Humoral Immune Responses against the \textit{Mycobacterium tuberculosis} 38-Kilodalton, MTB48, and CFP-10/ESAT-6 Antigens in Tuberculosis\footnote{Published ahead of print on 6 January 2010.}

Xueqiong Wu,\textsuperscript{1,\dagger} Yourong Yang,\textsuperscript{1} Junxian Zhang,\textsuperscript{1} Bangying Li,\textsuperscript{1} Yan Liang,\textsuperscript{1} Chuiying Zhang,\textsuperscript{1} Mei Dong,\textsuperscript{2} Hongbing Cheng,\textsuperscript{1} and Jufang He\textsuperscript{2}

Institute for Tuberculosis Research,\textsuperscript{1} and Department of Clinical Detection,\textsuperscript{2} the 309th Hospital of Chinese PLA, Beijing 100091, China

Received 13 July 2009/Returned for modification 3 August 2009/Accepted 28 December 2009

The control of tuberculosis (TB) remains challenging in China (18). Currently, the diagnosis of active TB mainly relies on clinical symptoms, radiologic findings, and the detection of \textit{Mycobacterium tuberculosis} in clinical samples using smear staining and mycobacterial culture. However, the diagnosis of TB in smear- and culture-negative TB patients is difficult. The detection of \textit{M. tuberculosis}-specific antibodies in human sera has been an important aid in diagnosis of TB. Notably, several antigens have been demonstrated to have merit in TB diagnosis, including the 38-kDa protein, which is commonly used in serodiagnostic tests (4, 5, 8, 13, 19, 22, 23). Previous studies suggest that the antibody responses to \textit{M. tuberculosis} antigens are heterogeneous among individuals (17) so that the detection of antibodies against a single antigen usually has a low sensitivity for diagnosis of TB, especially for bacterium-negative cases. Therefore, it may be valuable to evaluate antibodies against the 38-kDa antigen and other major antigens for the diagnosis of active TB (14, 15).

Notably, the MTB48, CFP-10 (culture filtrate protein 10), and ESAT-6 (6-kDa early secreted antigen target of \textit{M. tuberculosis}) genes are conserved in \textit{M. tuberculosis} and \textit{Mycobacterium bovis} isolates but partially deleted or absent in \textit{M. bovis} BCG as well as in most nontuberculous mycobacteria (NTM) (1–3, 10, 16). Importantly, the proteins encoded by these genes are immunogenic (7, 9, 12, 16). In this study, we cloned the 38-kDa, MTB48, and ESAT-6 genes and generated recombinant 38-kDa, MTB48, and CFP-10/ESAT-6 fusion proteins in \textit{Escherichia coli}. Subsequently, we developed an enzyme-linked immunosorbent assay (ELISA) for the characterization of serum antibodies against 38-kDa, MTB48, and CFP-10/ESAT-6 antigens in a population of 250 active TB patients and 260 healthy subjects. We found that characterization of antibodies against multiple \textit{M. tuberculosis} antigens were valuable for the diagnosis of active TB.

\textbf{MATERIALS AND METHODS}

\textbf{Bacterial strains.} \textit{Escherichia coli} strain BL21(DE3) (Invitrogen, Carlsbad, CA) was cultured in Luria-Bertani (LB) medium. \textit{Mycobacterium tuberculosis} reference strain (H37Rv) was obtained from the National Institute for the Control of Pharmaceutical and Biological Products, Beijing, China, and cultured on Lowenstein-Jensen slants at 37°C for 4 weeks (6).

\textbf{Generation of recombinant \textit{Mycobacterium tuberculosis} antigens.} The procedures for the cloning, expression, and purification of \textit{M. tuberculosis} 38-kDa, MTB48, and CFP-10/ESAT-6 antigens were described previously (15, 21, 24). Briefly, the genes encoding the \textit{M. tuberculosis} 38-kDa, MTB48, CFP-10, and ESAT-6 proteins were amplified by PCR using specific primers. The sequences of these primers were as follows. For the 38-kDa antigen, the forward primer was 5'-GGTATTTCAATGTGTGGCGGAAGCGGCGGCA-3', where the HindIII restriction enzyme site is underlined. The reverse primer was 5'-CCGGATCCATGGGACGAGATGAAGAC-3', where the NheI restriction enzyme site is underlined. For CFP-10, the forward primer was 5'-GCTAGCCAGTCGCAGACCGTGACG-3', the reverse primer was 5'-GGCTAGCCAGTCGCAGACCGTGACG-3', where the NheI restriction enzyme site is underlined, and the reverse primer was 5'-GGCTAGCCAGTCGCAGACCGTGACG-3', where the BamHI restriction enzyme site is underlined, and the reverse primer was 5'-GGTATTTCAATGTGTGGCGGAAGCGGCGGCA-3', where the HindIII restriction enzyme site is underlined, and the reverse primer was 5'-GGTATTTCAATGTGTGGCGGAAGCGGCGGCA-3', where the HindIII restriction enzyme site is underlined. The PCR products of the \textit{M. tuberculosis} 38-kDa and MTB48 DNA fragments were digested with NdeI/EcoRI or NheI/HindIII enzymes and cloned into pET24b (Novagen, San Diego, CA), followed by trans-
formation into E. coli BL21(DE3), respectively. The CFP-10 and ESAT-6 DNA fragments were used as the templates, together with a DNA strand linker encoding glycine-glycine-glycine-serine-glycine-serine-glycine-serine-glycine-glycine-serine-serine-glycine-glycine-glycine-serine, for generating the CFP-10–ESAT-6 fused gene by PCR using the following primers: forward (5'-CCGAGATCCATGGCAGAAGAGAACGACG-3') and reverse (5'-CCGATCTTGGCAACATCCAGTGA-3'). The PCR products were digested with BamHI and HindIII, gel purified, and cloned into PET-28a (Novagen, San Diego, CA), followed by transformation into E. coli BL21(DE3). After DNA sequencing, individual transformants were cultured in LB medium containing kanamycin (50 μg/ml) overnight and treated with 1 mM isopropyl-β-D-thiogalactopyranoside (IPTG) for 4 h to induce the expression of recombinant proteins. The recombinant proteins were purified by metal chelate column chromatography using Ni-nitrilotriacetic acid (Ni-NTA) resin, according to the manufacturer's protocol (Qiagen). The concentrations of the recombinant proteins were determined by spectrometry, and their molecular weights and purities were estimated by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and Coomassie brilliant blue, as described previously (21). Individual preparations with a purity of >90% were further aliquoted at 1 mg/ml, lyophilized, and then stored at −80°C.

Collection of blood samples. Blood samples were collected from individual TB patients in the hospital and control subjects at the clinical laboratory of the 309th Hospital of Chinese PLA from January to April 2007, and their sera were prepared by centrifugation and then stored at −80°C. The clinical data were surveyed retrospectively. A total of 250 serum samples were selected from the patients with pulmonary TB, including 119 sera from smear- or culture-positive patients and 131 from smear- or culture-negative patients confirmed retrospectively. The sera of bacillus smear and mycobacterium culture of sputa were performed in our laboratory according to the Chinese Laboratory Science Procedure of Diagnostic Bacteriology in Tuberculosis (6). An additional 260 serum samples from healthy volunteers were selected and used as controls. All patients and healthy controls in this study were negative for HIV antibodies. This study was performed in accordance with the guidelines of the Research Ethics Committee of the 309th Hospital of Chinese PLA.

ELISA. The humoral responses of individual subjects to M. tuberculosis antigens were determined by an ELISA as described previously (10). In brief, individual recombinant proteins (10 μg/well) were used to coat the wells in 96-well microtiter plates (Nunc; Nunc, Roskilde, Denmark) overnight at 4°C. After the wells were washed, they were blocked with 1% bovine serum albumin (BSA) in phosphate-buffered saline (PBS) for 1 h at room temperature. Subsequently, individual serum samples (1:100) were added in triplicate to the wells and incubated for 1 h at 37°C. After the wells were washed, the bound antibodies were detected by horseradish peroxidase (HRP)-conjugated goat anti-human IgG (1:10,000) for 1 h at 37°C and developed with o-phenylenediamine and hydrogen peroxide, followed by the addition of 2 mol/liter sulfuric acid and measurement at an optical density of 492 nm (OD492) in an ELISA plate reader.

Data management and statistical analysis. All data were entered into a Microsoft Office Excel file. The mean and standard deviation of the optical density of individual groups for antibody responses to each of the M. tuberculosis antigens were calculated. The differences between the values for the groups were analyzed by Student t test. Furthermore, the receiver operating characteristic (ROC) curves of the optical density values for antibody responses to each M. tuberculosis antigen were plotted using SPSS 9.06 software and the area under the curves and 95% confidence intervals (95% CIs) for responses to each M. tuberculosis antigen were calculated. In addition, the optimal cutoff values were chosen when Youden's index (sensitivity + specificity −1) was maximum. Subsequently, individuals were scored as positive for the specific antibody response when his/her optical density value was greater than or equal to the cutoff value, and the positive rates and 95% CIs of individual groups for antibody responses to each M. tuberculosis antigen were calculated and differences for the values of the groups were analyzed by χ² test.

RESULTS

M. tuberculosis antigens. After the DNA fragments were cloned by PCR, the individual positive colonies, which expressed each recombinant protein with six consecutive histidine residues at the carboxyl terminus, were confirmed by DNA sequencing. Expression of the recombinant 38-kDa, recombinant MTB48 (rMTB48), and recombinant CFP-10/ESAT-6 antigens were induced in E. coli BL21(DE3), and the recombinant proteins were purified using metal-chelate affinity chromatography. Individual preparations of recombinant protein antigens with a purity of >90% were used for subsequent experiments. The successful generation of recombinant 38-kDa, rMTB48, and rCFP-10/ESAT-6 proteins provided a basis for the characterization of antibody responses in different groups of subjects by an ELISA.

Serum antibody reactivities to M. tuberculosis antigens. The levels of antibodies against the recombinant 38-kDa, rMTB48, and rCFP-10/ESAT-6 antigens in individual sera were measured by an ELISA. The levels of antibodies against the recombinant 38-kDa, rMTB48, and rCFP-10/ESAT-6 antigens in TB patients were significantly higher than those in healthy controls (P < 0.001) (Table 1). Furthermore, antibody responses to those antigens in the bacterium-positive TB patients were stronger than those in the bacterium-negative TB patients (P < 0.05). Importantly, the levels of antibodies against these antigens in bacterium-negative TB patients were significantly higher than those in healthy controls (P < 0.001). In addition, the levels of antibodies against the recombinant 38-kDa antigen and rMTB48, but not rCFP-10/ESAT-6, in the PPD-positive subjects were significantly higher than those in the PPD-negative ones (P < 0.05). Apparently, characterization of antibodies against those M. tuberculosis antigens can effectively distinguish between TB patients and healthy controls.

Furthermore, individual values of antibodies against recombinant 38-kDa, rMTB48, and rCFP-10/ESAT-6 antigens were used for the generation of ROC curves (data not shown). The areas under the curves and 95% CIs were calculated in Table 2. Accordingly, the optimal cutoff values of the optical densities of antibody responses to the 38-kDa, MTB48, and CFP-10/ESAT-6 antigens for diagnosing TB patients were 0.0852, 0.0718, and 0.0690, respectively. As a result, the sensitivities of detecting antibody responses to the 38-kDa, MTB48, and CFP-10/ESAT-6 antigens for diagnosing TB patients were 0.213, 0.241, and 0.226, respectively. The levels of antibodies against the 38-kDa antigen and rMTB48, but not rCFP-10/ESAT-6, in the PPD-positive subjects were significantly higher than those in the PPD-negative ones (P < 0.05). Apparently, characterization of antibodies against those M. tuberculosis antigens can effectively distinguish between TB patients and healthy controls.

Furthermore, individual values of antibodies against recombinant 38-kDa, rMTB48, and rCFP-10/ESAT-6 antigens were used for the generation of ROC curves (data not shown). The areas under the curves and 95% CIs were calculated in Table 2. Accordingly, the optimal cutoff values of the optical densities of antibody responses to the 38-kDa, MTB48, and CFP-10/ESAT-6 antigens for diagnosing TB patients were 0.0852, 0.0718, and 0.0690, respectively. As a result, the sensitivities of detecting antibody responses to the 38-kDa, MTB48, and CFP-10/ESAT-6 antigens for diagnosing TB patients were 0.213, 0.241, and 0.226, respectively.
TABLE 2. Areas under the curve of antibody responses to *M. tuberculosis* antigens

<table>
<thead>
<tr>
<th>Antigen(s)</th>
<th>AUCa</th>
<th>SEM</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>r38kDa</td>
<td>0.788</td>
<td>0.021</td>
<td>0.747–0.829</td>
</tr>
<tr>
<td>rMTB48</td>
<td>0.773</td>
<td>0.021</td>
<td>0.732–0.814</td>
</tr>
<tr>
<td>rCFP-10/ESAT-6</td>
<td>0.762</td>
<td>0.022</td>
<td>0.720–0.805</td>
</tr>
</tbody>
</table>

a The P values for TB patients versus healthy controls were <0.001.
b AUC, area under the curve.
c r38kD, recombinant 38-kDa antigen.

TABLE 3. Positive rates of antibody responses to *M. tuberculosis* antigens

<table>
<thead>
<tr>
<th>Group and status</th>
<th>No. of patients</th>
<th>Positive rate of antibody response to <em>M. tuberculosis</em> antigen (95% CI)</th>
<th>Combinations of antigens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>r38kDa</td>
<td>rMTB48</td>
</tr>
<tr>
<td>Healthy controls</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPD+</td>
<td>129</td>
<td>16.3</td>
<td>10.4–23.8</td>
</tr>
<tr>
<td>PPD−</td>
<td>131</td>
<td>26.7</td>
<td>19.4–35.2</td>
</tr>
<tr>
<td>Total</td>
<td>260</td>
<td>21.5</td>
<td>16.6–27.0</td>
</tr>
<tr>
<td>TB patients</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacterium−</td>
<td>131</td>
<td>73.3</td>
<td>64.9–80.6</td>
</tr>
<tr>
<td>Bacterium+</td>
<td>119</td>
<td>73.9</td>
<td>65.1–81.6</td>
</tr>
<tr>
<td>Total</td>
<td>250</td>
<td>73.6</td>
<td>67.7–79.0</td>
</tr>
</tbody>
</table>

a r38kD, recombinant 38-kDa antigen.
b P < 0.05 versus PPD− controls determined by χ² test.
c P < 0.001 versus healthy controls determined by χ² test.
Unlike the tuberculin skin test (TST) and Quantiferon test, characterization of antibody responses to \textit{M. tuberculosis} antigens is less invasive and dangerous (adverse effects) and saves time. Furthermore, it does not require the patient to return to the clinic for evaluation. In addition, the serological assay can be developed into a user-friendly and field-ready format. Notably, T-cell and macrophage-related inflammation is critical for the pathogenesis and control of TB in humans. Accordingly, the results from TST and the Quantiferon test can reflect T-cell immunity and the status of inflammation in \textit{M. tuberculosis}-infected individuals. The Quantiferon test measures systemic T-cell immunity to the purified protein derivative of \textit{M. tuberculosis}, which can help in diagnosis of latent TB infection and evaluation of TB progression. Our findings indicated that simultaneous characterization of antibody responses to multiple \textit{M. tuberculosis} antigens effectively distinguished patients with active TB from healthy controls. However, besides the value of TB diagnosis, the implication of positive antibody responses to \textit{M. tuberculosis} antigens in the pathogenesis and progression of TB in patients with active TB is unclear. Given that antibody responses to \textit{M. tuberculosis} antigens usually depend on T cells, the results from our experimental system may partially reflect systemic immune responses to \textit{M. tuberculosis}. Therefore, characterization of antibody responses to multiple \textit{M. tuberculosis} antigens should aid in the diagnosis of active TB in clinic. We are interested in further simultaneous evaluation of the serological assay, TST, and the Quantiferon test in a larger population.

In summary, our data suggest that characterization of antibodies against 38-kDa, MTB48, and CFP-10/ESAT-6 antigens can increase the sensitivity and specificity for the diagnosis of active TB. Therefore, these \textit{M. tuberculosis} antigens can be used as cocktail antigens in the serodiagnosis of active TB, especially for smear- or culture-negative TB cases. We are interested in further screening and evaluating the serological responses to other antigens to identify the optimal combinations of antigens and/or polyproteins for the sensitive and specific diagnosis of active TB.

ACKNOWLEDGMENTS

This study was supported by the Serious Infectious Diseases Foundation of China (2008ZX-10003-001) and the Beijing Science and Technology Foundation of China (D08050700640802).

REFERENCES