Diagnostic Performance of Tuberculosis-Specific IgG Antibody Profiles in Patients with Presumptive Tuberculosis from Two Continents

Tobias Broger,1 Robindra Basu Roy,2 Angela Filomena,3 Charles H. Greef,4 Stefanie Rimmels,3 Joshua Havumaki,1 David Danks,5 Nicole Schneiderhan-Marra,3 Christen M. Gray,1 Mahavir Singh,1 Ida Rosenkrands,7 Peter Andersen,7 Gregory M. Husar,4 Thomas O. Joos,3 Maria L. Gennaro,6 Michael J. Lochhead,4 Claudia M. Denkinger,3 and Mark D. Perkins1

1FIND, Chemin des Mines 9, Geneva, Switzerland; 2Section of Paediatrics, Imperial College London, United Kingdom; 3Natural and Medical Sciences Institute at the University of Tübingen, Reutlingen, Germany; 4MBio Diagnostics Inc., Boulder, Colorado; 5Department of Philosophy, Carnegie Mellon University, Pittsburgh, Pennsylvania; 6Lionex GmbH, Braunschweig, Germany; 7Statens Serum Institut, Copenhagen, Denmark; 8Public Health Research Institute, Rutgers New Jersey Medical School, New Brunswick

Background. Development of rapid diagnostic tests for tuberculosis is a global priority. A whole proteome screen identified Mycobacterium tuberculosis antigens associated with serological responses in tuberculosis patients. We used World Health Organization (WHO) target product profile (TPP) criteria for a detection test and triage test to evaluate these antigens.

Methods. Consecutive patients presenting to microscopy centers and district hospitals in Peru and to outpatient clinics at a tuberculosis reference center in Vietnam were recruited. We tested blood samples from 755 HIV–uninfected adults with presumptive pulmonary tuberculosis to measure IgG antibody responses to 57 M. tuberculosis antigens using a field-based multiplexed serological assay and a 132-antigen bead-based reference assay. We evaluated single antigen performance and models of all possible 3-antigen combinations and multiantigen combinations.

Results. Three-antigen and multiantigen models performed similarly and were superior to single antigens. With specificity set at 90% for a detection test, the best sensitivity of a 3-antigen model was 35% (95% confidence interval [CI], 31–40). With sensitivity set at 85% for a triage test, the specificity of the best 3-antigen model was 34% (95% CI, 29–40). The reference assay also did not meet study targets. Antigen performance differed significantly between the study sites for 7/22 of the best-performing antigens.

Conclusions. Although M. tuberculosis antigens were recognized by the IgG response during tuberculosis, no single antigen or multiantigen set performance approached WHO TPP criteria for clinical utility among HIV-uninfected adults with presumed tuberculosis in high-volume, urban settings in tuberculosis-endemic countries.

Keywords. serologic tests; tuberculosis; biomarkers; antibodies; diagnosis.

Despite advances in rapid molecular diagnostic techniques for tuberculosis, an unmet need remains for a point-of-care nonsputum-based test [1]. The World Health Organization (WHO) has defined high-priority target product profiles (TPPs) for tuberculosis diagnostics [2]. These include a rapid nonsputum-based test for detecting tuberculosis with the purpose of initiating tuberculosis treatment on the same day (tuberculosis detection test henceforth) and a community-based triage or referral test for differentiating patients with signs and symptoms of active tuberculosis who need referral for further confirmatory testing from those who do not have tuberculosis (tuberculosis triage test henceforth). Serological tests such as lateral flow assays are appealing for these applications due to their simplicity, lack of specimen processing requirements, and implementation record. However, performance of serodiagnostics for tuberculosis has been disappointing, leading the WHO to issue a strong recommendation against the use of serological tests commercialized for the diagnosis of active tuberculosis [3, 4]. In the WHO policy statement, further research was encouraged, specifically with representative populations with presumptive tuberculosis in studies with prospective follow-up and blinding [4].

One reason why serological diagnosis of tuberculosis has been challenging is that immunoglobulin G (IgG) responses to tuberculosis are heterogeneous across patient populations and most tuberculosis serologic tests use a single or small number of antigens [5–9]. Therefore, FIND, a nonprofit organization that enables diagnostic development for poverty-related diseases, has
been systematically working to define the diagnostic potential of tuberculosis serological responses. Using a high-throughput expression system, the entire tuberculosis proteome was tested with globally collected sera from more than 500 patients with tuberculosis disease or nontuberculous pulmonary disease [6]. Although antibody responses were detected against approximately 10% (or 484 proteins) of the bacterial proteome, a much smaller fraction generated responses that might distinguish active tuberculosis from nontuberculous pulmonary disease. We prioritized proteins that exhibited the best discriminating capacity toward the development of new tuberculosis detection or tuberculosis triage tests.

Here, we report the diagnostic performance of a custom, portable multiplexed serology assay (MBio Diagnostics) that was used to measure antibody responses to 57 selected antigens in blood from more than 750 prospectively enrolled adults with presumptive pulmonary tuberculosis at 2 trial sites in Vietnam and Peru. Antibody response to a broader set of 132 antigens in frozen sera was also measured using a multiplex bead-based Luminex assay at a reference research laboratory.

METHODS

Study Design

Adults who presented to ambulatory healthcare centers with symptoms suggestive of pulmonary tuberculosis in Peru and Vietnam were consecutively enrolled in the study. The site in Peru is a research institute in Lima that recruits patients from microscopy centers and district hospitals in a high tuberculosis prevalence area. The site in Vietnam is a tuberculosis and lung disease reference center in Ho Chi Minh City that recruits patients from its outpatient clinic. Inclusion and exclusion criteria for entry into the trial are detailed in Supplementary Table 1, and criteria to exclude recruited patients from the analysis are provided in Supplementary Appendix 1. Patient characteristics, comorbidities, and tuberculosis history were recorded. Human immunodeficiency virus (HIV)–positive individuals were excluded from this feasibility study in view of potentially altered serological responses [10]. Written informed consent was obtained from all patients. Study participation did not alter the standard of care. Figure 1 depicts the patient and specimen flow. Recruitment was done in 2 phases: phase 1 was used to validate the field-based MBio platform against the reference assay before proceeding to the larger phase 2.

Sample Procedures

At least 2 sputum samples were collected from each patient and tested with direct smear microscopy, solid and liquid culture, and with Xpert® MTB/RIF (Cepheid, Sunnyvale), when available. The presence of *Mycobacterium tuberculosis* complex in cultures was confirmed by MPT 64 antigen detection (Capilia TB, Tauns Laboratories, Japan). Serum (SE), whole

Figure 1. Patient and specimen flow. Abbreviations: HIV, human immunodeficiency virus; LJ, Löwenstein–Jensen solid medium; MGIT, BACTEC mycobacteria growth indicator tube 960 culture; NALC-NaOH Decon., N-acetyl-L-cysteine-sodium hydroxide decontamination; NMI, Natural and Medical Sciences Institute at the University of Tübingen; Xpert, Xpert® MTB/RIF.
blood (WB), and frozen serum (FZ) were collected for analysis (Supplementary Appendix 2).

**Case Definitions**

Supplementary Table 2 summarizes the case definitions. Patients were categorized based on clinical and microbiological results. Patients with positive *M. tuberculosis* cultures were diagnosed as definite tuberculosis and subcategorized into smear-positive and smear-negative groups. Participants who were smear negative and culture negative but responded to empiric tuberculosis treatment were classified as “clinical tuberculosis.” Participants who were smear negative and culture negative on all sputum samples and who exhibited symptom resolution in the absence of tuberculosis treatment at the 2-month follow-up visit were classified as “non-tuberculosis disease.”

**Antigen Selection**

The antigen selection process is described in Supplementary Appendix 3 and Supplementary Figure 1. In summary, 62 antigens from the whole proteome screen [6] were selected for expression and purification on the basis of odds ratios, area under the curve (AUC), or high model importance in random forest analysis. An additional 41 antigens were selected in independent research studies performed by institutions that collaborate with FIND. The resulting antigen panel was prescreened with 1321 patient sera by a multiplex Luminex assay [11] to define the subset of 57 recombinant antigens (Figure 2B) used in this study. To validate the down-selection of target antigens, we retained the Luminex assay and added additional antigens such that this platform contained 132 antigens (including recombinant proteins, fusion proteins, antigen cocktails, and native protein preparations; Figure 2C). There were 93 unique antigens. The antigen list and expression, purification, and quality details are listed in Supplementary Appendix 4 and Supplementary Table 3.

**MBio Multiplexed Serological Assay**

The MBio multiplexed immunoassay system uses disposable cartridges that have a 2-dimensional array of antigens and controls along with a laptop-connectable reader (SnapEsi; Supplementary Appendix 5) [12]. Briefly, diluted sample is added to the cartridge and, after an incubation and wash, fluorescently labeled anti-human IgG is used to measure antigen-bound human IgG for each spot in the array.

**Serological Luminex Assay**

The multiplex bead-based Luminex assay, which measures IgG antibodies in FZ, was performed as described in Planatscher et al [13] and Supplementary Appendix 6.

**Diagnostic Performance of Single Antigens and Antigen Models**

The WHO TPP for the tuberculosis detection test and tuberculosis triage test are summarized in Table 1, alongside the study targets for the MBio and Luminex platforms. The performance of antigens (or antigen sets) were evaluated against the following 3 targets: tuberculosis detection test sensitivity at preset specificity, tuberculosis triage test specificity at preset sensitivity, and AUC (Supplementary Appendix 8).

**Statistical Analysis for Multiantigen Combinations**

Generalized linear models (GLMs), generalized additive models (GAMs), and naive Bayes (NB) with 8-fold cross-validation were used to test all possible 3-antigen combinations and to...

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**Figure 2.** Summary of patient and antigen selection. A, Recruitment flow diagram for patients enrolled in the study. B, MBio field platform antigens. C, Luminex reference platform antigens. All MBio field platform antigens were also measured on the Luminex reference platform. Some of the antigens used have the same Fv number (see http://tuberculist.epfl.ch/) and amino acid sequence, but were provided by different suppliers or expressed in different production strains. Therefore, the number of unique antigens is shown in brackets. A comprehensive list can be found in Supplementary Table 3. Abbreviations: CRF, Case report form; HIV, human immunodeficiency virus.
identify a subset of antigen combinations by stepwise regression for each platform and sample type (Supplementary Appendixes 9 and 10). The models were set to optimize sensitivity at preset specificity for tuberculosis detection tests, specificity at preset sensitivity for the tuberculosis triage tests, and AUC.

RESULTS

Study Participants

A total of 844 eligible patients with presumptive tuberculosis were recruited to the study (Figure 2A). A total of 73 were excluded from analysis due to new diagnosis of HIV or discrepancies in study documentation, microbiological test results, or study sample collection (Figure 2A, Supplementary Appendix 1). There were 16 additional exclusions due to missing MBio data or cartridge errors (Figure 2A). A total of 755 adults were therefore eligible for analysis with 447 definite tuberculosis cases, 13 cases of clinical tuberculosis, and 295 of non-tuberculosis disease (Figure 2A, Table 2).

Validation of MBio and Luminex Platforms

In phase 1, samples from 184 patients (Supplementary Table 4) were used to validate the MBio system, which showed high concordance with the Luminex assay (Supplementary Appendix 7) and met all endpoints at both sites [14]. The Luminex assay had intra- and inter-assay coefficients of variation of <20% for 128/132 antigens (Supplementary Appendix 6). Antigen coupling efficiency of all His-tagged antigens (n = 125) was confirmed using an anti-His antibody (Supplementary Table 11). MBio analysis was based on all 755 patients; for Luminex, we focused on the larger phase 2 (571 valid results), as the signal ranges in the 2 experimental runs did not permit combination.

Single Antigen Performance

When we analyzed performance of the 57 single antigens on the MBio platform, we identified 22 top-ranking antigens (Supplementary Appendix 5). The best antigen for a tuberculosis detection test with a predefined specificity of 90% was Rv2031c_1a, with highest sensitivity of 25% (95% confidence interval [CI], 21–29) on fresh serum. The best antigen for a tuberculosis triage test with a predefined sensitivity of 85% was Rv1860_1a, with highest specificity of 32% (95% CI, 26–37) on frozen serum (Supplementary Figure 2). Comparing the performance of the same 57 antigens on the Luminex platform, we found that although AUCs tended to be higher on Luminex, only 5 of the 22 top-ranked antigens performed significantly better than on MBio (Figure 3A, Supplementary Table 5). The highest AUC was 0.69.
(Rv2031c_1a) on Luminex and 0.64 (RV1860_1a, MBio FZ) on MBio (Supplementary Table 5).

When we analyzed the performance of the 75 additional antigens that were only measured on the Luminex platform, we identified antigens that performed slightly better (Supplementary Table 6), with the sensitivity of the best antigen for the tuberculosis detection test being 31% (95% CI, 27–36) for Rv1886_5. The highest AUC of a single antigen on Luminex was 0.72 from WCL_H37Rv_6.

Influence of Study Site and Previous History of Tuberculosis on Performance

Given the study design and the study participants' characteristics (Table 2), we carried out post hoc subanalyses to determine whether performance varied between the study sites and by the participants who had a previous history of tuberculosis.

Figure 3B shows immunological responses of 755 patients to the 22 highest ranked antigens on the MBio assay categorized by study site. Patient-to-patient antibody response was variable, and

![Figure A](image.png)

**Figure A.** Summary of individual antigen performance. A, Area under the curve (AUC) histograms by sample type and platform for the 57 antigens that were measured on both platforms. AUCs of fresh (serum, whole blood) and frozen (serum) samples from MBio are in the same range, and no difference per sample type could be observed. There was a tendency for higher AUCs from Luminex compared to MBio, but differences were only significant for 5 antigens (Supplementary Table 5). Approximate AUC targets (blue and green lines) were estimated based on study targets (AUC estimated by receiver operating characteristic (ROC) curve fitting through the study target points using a binormal model) and were not met by single antigens.

![Figure B](image.png)

**Figure B.** Heterogeneous antibody response pattern of 755 tuberculosis patients. The heat map shows the reactivity of sera (standardized z-scores of MBio fresh serum intensity signals) to the 22 highest ranked MBio antigens. Abbreviations: FZ, frozen serum; SE, fresh serum; WB, fresh whole blood.
false-positive reactivity can be observed in the non-tuberculosis disease groups of both sites. Antibody responses to some antigens, including the top 3 MBio antigens, were dependent on study site. Antibody response against Rv1860_1a was higher in the Vietnam cohort, resulting in a significantly higher tuberculosis detection test sensitivity (38% in Vietnam vs 10% in Peru). Antibody response against Rv2031c_1a and Rv1886_2 had significantly higher AUCs in Peru due to increased reactivity in the Peruvian definite tuberculosis group (Figure 3B, Supplementary Table 9).

Given the relatively high proportion of patients with a history of previous tuberculosis in our cohort (Table 2), we also carried out a subanalysis where patients with a history of tuberculosis or unknown history of tuberculosis were excluded (Supplementary Table 10). There were no significant differences in AUC when compared to analysis of the whole cohort.

Three-Antigen Models

We then determined whether combinations of responses to 3 antigens would improve diagnostic performance. We used GAM, GLM, and NB models for all possible 3-antigen sets for the 57 antigens measured on MBio (29 260 input sets). The best tuberculosis detection sensitivity was 35% (95% CI, 31–40) for the combination of Rv1860_1a, Rv1886_2, and Rv3881c_1a (Table 3A). The best tuberculosis triage test specificity was 34% (95% CI, 29–40) for the combination of Rv1860_1a, Rv1886_2, and Rv3874_1a (Table 3B), which is significantly above the performance of the best single antigens. The frequency of the top 22 ranked single antigens in the best 3-antigen models is presented in Supplementary Table 7, confirming that antigens with a high single-antigen performance occur very frequently in the best models.
Multiantigen Models

We also looked at models that contained larger numbers of antigens, with stepwise regression yielding 4 to 12 antigens depending on model and sample type. The best model for tuberculosis detection involved 7 antigens and had a sensitivity of 36% (95% CI, 32–41). The best model for tuberculosis triage test had specificity of 37% (95% CI, 31–43) based on 9 antigens. We further conducted the same subanalyses using only the 439 patients with no tuberculosis history. Similar to the subanalysis for single antigens, performance did not significantly improve (tuberculosis detection test sensitivity of 37% and tuberculosis triage test specificity of 40% respectively).

Evaluation of Diagnostic Performance Against WHO Target Product Profiles

Finally, we compared the performance of single antigens, 3-antigen models, and multiantigen models on both platforms against each other, against the serological tests evaluated by the WHO in 2008, and against the study and TPP targets (Figure 4). The 3-antigen models performed significantly better than single antigens and previously evaluated tests by the WHO, but multiantigen combinations did not further improve performance. No model on either platform approached the study or TPP targets.
Expression of selected antigens in *Mycobacterium smegmatis* might therefore be advantageous [25, 26]. The mode of antigen display may also influence antibody binding. However, we could only see marginal differences in diagnostic performance when we used two independent immobilization technologies (antigen printing on plastic substrates and covalent antigen coupling to beads).

As noted in previous IgG biomarker studies, there is remarkable patient-to-patient variability in antibody responses [5–7, 9]. We found the same heterogeneity in individual responses and also that performance of 7 of the 22 high ranked antigens were significantly associated with study location (Figure 3B). Differences in the referral pathways, genetic diversity among tuberculosis strains, host genetic differences [27], differing vaccination status, or exposure to environmental mycobacteria might explain some of this variability [7]. Patients being at different stages of the spectrum of latent to active tuberculosis disease could also contribute [28–30]. Latent tuberculosis infection was not determined by tuberculin skin test or interferon gamma release assay in our study, which is a limitation. Categorized radiological interpretations of the chest radiographs were not available; therefore, we could not analyze data based on cavitory status. Subanalyses excluding patients with a prior history with tuberculosis showed comparable results to the whole data-set. Our findings cannot be applied to children, people living with HIV with presumptive tuberculosis, or to systematic screening or active case-finding.

Our results confirm that a defined pool of antigens are recognized by the IgG antibody response during active tuberculosis and that no single antigen or combination is sufficient to clearly identify patients with active tuberculosis disease [6, 7, 9, 16, 31, 32]. The results of our study of HIV-uninfected patients with presumptive tuberculosis from high-volume settings in tuberculosis endemic countries, which evaluated multiple antigens, sample types, and 2 test platforms, suggests that a conventional antigen-based IgG detection test is unlikely to meet requirements for novel tuberculosis diagnostics in symptomatic patients. This is in concordance with systematic reviews and metaanalyses of serologic testing in tuberculosis [3, 4], although combination with other biomarkers and IgG properties such as FcR-binding and glycosylation characteristics may have potential [33, 34].

**Supplementary Data**

Supplementary materials are available at *Clinical Infectious Diseases* online. Consisting of data provided by the author to benefit the reader, the posted materials are not copyrighted and are the sole responsibility of the author, so questions or comments should be addressed to the author.

**Notes**

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Disease Research Institute (IDRI), Lionex, and Cornell University for providing the antigens; and Nora Champlouillon (FINDI) for her logistic support. **Author contributions.** M. D. P. T. B., and C. M. G. designed the study. M. L. G. and M. D. P. contributed knowledge on the seroreactive immune proteome of *M. tuberculosis*. I. R., P. A., and M. S. provided recombinant antigens. M. J. L., C. H. G., and G. M. H. led the assay and cartridge development. A. F., S. R., N. S., and T. J. did the Lumixin-related work. J. H., D. D., A. F., C. M. D., and T. B. analyzed the data. R. B., T.B., C. M. D., M. L. G., and M. D. P. wrote the manuscript and all authors contributed to and approved the final version.

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**References**


