 1700 patients who were suspected of having either drug sensitive or drug resistant pulmonary TB. Each participant provided three sputum samples, which underwent various testing methods, including smear microscopy, culture, and the novel MTB/RIF molecular test. This automated PCR based assay detects Mycobacterium tuberculosis and mutations linked to rifampin resistance directly from sputum, offering results in under two hours with minimal manual handling. Impressively, among culture confirmed TB cases, a single direct test identified 98.2% of smear positive and 72.5% of smear negative cases. Specificity was high as well, reaching 99.2% among non TB patients. Furthermore, the test showed strong agreement with traditional drug susceptibility testing, accurately detecting 97.6% of rifampin-resistant and 98.1% of rifampin-sensitive strains. With minimal infrastructure requirements and the ability to run in general lab settings, this tool represents a major leap forward in TB diagnostics. All procedures followed strict ethical oversight, with informed consent obtained and diagnostic interpretations made independently to reduce bias. The results highlight the test's potential to dramatically improve TB control in resource limited settings, where early diagnosis and prompt treatment can save lives and reduce transmission (Boehme et al., 2010).

(MDR-TB) is a significant public health issue internationally and regionally due to its resistance to at least isoniazid and rifampicin, the two most potent first-line drugs used to treat tuberculosis. To truly tackle MDR-TB, it's not enough to just treat the disease, we have to stop it before it starts and spreads. That means making sure people get diagnosed early, complete the right treatment, and are supported throughout. At the same time, we need to prevent it from moving through communities and hospitals, especially in places where the healthcare system is already struggling. Primary, secondary, and tertiary prevention are the three main categories into which MDR-TB prevention can be divided. Each of these approaches is essential for limiting transmission and the emergence of resistance (American Public Health Association, 2018).

PRIMARY PREVENTION: The goal of primary prevention is to stop MDR-TB from developing in the first place. The early and precise diagnosis of drug susceptible TB, followed by

implementing suitable treatment regimens, is essential to this strategy. Patient's compliance with treatment by DOT (Directly Observed Therapy), counseling of patients, and supportive therapy should be ensured to prevent the emergence of drug resistance. Rational use of anti-TB drugs by preventing monotherapy or inappropriate combinations is also paramount in ensuring drug efficacy. On a larger scale, community control initiatives such as BCG vaccination, health education, and higher living standards also help stop the spread of TB and, consequently, the risk of MDR-TB (Ehrlich et al., 2020).

SECONDARY PREVENTION: To stop the spread of MDR-TB, secondary prevention entails the early identification and classification of cases. It includes routine drug susceptibility testing (DST) for all TB cases with bacteriological confirmation, particularly in high burden areas (WHO, 2015). The detection rate of early MDR-TB has significantly increased with the use of rapid molecular tests like GeneXpert MTB/RIF, Early detection of latent or active TB infection is made possible by contact tracing and screening of close contacts of current MDR-TB patients, High risk patients may receive preventive therapy, though this is still a developing field of study for MDR-TB (American Public Health Association, 2018; Ehrlich et al., 2020).

TERTIARY PREVENTION: Tertiary prevention focuses on limiting complications and averting secondary transmission from confirmed cases of MDR-TB. This includes patient management to complete the complete course of treatment with appropriate second line regimens. Limiting complications and avoiding secondary transmission from confirmed MDR-TB cases are the main goals of tertiary prevention (Ehrlich et al., 2019).

MDR-TB remains a major health threat in many countries, which is exacerbated by poor living conditions, limited access to healthcare, and a shortage of medical personnel. Telemedicine offers a promising solution, allowing doctors to reach patients in remote and underserved areas, reducing diagnostic delays and improving treatment adherence. With most healthcare resources concentrated in cities, telemedicine can bridge the gap in rural communities and help more effectively address the spread of MDR-TB. It can also reduce the overall cost of TB management while easing the burden on overstretched healthcare workers. Despite challenges such as poor infrastructure and data privacy concerns, the use of mobile technology and remote care can significantly enhance Nigeria's TB control efforts. Adopting telemedicine is not just a recent innovation; it is a necessary step toward saving lives, achieving better coverage, and supporting communities most in need of care. For these reasons, exploring and investing in telemedicine is critical to overcoming one of the most pressing public health challenges (Olowoyo et al., 2024).

The Xpert MTB/RIF Ultra test (Ultra) is a newer and more sensitive version of the Xpert MTB/RIF test used to detect tuberculosis (TB) by identifying the DNA of Mycobacterium tuberculosis in respiratory samples. Studies have shown that Ultra has higher sensitivity than Xpert, especially in patients with low bacterial load (paucibacillary cases), such as smear-negative TB, HIV-positive patients, and children. For example, Ultra showed improved sensitivity in smear-negative cases (up to 91.7% vs. 66.7% for Xpert), HIV-positive adults (90% vs. 77%), and HIV-positive children (88.9% vs. 67.7%). In smear-positive cases, both tests performed similarly well (about 98–100% sensitivity). This makes Ultra particularly useful in detecting TB early or in difficult cases (Opota et al., 2019).

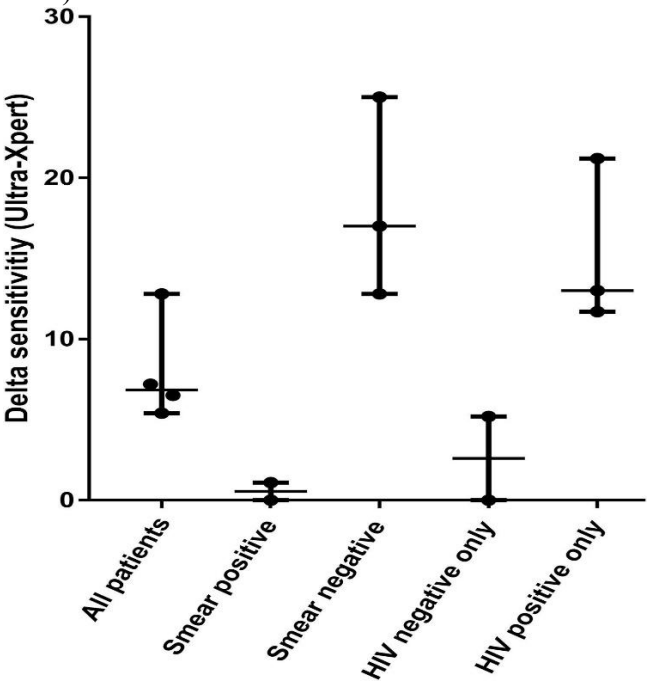

Figure 1: Difference in sensitivity (Ultra-Xpert) across patient subgroups, showing improved

performance of Ultra in smear-negative and HIV-positive cases.

One important but frequently overlooked factor affecting the reliability of clinical trials and the

effectiveness of TB care programs is adherence to TB treatment. Early TB research has historically highlighted poor adherence as a factor that can reduce real world effectiveness in pragmatic trials and cause efficacy in explanatory trials to be misinterpreted. Non adherence, particularly during the intensive phase of treatment, can raise the risk of treatment failure and resistance, and differences in adherence between trial arms may complicate results. According to recent studies, even small adherence errors (such as missing more than 10% of doses) greatly raise the likelihood of adverse outcomes. As a result, trial design and the execution of TB programs depend on precise adherence measurement, regimen "forgiveness" for missed doses, and sophisticated monitoring tools (such as electronic dose tracking). Both are completely noncompliant. Therefore, accurate measurement of adherence, consideration of regimen "forgiveness" for missed doses, and advanced monitoring tools (like electronic dose tracking) are essential in both trial design and TB program implementation. (Vernon et al., 2019). Both total non-adherence and its timing and intensity must be analyzed to ensure robust evaluation of TB regimens. Technology won't fix everything, but it can make a real difference. Simple tools like reminder apps, digital pillboxes that record when a dose is taken, or even text messages from healthcare workers can help patients stay on track. Video-observed therapy (VOT), where patients send a short clip of themselves taking the medicine, is already replacing in-person supervision in some countries, making treatment more flexible and private. The point isn't to monitor people like machines it's to support them in a way that fits into their real lives. If we design tech with empathy and understanding, we might finally solve one of the oldest problems in TB care (Vernon et al., 2019).

After COVID hit, everything changed not just for patients, but for entire health systems. TB services, which were already under strain, took a huge step backward. Suddenly, fewer people were being diagnosed, fewer were getting treated, and drug-resistant cases were slipping through the cracks. It's like we lost years of progress in just a few months. Even before the pandemic, detecting TB in children was tough. Getting proper samples from kids isn't easy, and testing for drug resistance takes time and resources that many places still don't have. And while we've improved testing for some types of resistance, like rifampicin, other forms like isoniazid resistance are still being missed. That means many people are on the wrong treatments, which can do more harm than good. Newer drug regimens are promising, but they come with their problems. Testing for resistance to drugs like bedaquiline and linezolid still relies on slow, old school lab methods. And when health systems don't have a way to link test results to the right patient, or they lose track of someone moving between clinics, it's hard to act on results even when they exist. Here's where technology could help, not with flashy apps, but with simple, solid systems: better digital records, smarter sample tracking, faster communication between labs and clinics. It's not about replacing people, it's about giving them better tools to do the job (Dean et al., 2022).

Despite numerous efforts to curb the spread of multidrug-resistant tuberculosis (MDR-TB), significant challenges persist in both high and low resource settings. Limited access to precise and advanced tools is one of the main problems for successful prevention. While molecular techniques, such as GeneXpert MTB/RIF, have significantly improved the speed of diagnosis, many areas with high TB burdens still rely on slower, traditional diagnostic methods. This delay in diagnosing MDR-TB hampers the timely initiation of the appropriate treatment and heightens the risk of transmission (Vishwakarma et al.,2023).

Another major challenge is the absence of standardized protocols for preventing MDR-TB in individuals exposed to the disease. While preventive strategies for drug-susceptible TB are well-established, there is a lack of widely available and standardized preventive treatment for contacts of MDR-TB patients, which makes secondary prevention less effective. This has made it difficult to protect individuals at high risk of contracting MDR-TB, especially in the absence of early detection. Poor treatment adherence remains a considerable obstacle, driven by the complex and often lengthy nature of MDR-TB treatment regimens. Treatment is often interrupted or left incomplete due to the side effects of second line drugs and the financial burden of extended therapy. The prevention of MDR-TB is also challenged by structural weaknesses in the healthcare system. Insufficient training for healthcare workers, particularly in high-burden areas, and a lack of

cohesive infection control measures hinder effective management. Moreover, logistical issues, such as inconsistent drug availability and gaps in TB program integration, exacerbate the difficulty in managing MDR-TB prevention strategies effectively (Dartois & Rubin, 2022).

RESULTS

In our review of 25 recent studies, the most consistently identified drivers of MDR-TB were incomplete or irregular treatment (reported by roughly 80% of the studies), weak health-care systems including drug stockouts and poor monitoring (72%), and previous treatment failure (60%), with HIV co-infection and overcrowded, poorly ventilated living conditions each noted in about 50% of the reports; socioeconomic factors such as poverty, stigma, and malnutrition were also implicated in over half of the studies. On the technology front, video-observed therapy regularly achieved adherence rates of around 85–95%, SMS reminders reduced missed doses by approximately 20–30%, and smart pillboxes and mobile apps enabled real-time monitoring and patient engagement, while biometric attendance systems strengthened accountability in clinic-based programs. Together, these findings underscore that a dual approach fortifying traditional treatment infrastructures and harnessing telemedicine innovations offers a comprehensive and effective strategy to curb the global burden of MDR-TB.

CONCLUSION

Preventing (MDR-TB) requires a comprehensive, multi-level approach. Primary prevention aims to stop resistance from emerging through accurate diagnosis, rational drug use, BCG vaccination, and ensuring treatment adherence, especially via Directly Observed Therapy (DOT). Secondary prevention focuses on interrupting transmission by using rapid diagnostics like GeneXpert, conducting contact tracing, and providing preventive therapy for high-risk individuals. Tertiary prevention supports patients already diagnosed with MDR-TB through shorter, all-oral regimens (e.g., BPaL/BPaLM), nutritional and psychosocial support, and strict infection control. major challenges still exist such as limited access to diagnostics, poor adherence due to side effects and financial hardship, weak healthcare systems, and social barriers like stigma and poverty. Addressing these issues requires not just medical solutions, but patient-centered strategies, health system strengthening, and community engagement. but in this evolving era of healthcare, digital innovation is transforming the way TB care is delivered. Tools like video-observed therapy (VOT), smart pillboxes, and SMS reminders are not only improving adherence, they are creating trust, connection, and dignity. Especially in low-resource settings, these technologies offer scalable, compassionate alternatives to traditional approaches. Ultimately, ending MDR-TB is not just about drugs and diagnostics. It's about listening to patients, supporting their journeys, and building systems that serve people, not just diseases. With innovation, empathy, and collaboration.

Ethical approval

The study does not require ethics committee approval.

Author contribution

The authors declare contribution to the paper as follows: Study conception and design: RI; data collection: NH and DA; analysis and interpretation of results: WM and SQ; draft manuscript preparation: AH and NH, Critical review: AG.

All authors reviewed the results and approved the final version of the article.

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Conflict of interest

The authors declare that there is no conflict of interest

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