In Vitro Modulation of Proliferation and Cytokine Production by Human Peripheral Blood Mononuclear Cells from Subjects with Various Forms of Coccidioidomycosis

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Using peripheral blood mononuclear cells (PBMC) from individuals with or without coccidioidal delayed-type hypersensitivity (DTH), we examined and attempted to modulate the in vitro responses of PBMC from various donors to the coccidioidal antigen toluene spherule lysate (TSL). Among healthy DTH-positive donors, 100 ng of human recombinant interleukin-10 (IL-10) per ml suppressed both PBMC proliferation \((P = 0.01)\) and gamma interferon \((\text{IFN-}\gamma)\) and IL-12 production \((P < 0.05)\). In vitro proliferation and production of \text{IFN-}\gamma and IL-12 by PBMC were significantly higher in DTH-positive donors with active coccidioidomycosis than in healthy, nonimmune controls \((P < 0.05)\) but not in active DTH-negative donors with or without human immunodeficiency virus infection \((P > 0.05)\). Human recombinant IL-12 increased \text{IFN-}\gamma production by PBMC from active, DTH-positive donors \((P = 0.01)\) but not by PBMC from DTH-negative groups. For healthy DTH-negative donors, the median antigen-reactive cell frequency per \(10^6\) PBMC was 3.7, compared to 1.7 in DTH-negative donors with active coccidioidomycosis \((P = 0.03)\). These data indicate that the in vitro TSL response is highly dependent on coccidioidal DTH. Not only do PBMC from individuals with DTH appear to respond to TSL, but their response can be modulated in vitro with either IL-10 or IL-12. On the other hand, PBMC from DTH-negative individuals do not respond in vitro to TSL and their response is not modulable, suggesting a lack of antigen response.

The clinical expression of human coccidioidomycosis extends over a wide range. On one end are the majority of individuals, in whom infection is completely asymptomatic except for the expression delayed-type hypersensitivity (DTH). At the other extreme are individuals who develop widely disseminated infection without DTH and who have elevated serum anticyclocoidal antibodies \((16)\). This pattern is reminiscent of a murine model first described by Mosmann and colleagues in which T-helper lymphocytes are categorized based on their cytokine response to antigen \((33)\). In this model, a T-helper lymphocyte type 1 (Th1) response is characterized by the production of interleukin-2 \((\text{IL-2})\) and gamma interferon \((\text{IFN-}\gamma)\) and a strong cellular immune response. On the other hand, a Th2 response is characterized by production of IL-4, IL-5, and IL-10 and the lack of cellular immune response \((34)\).

More recent data have suggested that IL-10 has a counter-regulatory effect on the Th1 response \((19, 20)\). IL-10 inhibits macrophage production of IL-12, which itself stimulates Th1 cells to produce IFN-\gamma \((15)\). However, the roles of the Th2 response and of IL-10 in human infectious diseases are far from established \((29, 39)\). We recently showed that peripheral blood mononuclear cells (PBMC) obtained from patients with disseminated coccidioidomycosis and stimulated in vitro with the coccidioidal antigen toluene spherule lysate (TSL) produced significantly less IFN-\gamma than did PBMC from healthy, immune donors. However, PBMC production and mRNA expression of IL-10 were low and not significantly different between these two groups \((9)\).

However, that study left unanswered several questions, including the timing of cytokine production, the relation of in vitro PBMC proliferation and cytokine production to clinical expression of DTH, and whether in vitro PBMC proliferation and cytokine production could be modulated by the addition of cytokines or antibodies against cytokines. To answer these questions, we examined the in vitro responses to TSL among donors with different forms of coccidioidomycosis. We hypothesized that there would be significant differences in the in vitro responses to TSL based on the DTH responses of the subjects and that these responses would be modulable in vitro.

MATERIALS AND METHODS

Subjects. The use of human subjects in this study was performed under the guidelines and approval of the Human Subjects Committee of the University of Arizona. In total, five different groups of subjects were recruited. Healthy adults without active coccidioidomycosis with coccidioidal DTH made up the healthy, immune control group. Healthy adults without active coccidioidomycosis and without coccidioidal DTH made up the healthy, nonimmune control group. Individuals with chronically active coccidioidomycosis requiring antifungal therapy were recruited consecutively from the Infectious Diseases Clinic of the Tucson Veterans Affairs Medical Center and comprised the active group. All these subjects were clinically stable at the time of study. These individuals were divided into those with coccidioidal DTH and those without. The final group of subjects consisted of individuals with known infection with human immunodeficiency virus type 1 (HIV) and concomitant coccidioidomycosis requiring antifungal therapy. For the nine patients with HIV infection, the median peripheral blood CD4 lymphocyte count was 135/\(\mu\)l \((range, 2 to 291/\mu l)\).

Assessment of DTH. Coccidioidal DTH was determined by injecting 0.1 ml of usual-strength Spherulin (ALK Laboratories, Berkeley, Calif.) intradermally by a trained individual. Induration of the skin over the injection site of \(5 \text{mm}\) after 24 or 48 h was considered indicative of DTH. To exclude any possibility that DTH testing might affect the results of in vitro assays, DTH testing was done immediately after blood was drawn for study in subjects with active coccidioidomycosis and was done >3 months prior to the study in the healthy, control subjects.

Clinical scoring. The clinical scoring of subjects with active coccidioidomycosis at the time of the study was performed by using a previously established system \((25)\). A point was awarded for each symptom related to coccidioidomycosis, and

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points were awarded for each coccidioidal lesion and its severity based on physical and radiological examination. In addition, points were awarded for whether an involved site was culture positive and for the serum titer of complement fixation antibody. The final clinical score was the sum of all points awarded.

**LT assay.** The lymphocyte transformation (LT) assay was performed as previously described (1). Briefly, PBMC were isolated from heparinized blood by using Ficoll-Hypaque (Pharmacia, Piscataway, N.J.). Subsequently, 5 × 10^5 PBMC in RPMI 1640 (GIBCO, Grand Island, N.Y.) and 10% heat-inactivated pooled AB human serum (GIBCO) were added to flat-bottom wells of 96-well plates (Corning Glass Works, Corning, N.Y.). Either a final concentration of 100 μg of TSL per ml or RPMI 1640 alone was added to the wells in replicates of four. Cultures were incubated at 37°C in 95% air–5% CO2 for 5 days, after which time [3H]thymidine (0.5 μCi/ml; NEN, Boston, Mass.) was added. After an additional 18 h of incubation, the wells were harvested onto glass filter paper and counted by scintillation spectrometry. Results were expressed in counts per minute.

**Cytokine assay of cell supernatants.** Cell supernatants were prepared by placing 5 × 10^5 viable PBMC into flat-bottom wells in the same manner as in the proliferation assay. Cell supernatants were harvested after 4, 24, 48, and 72 h of incubation. Supernatants were immediately frozen and stored at −70°C until assayed. Concentrations of IFN-γ and IL-10 in PBMC supernatants were determined by enzyme-linked immunosorbent assay (ELISA; Genzyme, Cambridge, Mass., and Biosource International, Camarillo, Calif.). Preliminary experiments revealed that the median superantigen concentration of IL-12, using an assay which measured only the p70 heterodimer (R&D Systems, Minneapolis, Minn.), among six healthy donors with coccidioidal DTH was 10.4 pg/ml (range, 4.9 to 54.5 pg/ml), compared to 456.4 pg/ml (range, 17.2 to 472.9 pg/ml) in supernatants from five other healthy DTH-positive donors when measured by an ELISA which detected both p70 and p40 IL-12 (Biosource International). In subsequent experiments, supernatant IL-12 was determined by the ELISA which measured both p70 and p40 (Biosource International).

**Modulation of cytokines by cytokines and anticytokine.** For experiments involving healthy immune donors, human recombinant IL-10 (hu rIL-10; Pharmingen, San Diego, Calif.) was added to wells at a concentration of from 1 to 100 ng/ml with either 100 μg of TSL per ml or RPMI-1640 alone. For experiments using donors with active coccidioidomycosis, either hu IL-12 (R&D Systems) at a final concentration of 10 ng/ml or low-LPS, rat anti-human IL-10 (anti-IL-10; Pharmingen) at a final concentration of 10 μg/ml was added at the same time as TSL, and experiments were carried out as described above.

**Modification of ARC frequency.** A variant of the LT assay using limiting-dilution analysis was used to estimate the antigen-reactive cell (ARC) frequency. Briefly, specific arithmetic dilutions of PBMC ranging from 10^6 to 10^3 PBMC/ml were added to flat-bottom wells in 96-well plates in replicates of 24 wells in 200-μl volumes. The control wells consisted of the highest concentration of PBMC tested and incubated without TSL. All other wells contained 100 μg of TSL per ml. After 6 days of incubation, wells were labeled with [3H]thymidine, harvested onto glass filter paper 18 h later, and then counted by scintillation spectrometry.

Individual wells were counted as nonreactive after incubation with TSL if the counts per minute of that well was less than the mean plus 3 standard deviations of the control wells not incubated with TSL. The fraction of wells at each PBMC concentration incubated with TSL which were nonreactive was then calculated. Based on each concentration of PBMC tested, the number of different concentrations of PBMC tested, the number of replicates in each concentration, and the fraction of nonreactive wells at each concentration, the ARC frequency in the PBMC population for each subject was determined by the method described by Fazekas de St. Groth (17), which uses an estimation of the multiplicity followed by an iterative solution of the maximum likelihood equation, as described by Finney (18). Iteration was continued until the improvement over the previous estimate was <10^−6 (17).

**Statistical analysis.** Continuous unpaired variables in two groups were analyzed by the Mann-Whitney U test, while continuous paired data were analyzed by the Wilcoxon signed rank test. A two-tailed P value of <0.05 was considered statistically significant (36).

**RESULTS**

**Modulation of cytokine response of PBMC from healthy, immune donors.** We initially chose to examine the response over time of PBMC from eight healthy, immune donors. The median proliferative response of TSL-stimulated PBMC from these donors was 25,807 cpm (range, 5,302 to 48,855 cpm), significantly higher than the response of 471 cpm (range, 197 to 775 cpm) when PBMC were incubated in cell culture medium only (P = 0.01). Addition of hu rIL-10 at concentrations of 1 and 10 ng/ml did not significantly diminish PBMC proliferation in response to TSL (for both, P > 0.10 [data not shown]). However, the proliferative response to TSL was reduced to a median of 13,627 cpm (range, 390 to 43,138 cpm) when hu rIL-10 at 100 ng/ml, the highest concentration tested, was added to the wells (P = 0.01).

Concentrations of IFN-γ, IL-12, and IL-10 in PBMC supernatants over time were determined in samples from seven of these eight healthy immune subjects (Fig. 1). Incubation of PBMC with TSL and 100 ng of hu rIL-10 per ml for 72 h resulted in supernatant concentrations of IFN-γ that were significantly higher than for TSL alone (P = 0.04). PBMC incubated for 72 h with TSL and 100 ng of hu rIL-10 per ml also produced significantly less IL-12 than PBMC incubated with TSL alone (P = 0.04). Median concentrations of IL-10 in TSL-stimulated PBMC supernatants were all <50 pg/ml but after 72 h of incubation were significantly higher than those from unstimulated PBMC (P = 0.04).

**In vitro responses among donors with active coccidioidomycosis.** The proliferative responses of PBMC after stimulation with TSL (100 μg/ml) from individuals with chronic active coccidioidomycosis are shown in Fig. 2. There were a total of 12 subjects with active coccidioidomycosis without HIV infection and 9 subjects with coccidioidomycosis and HIV infection. Among those without HIV infection, eight manifested a positive coccidioidal DTH response. Two of these subjects had chronic pulmonary coccidioidomycosis, and six had disseminated extrapulmonary infection. Of the five who were DTH negative, all had disseminated extrapulmonary coccidioidomycosis. The clinical assessment scores between the two groups were not significantly different. For the DTH-positive subjects, the median score was 1.0 (range, 0 to 9), compared with a median of 1.5 (range, 0 to 4) for DTH-negative subjects (P = 0.54).

The proliferative response of PBMC from HIV-negative, DTH-positive donors was significantly greater than the re-
response of HIV-negative, DTH-negative donors (P = 0.01) and was greater than the response of donors with coccidioidomycosis and HIV infection (P < 0.001), all of whom were DTH negative. While anti-IL-10 did not alter the proliferative response of PBMC from any of the donors, the addition of 10 ng of hu rIL-12 per ml resulted in a significant increase in proliferation in samples from donors with HIV (P = 0.01) but not in donors without HIV infection, regardless of their DTH response (for both, P > 0.05). The proliferative responses after stimulation with TSL and hu rIL-12 for both the HIV-infected group and the DTH-negative group without HIV infection were still significantly below that of DTH-positive donors (for both, P < 0.03) and were not significantly different from responses of PBMC from healthy, nonimmune donors incubated with TSL and hu rIL-12 (for both, P > 0.10).

From the same group of donors, supernatants were harvested after 4 to 72 h of incubation and were assayed for IFN-γ, IL-12, and IL-10. Peak levels of IFN-γ, IL-12, and IL-10 occurred after 72 h of incubation. As shown in Table 1, levels of IFN-γ and IL-12 were significantly higher than in nonimmune controls among active DTH-positive subjects but not DTH-negative subjects, with or without HIV infection. Levels of IL-10 were not significantly higher than in nonimmune controls in any of the three groups. The addition of hu rIL-12 significantly and markedly increased levels of IFN-γ in samples from DTH-positive donors but not in other groups of subjects. In addition, production of IFN-γ by PBMC from five healthy, immune donors also significantly increased from a median of 125 pg/ml (range, 69 to 407 pg/ml) with TSL alone to 1,323 pg/ml (range, 348 to 4514 pg/ml) with the addition of hu rIL-12 (P = 0.04).

**Comparison of ARC frequency.** Five healthy DTH-positive subjects and five DTH-negative subjects with active coccidioidomycosis were assayed to determine the frequency of cells reactive to TSL in vitro. As shown in Fig. 3, the median ARC frequency per 10^6 PBMC stimulated with TSL was 3.7 (range, 2.6 to 4.1) for the healthy, immune subjects compared to 1.7 (range, 1.1 to 3.3) for the subjects with active coccidioidomycosis and negative DTH (P = 0.03).

**DISCUSSION**

It has long been recognized that patients with disseminated coccidioidomycosis have a diminished in vitro response to a variety of coccidioidal antigens and that this lack of response is associated with a failure to manifest cutaneous DTH (3, 11, 14). This lack of response has led to speculation that cytokine imbalances may play a role in the failure of patients with disseminated coccidioidomycosis to control their disease. This concept is bolstered by animal data showing that genetically susceptible mice produce IL-4 in lung extracts after coccidoidal infection, whereas genetically resistant mice produce IFN-γ (30). Moreover, systemic administration of IL-12 to susceptible mice results in significant amelioration of disease and shifts the cytokine message expression from a Th2 to a Th1 pattern (31). However, no data supporting this model have been obtained in human studies.

The most striking finding of the present study was that there was a profound difference in antigen responsiveness in vitro based on whether the donors with active coccidioidomycosis manifested coccidioidal DTH. PBMC from donors with DTH had significantly increased proliferation as well as increased production of IFN-γ and IL-12 in response to TSL, while PBMC from donors without DTH were not different from PBMC from nonimmune controls. All subjects with active coccidioidomycosis were stable and receiving antifungal therapy at the time of study. There was no difference in clinical score between the subjects with active coccidioidomycosis who expressed DTH and those who did not. These data suggest that

**TABLE 1.** Supernatant concentrations of IFN-γ, IL-12, and IL-10 among four groups of donors

<table>
<thead>
<tr>
<th>Cytokine</th>
<th>Supplement</th>
<th>Median supernatant concn (pg/ml) in indicated donor group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DTH+</td>
</tr>
<tr>
<td>IFN-γ</td>
<td>TSL</td>
<td>195 (40–862)</td>
</tr>
<tr>
<td></td>
<td>+ IL-12</td>
<td>3,798 (902–11,357)</td>
</tr>
<tr>
<td></td>
<td>+ αIL-10</td>
<td>186 (42–438)</td>
</tr>
<tr>
<td>IL-12</td>
<td>TSL</td>
<td>54 (31–81)</td>
</tr>
<tr>
<td></td>
<td>+ αIL-10</td>
<td>52 (15–86)</td>
</tr>
<tr>
<td>IL-10</td>
<td>TSL</td>
<td>16 (12–23)</td>
</tr>
<tr>
<td></td>
<td>+ IL-12</td>
<td>30 (15–68)</td>
</tr>
<tr>
<td></td>
<td>+ αIL-10</td>
<td>14 (12–22)</td>
</tr>
</tbody>
</table>

*Samples were incubated for 72 h with either 100 µg of TSL per ml (TSL), TSL plus 10 ng of hu rIL-12 per ml (+ IL-12), or TSL plus 10 µg of anti-IL-10 per ml (+αIL-10).

*Ranges are given in parentheses. Donor groups: DTH+, DTH-positive subjects with active coccidioidomycosis (n = 8); DTH−, DTH-negative subjects with active coccidioidomycosis (n = 4; HIV, subjects with active coccidioidomycosis and HIV infection (n = 9); nonimmune, DTH-negative healthy subjects without coccidioidomycosis (n = 3). *P < 0.05 compared to results for nonimmune donors in the same row. †, P < 0.05 compared to results with TSL alone for the same cytokine.
even under therapy, there are distinct groups of subjects with active coccidioidomycosis based on immunological responsiveness. Although this study has no data regarding clinical response, others have found that expression of DTH and in vitro proliferation are associated with improved outcome in coccidioidomycosis (3).

The in vitro response was modulable in donors who expressed coccidioidal DTH. Among healthy, immune donors, the addition of IL-10 resulted in virtually complete suppression of IL-12 and partial suppression of proliferation and IFN-γ. These findings do not directly implicate IL-10 as an in vivo modulator in human coccidioidomycosis, however. In fact, the lack of complete suppression of proliferation and IFN-γ production by relatively high concentrations of IL-10 (15) indicates that these responses are, at most, only under partial control of IL-10.

The assay used to measure IL-12 in PBMC supernatants detected both the p40 monomer and the p70 heterodimer of the cytokine. Preliminary data indicated that the levels of IL-12 were approximately 45 times higher than the levels seen when only p70 was measured. This difference is in keeping with observations of a marked overproduction of the p40 subunit of IL-12 when the entire heterodimer is produced (37). While recombinant p40 has been reported to inhibit IL-12 activity in mice (7, 22, 23, 32), there is no evidence that native p40 is inhibitory in humans either in vitro or in vivo (37). Moreover, others have used the measurement of either p40 mRNA (21) or p40 itself (8) as indicators of total IL-12 production in humans. The data from our study support the concept that production among DTH-negative donors with active coccidioidomycosis are unable to recognize, process, or respond to the appropriate antigens within TSL to generate a Th1 type response.

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REFERENCES


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