Impact and cost-effectiveness of current and future tuberculosis diagnostics: the contribution of modelling

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S U M M A R Y

The landscape of diagnostic testing for tuberculosis (TB) is changing rapidly, and stakeholders need urgent guidance on how to develop, deploy and optimize TB diagnostics in a way that maximizes impact and makes best use of available resources. When decisions must be made with only incomplete or preliminary data available, modelling is a useful tool for providing such guidance. Following a meeting of modelers and other key stakeholders organized by the TB Modelling and Analysis Consortium, we propose a conceptual framework for positioning models of TB diagnostics. We use that framework to describe modelling priorities in four key areas: Xpert® MTB/RIF scale-up, target product profiles for novel assays, drug susceptibility testing to support new drug regimens, and the improvement of future TB diagnostic models. If we are to maximize the impact and cost-effectiveness of TB diagnostics, these modelling priorities should figure prominently as targets for future research.

K E Y W O R D S : tuberculosis; modelling; diagnostics

THE FUTURE OF DIAGNOSTIC TESTING for active tuberculosis (TB) has never been more promising. In addition to the Xpert® MTB/RIF assay (Cepheid, Sunnyvale, CA, USA), a number of other promising assays are being evaluated in trials,[1] and profiles for next-generation diagnostic tests are being developed.[2] Novel regimens for anti-tuberculosis treatment are being launched,[3] and corresponding diagnostics for drug susceptibility testing (DST) have emerged as a priority.[4] For the first time, tests capable of detecting 80% of all cases of pulmonary TB—including DST profiles—may become reality.[5] As these tests emerge, the need to understand their potential impact and cost-effectiveness has never been more urgent. These emerging diagnostic tests will likely be much more expensive than sputum smear microscopy, and the effects of their introduction into health systems (with existing algorithms and patterns of clinical/empiric diagnosis) are unclear.[6,7] Ultimately, we must strive to leverage these tests in a way that improves population health, using scarce economic resources as carefully as possible. In the context of incomplete data and urgent decision-making timelines, models may play an invaluable role.[8] Models commonly used to evaluate TB diagnostics include epidemiological transmission models,[9] economic evaluation models[10] and health system models.[11] Conclusions from all such models are subject to uncertainty, as data that inform estimates of parameter values are limited and our knowledge of the natural history of TB is incomplete. Where population-level data on the impact of interventions do not exist, models are often the only way to translate existing empirical data into projections of impact and cost-effectiveness for decision-making purposes.

It is in this environment that the TB Modelling and Analysis Consortium (TB MAC) held its second meeting on the 'impact and cost-effectiveness of current and future TB diagnostics' in Amsterdam, The Netherlands, in April 2013 (Table 1). The aim of this meeting was to advance modelling efforts in four

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Table 1 TB Modelling and Analysis Consortium (TB MAC): diagnostics meeting structure

Planning for this meeting of 50 participants began more than 6 months in advance, with discussions among an eight-member steering committee including transmission modelers, economists, epidemiologists, and representatives from the funding agency (Bill and Melinda Gates Foundation). Through these discussions, a series of four 'workstreams' was envisioned; these streams were selected as meeting three criteria:
   1)   They must address an urgent near-term need, questions of which are amenable to modelling
   2)   a body of empirical and/or conceptual work to support models must be emerging, and
   3)   sufficient future (financial and political) support for models must be feasible.

Each stream was assigned:
   1)   a short-term deliverable (usually a list of priorities) to be completed by the end of the 2-day workshop
   2)   a long-term deliverable (either a scientific paper or a modelling project) to be completed within a set time period, and
   3)   an invited chairperson.

Before the meeting, the following steps were taken:
   1)   potential funding sources were identified to enable each stream to complete the long-term deliverables
   2)   a participant list consisting of modelers, epidemiologists, key stakeholders and trainees was developed; all meeting participants were asked to select a stream for primary participation
   3)   each stream chair was asked to coordinate a pre-meeting conference call among participants who selected to participate in that stream
   4)   a systematic literature review (to be reported elsewhere, summary available at: www.tb-mac.org/resources) was commissioned to describe existing epidemiological and economic models of TB diagnostic tests.

During the meeting, each stream (under the direction of the chairperson) coordinated:
   1)   a series of scientific presentations to the full group
   2)   a breakout session for initial planning
   3)   a report back to the full group of participants
   4)   a second breakout session for meeting the assigned deliverables and
   5)   a final summary of progress.

TB = tuberculosis.

major areas identified as priorities through collaborative pre-meeting discussions:

1 Informing scale-up strategies for Xpert
2 Developing and setting target product profiles (TPPs) for novel TB assays
3 Understanding the role of DST in existing and novel TB drug regimens
4 Describing analytical and modelling needs for better models of TB diagnostics.

Although other needs for modelling TB diagnostics exist, these four 'streams' were felt to represent focused areas in which well-designed models could have an important and rapid impact on urgent policy decisions.

MODELLING TB DIAGNOSTIC TESTS: A CONCEPTUAL FRAMEWORK

We developed a conceptual framework to help position models of TB diagnostic testing. In this framework (Figure), models generally consider diagnostics at a point along the timeline from development (future tests), to deployment (recently released tests), to optimization (existing tests). This timeline is an iterative one; for example, optimization can inform future deployment efforts, and both can inform development of the next generation of novel tests. The outcomes of these modelling analyses may include different combinations of epidemiology (population level impact), implementation (patient and health system impact), and economics (resource requirements and cost-effectiveness). Thus, for example, a model of hypothetical cost-effectiveness of diagnostics[12] may position itself to the far lower left of this grid, whereas an Xpert scale-up model within populations and health systems[11] may position itself to the mid-upper right.

WORKSTREAM PRIORITIES

After constructing the conceptual framework above, we developed a list of priorities in each of the four streams for which models could improve decision making and ultimately population health (Table 2).

Stream 1: Informing scale-up strategies for Xpert MTB/RIF

Given the rapid global scale-up of Xpert,[13] there is considerable pressure for country-level policy makers to decide if and how to introduce and/or scale up Xpert within existing programs. High-quality evidence exists as to the accuracy of Xpert,[5] but to quantitatively project the population-level impact and cost-effectiveness of different Xpert scale-up strategies, estimates of numerous other parameters (e.g., rates of TB transmission, diagnosis and mortality) must be incorporated into a unified modelling framework.[14] Models that provide evidence-based estimates of cost and/or avertible morbidity and mortality under different implementation policies would provide valuable platforms to guide rational decision making (Figure, column 2, rows 1–3). In most cases, however, policy decisions related to Xpert implementation are made without the benefit of such model-based guidance. A small number of existing models have indicated that
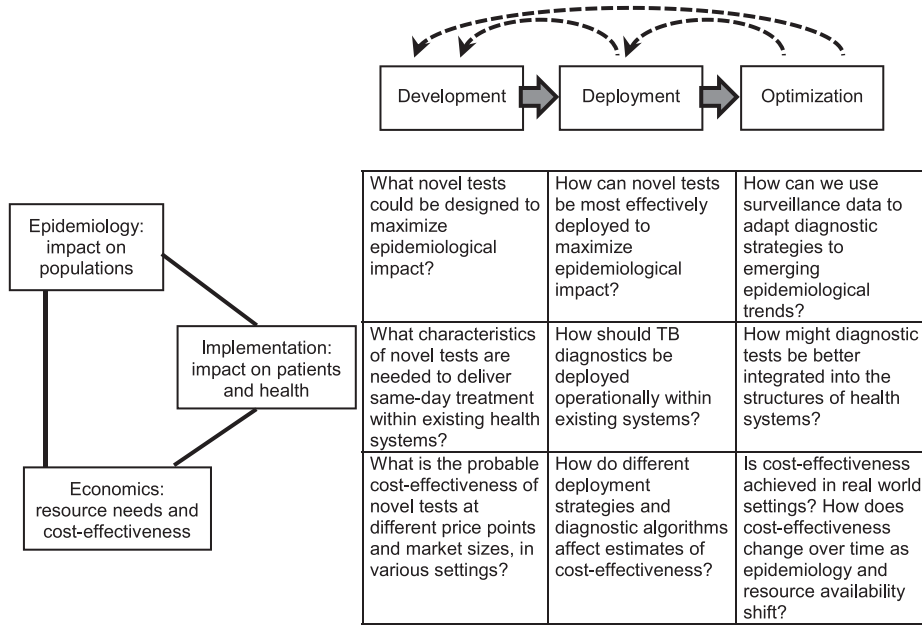
Figure   A conceptual framework for models of current and future TB diagnostic tests. Models can be positioned along a spectrum of development-deployment-optimization on one axis and an interface between outcomes related to epidemiology, health systems and economics on the other. Models can address more than one box at a time; representative modelling questions are provided, although others might reasonably be posed. TB = tuberculosis.

Xpert scale-up is likely to be cost-effective (using conventional thresholds of willingness to pay) in a limited number of settings.[14–18] However, these models may not be generalizeable, and in areas with severe resource constraints, anti-tuberculosis treatment may be relatively cheap, whereas Xpert may be less affordable, thereby generating high opportunity costs for Xpert-based diagnosis.[19] Furthermore, scale-up of Xpert may entail massive downstream costs, including treatment for multidrug-resistant TB[20] and long-term human immunodeficiency virus (HIV) therapy for people cured of TB.[21] Models must also consider the additional costs of embedding Xpert effectively within health systems (e.g., power and climate control, staff retraining and backup systems when equipment fails).

Against this background, we present a list of high-priority questions that should be addressed in model-based analyses of Xpert scale-up, including questions related to epidemiology, health systems and economic impact (Table 2). A key consideration is the outstanding need for setting-specific models that are calibrated to existing epidemiological data (e.g., TB incidence, HIV prevalence and multidrug-resistant TB [MDR-TB] prevalence) and structured to consider practical details related to health system access and diagnostic pathways for TB. These features are important in guiding the best approach for Xpert scale-up within existing programs (Questions 1 and 2), determining how modifications of existing pathways to diagnosis and care can be modified to

maximize the benefits of Xpert (Question 3) and understanding how Xpert scale-up might affect broad resource needs (e.g., MDR-TB or HIV treatment capacity) (Question 4). In summary, new models addressing these priority needs would facilitate country-level decision making by providing quantitative, evidence-based comparisons of alternative strategies for Xpert scale-up. Critical to the success of these models is early and ongoing engagement with local organizations (e.g., national tuberculosis programs) that are tasked with actual scale-up decisions.

Stream 2: Developing and selecting target product profiles for novel TB assays

There is currently great industry interest in TB diagnostics, with more than 50 companies actively developing TB diagnostic technologies.[22] This interest reflects many unmet needs. Not only is Xpert too expensive and infrastructure-dependent to be widely deployed in decentralized settings,[23] we also lack good tests for latent tuberculous infection, and extra-pulmonary and childhood TB. Given these pressing needs, it is essential to guide test developers as to which assays will have the greatest impact on TB epidemiology, health systems/clinical care and economic considerations (i.e., Figure, column 1, rows 1–3). By comparing assays with different niches and different specifications according to these three classes of outcomes, models can help test developers focus on those products likely to have not only the largest market but also the most potential to reduce

Table 2 Modelling priorities: diagnostic tests for active TB

Stream 1 — Informing scale-up strategies for Xpert® MTB/RIF
   What are the most important modelling questions related to Xpert scale-up that are likely to remain unanswered by 2014?
    1) How can Xpert infrastructure best be deployed within a country?
    2) Which population groups and clinical contexts represent the highest impact targets for Xpert?
    3) What are priority aspects of TB diagnosis and treatment programs to be strengthened to maximize the impact of Xpert?
    4) How might Xpert implementation affect the uptake, use, and resource needs of related health services?

Stream 2 — Developing and selecting TPPs for novel TB assays
   What TPPs should be compared and refined with well-designed models?
    1) Triage test for those seeking care, to identify individuals who require confirmatory testing for pulmonary TB
    2) HIV clinic-based test to rule out active TB and facilitate same-day initiation of preventive therapy in HIV-infected persons
    3) Systematic screening test (provider-initiated) for active case finding that targets people who may not seek care
    4) Rapid sputum-based, cartridge-based, molecular test for microscopy centers (with the option of add-on DST)
    5) Rapid biomarker-based, instrument-free test for non-sputum samples that can also detect childhood and extra-pulmonary TB
    6) Multiplexed test for TB and other infectious diseases
    7) Centralized, high-throughput DST incorporating new drugs to support the roll-out of new anti-tuberculosis treatment regimens
    8) Treatment monitoring test (test for cure)
    9) Predictive test for latent tuberculous infection progressing to active TB
    10) Home-based unsupervised self-test for TB that is extremely simple and will trigger self-referrals

Stream 3 — Understanding the role of DST in existing and novel TB regimens
   What scenarios/algorithms should be explored for development and deployment of DST assays?
Scenarios:
    1) High MDR-TB prevalence/all people with suspected or confirmed TB
    2) High MDR-TB prevalence/retreatment or failure cases only
    3) Low MDR-TB prevalence/all people with suspected or confirmed TB
    4) Low MDR-TB prevalence/retreatment or failure cases only
Algorithms:
    1) RMP, then FQ ($\pm$ PZA)
    2) RMP and FQ, then PZA
    3) RMP, FQ and PZA ('front-loaded')
    4) Algorithms including novel chemical entities

Stream 4 — Describing analytical and modelling needs for better models of TB diagnostics
   What improvements to models, if implemented, would improve predictions of the impact of TB diagnostics?
Feasible improvements in data
    1) Evaluating when in the course of disease transmission (leading to secondary cases) occurs, vs. timing of (active or passive) diagnosis, treatment initiation and treatment completion, including losses to follow-up
      i) Time course of infectiousness and symptoms
      ii) Time course of contacts of susceptible individuals
    2) Measuring the number, quality, and timing of interactions with the health system (including losses to follow-up) from the start of the course of TB disease
    3) Establishing the resource requirements and patient costs associated with each interaction
      i) Including affordability/health system spend
Feasible improvements in model structure
    1) Further developing health systems models to understand health systems questions and link to cost, cohort, and transmission models
    2) Creating user-friendly models.

TB = tuberculosis; TPP = target product profiles; HIV = human immunodeficiency virus; DST = drug susceptibility testing; MDR-TB = multidrug-resistant TB; RMP = rifampin; FQ = fluoroquinolones; PZA = pyrazinamide.

disease burden. One mechanism for providing such guidance is through the development of TPPs, which are widely used in the pharmaceutical industry to focus drug development on key attributes.[24,25] TPPs are being developed for a wide array of TB diagnostic tests, and well-designed models can guide developers as to which new TB tests need to be prioritized for development and, within those TPPs, those attributes that are of critical importance.[26]

Of particular importance is a working definition of point-of-care (POC) testing.[2] Whereas most current definitions of a POC test are product-oriented (e.g., a simple, low-cost dipstick deployable in the community), we argue that the most critical goal of a POC testing process is to ensure rapid treatment, as treatment is required to improve patient health and reduce transmission. Thus, we propose a new definition of POC testing for TB, i.e., testing that will result in a clear, actionable management decision within the same clinical encounter. This goal-oriented definition suggests that TPPs should explicitly describe a test's clinical purpose (e.g., triage, diagnosis of pulmonary TB, DST); therapeutic goal (e.g., same-day treatment initiation); target population (e.g., children, community-dwelling adults, HIV clinic); level of implementation (home, community, clinic, peripheral laboratory, hospital); and likely users.

In response to this need, we identified a list of 10 potential TPPs that well-designed comparative models could prioritize (Table 2). Once priority TPPs are selected, more focused models can prioritize further among the various attributes included in the TPP, such as accuracy, turnaround time, price, patient acceptability (e.g., blood and urine more often

preferred over sputum) and the ability to be deployed within existing health systems as part of a POC testing program. Ultimately, TPP development and modelling represent an iterative process, with models helping to refine and compare each successive TPP as knowledge and prototypes emerge.

Stream 3: Understanding the role of drug susceptibility testing in existing and novel TB regimens

With several new TB drugs in the pipeline, the prospect of a first-line treatment regimen against which no resistance exists may eventually become a reality.[24] More immediately, shortened first-line regimens based on combinations of current and repurposed TB drugs are emerging.[4] Fluoroquinolone-based regimens are of particular interest, and a clinical trial was recently initiated based on the early bactericidal activity of a regimen in which the novel nitroimidazo-oxazine PA-824 is combined with moxifloxacin and pyrazinamide (PaMZ).[27] As many novel regimens rely heavily on fluoroquinolones and pyrazinamide (PZA), they may need to be restricted to patients with organisms susceptible to these drugs; unlike for rifampin (RMP), stand-alone DST for these two drugs currently does not exist. DST against PZA is particularly difficult, as phenotypic testing requires acidic conditions, and genotypic testing must account for over 200 mutations (mostly in a single gene, *pnc*A) potentially associated with resistance.[28] It is therefore important to specify the DST assays most urgently needed for development (e.g., combined assay for RMP, fluoroquinolones and PZA resistance vs. stand-alone tests for each drug) and the most important assay attributes, including accuracy, infrastructure and biosafety requirements, and price. In other words, we need a TPP for next-generation DST. In addition to assay development, it is also critical to understand how these assays should best be deployed. For example, must all individuals receiving a novel first-line regimen be tested for full susceptibility or can we restrict testing to people at high risk for drug resistance (e.g., RMP-resistant on Xpert, previously treated for TB) and/or death (e.g., HIV)? These questions of optimal DST assay development and deployment can be answered by assessing the impact of each alternative on epidemiology, health systems and economics (Figure, column 1, rows 1–3). Models provide a quantitative, structured mechanism for making such comparisons.

We propose that these questions be addressed over both short-term horizons (informing urgent policy decisions) and longer-term ones (informing sustainable approaches), acknowledging that epidemics of drug-resistant TB are often slow to emerge.[29] We define a series of clinically oriented scenarios and assay-oriented algorithms that should be considered by models (Table 2). For shorter horizons (e.g., 5 years), decision analytic models could assess the

implementation and cost-effectiveness (i.e., health systems and economic impact) of these scenario-algorithm combinations for both RMP-containing, fluoroquinolone-based regimens and realistic RMP-free regimens (e.g., PaMZ). For longer horizons (e.g., 20–50 years), dynamic models incorporating assumptions about TB transmission could compare the epidemiological impact on the emergence of drug-resistant TB, considering also regimens of entirely novel compounds. Ultimately, as with Xpert scale-up, these questions must be answered in a variety of epidemiological and economic settings, and in close communication with the relevant stakeholders.

Stream 4: Describing analytical and modelling needs for better models of TB diagnostics

As demonstrated by our systematic review (TB MAC 2: review of TB diagnostic modelling, available at www.tb-mac.org/resources), current models of TB diagnostics have a limited literature base on which to draw. Existing transmission models of TB diagnosis suffer from fundamental parameter and structural uncertainties, including questions regarding the amount of transmission that occurs before patients seek diagnosis, the trajectory of infectiousness over time and effects of contact structure on the timing of transmission.[30] Data are also scarce as to how patients access diagnostic testing within existing health systems (e.g., public vs. private sector diagnosis) and how diagnostic test results subsequently affect outcomes (e.g., if patients are lost to care before receiving test results). From the economic perspective, there is also a dearth of geographically representative data on the costs of key TB diagnostic assays and the costs incurred by patients specifically during the diagnostic process, despite recent systematic reviews[31–33] of the overall costs to patients of health care seeking for TB. These questions are particularly relevant to deploying emerging tests and optimizing existing diagnostic algorithms (Figure, columns 2–3).

We identified a set of critical analytical and modelling needs required to improve existing models of TB diagnostics (Table 2). First, we need to more clearly understand when TB transmission occurs relative to the timing of diagnosis, treatment initiation, and losses to follow-up. For example, how much transmission occurs between a missed diagnosis and subsequent diagnosis leading to treatment initiation? How much transmission can be averted through active TB screening? We disaggregate these considerations into biological and behavioral components; specifically, we lack data on how symptoms and infectiousness evolve over an individual's disease course, and on how contact patterns and care-seeking behavior differ over time and space. Studies to fill these gaps could include intensified evaluations of contact networks and outbreaks linking records of patient behavior with advanced molecular epidemi-

ology (e.g., whole-genome sequencing) to better pinpoint the timing of transmission and disease.[34] Second, we need a better understanding of how TB patients interact with the health system during the diagnostic process, including the number, type and timing of interactions (and losses to follow-up) within that system over their disease course (Figure, row 2). Detailed data on health service utilization might be better collected during pragmatic clinical trials of TB diagnostics,[35] including more detail on the pathways of those patients lost to care. Third, to better inform economic evaluations (Figure, row 3), we need better data on health systems resource requirements and patient costs associated with TB diagnosis. To meet this need, we cannot conduct costing studies in each country, but well-selected, comprehensive costing studies in different regions and income levels, coupled with econometric models to extrapolate data to other settings, could be invaluable. Two priority model-development needs identified were improved health systems models to better assess the operational placement of new TB diagnostics, and user-friendly models for decision making at the country level.

SUMMARY: MODELLING CURRENT AND FUTURE TB DIAGNOSTICS

In the rapidly shifting landscape of TB diagnosis, stakeholders—including industry leaders, policy makers and implementers—need data-driven guidance about which assays to develop, how to deploy emerging assays within existing health systems, and how to optimize existing assays and algorithms in the field. These decisions must maximize the impact of diagnostics on epidemiology, health systems and clinical management using tightly constrained resources. The urgency of the decision-making process greatly outpaces our present ability to collect definitive data on these outcomes. As such, models serve a key role. We present a conceptual framework for models of TB diagnostics (Figure) and define modelling priorities in four streams (Table 2). In an environment characterized by urgent questions and severe resource constraints, this framework may help guide data gathering and modelling efforts, with the ultimate goal of enabling decision makers to develop, deploy and optimize TB diagnostics in a way that maximizes impact and effectively translates resources into better health.

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RESUME

Le paysage des tests de laboratoire de la tuberculose (TB) change rapidement et les parties prenantes ont besoin de directives urgentes sur la manière d'élaborer, de diffuser et d'optimiser le diagnostic de la TB de façon à maximiser son impact et faire le meilleur usage des ressources disponibles. Quand il faut prendre des décisions basées sur les données incomplètes ou préliminaires qui sont les seules disponibles, la modélisation est un outil utile pour fournir ce type de directive. A la suite d'une réunion de modélisateurs et d'autres intervenants majeurs organisée par le « TB Modelling and Analysis Consortium ', nous proposons un cadre conceptuel pour intégrer de nouveaux modèles de diagnostic de la TB. Nous utilisons ce cadre pour décrire les priorités de la modélisation dans quatre domaines principaux : l'expansion du test Xpert® MTB/ RIF, le ciblage de produits pour de nouveaux tests, les tests de pharmaco-sensibilité afin d'élaborer de nouveaux protocoles thérapeutiques et la nécessité d'améliorer les modèles futurs de diagnostic de la TB. Si nous voulons maximiser l'impact et la rentabilité du diagnostic de la TB, ces priorités doivent être les cibles principales de la recherche future.

RESUMEN

El panorama de las pruebas diagnósticas de la tuberculosis (TB) está evolucionando rápidamente y los interesados directos precisan con urgencia directrices en materia de desarrollo, despliegue y optimización de estos métodos, de manera que se obtenga el máximo impacto, mediante el uso óptimo de los recursos existentes. Cuando se deben adoptar decisiones solo con base en datos incompletos o preliminares, la modelización aparece como un instrumento útil que puede aportar esta orientación. Tras una reunión con modeladores y otros interesados clave, organizada por el 'TB Modelling and Analysis Consortium', se propuso un marco teórico destinado al posicionamiento de los modelos de pruebas diagnósticas de la TB. A partir de este marco, se describen las prioridades de la modelización en cuatro esferas principales: las estrategias de ampliación de escala de la prueba Xpert® MTB/RIF, la definición de las características de las nuevas pruebas, las pruebas de sensibilidad a los medicamentos que fundamenten los nuevos regímenes terapéuticos y las deficiencias que se deben superar a fin de mejorar los futuros modelos de métodos diagnósticos de la TB. Si se busca obtener el máximo impacto y la mayor rentabilidad de los medios diagnósticos, estas prioridades de modelización deben ocupar un puesto prominente en los objetivos de las investigaciones futuras.