Antibody Responses and Avidity of Naturally Acquired Anti-Plasmodium vivax Duffy Binding Protein (PvDBP) Antibodies in Individuals from an Area with Unstable Malaria Transmission

Sedigheh Zakeri,* Laleh Babaeekhou, Akram Abouie Mehrizi, Maryam Abbasi, and Navid Dinnarast Djadid
Malaria and Vector Research Group (MVRG), Biotechnology Research Center (BRC), Pasteur Institute of Iran, Tehran, Iran

Abstract. Plasmodium vivax remains an important cause of morbidity outside Africa, and no effective vaccine is available against this parasite. The P. vivax Duffy binding protein (PvDBP) is essential during merozoite invasion into erythrocytes, and it is a target for protective immunity against malaria. This investigation was designed to evaluate naturally acquired antibodies to two variant forms of PvDBP-II antigen (DBP-I and -VI) in malaria individuals (N = 85; median = 22 years) who were living in hypoenzemic areas in Iran. The two PvDBP-II variants were expressed in Escherichia coli, and immunoglobulin G (IgG) isotype composition and avidity of naturally acquired antibodies to these antigens were measured using enzyme-linked immunosorbent assay (ELISA). Results showed that almost 32% of the studied individuals had positive antibody responses to the two PvDBP-II variants, and the prevalence of responders did not differ significantly (P > 0.05; χ² test). The IgG-positive samples exhibited 37.03% and 40.8% high-avidity antibodies for PvDBP-I and PvDBP-VI variants, respectively. Furthermore, high-avidity IgG1 antibody was found in 39.1% of positive sera for each examined variant antigen. The avidity of antibodies for both PvDBP variant antigens and the prevalence of responders with high- and intermediate-avidity IgG, IgG1, and IgG3 antibodies were similar in patients (P > 0.05; χ² test). Moreover, the prevalence of IgG antibody responses to the two variants significantly increased with exposure and host age. To sum up, the results provided additional data in our understanding of blood-stage immunity to PvDBP, supporting the rational development of an effective blood-stage vaccine based on this antigen.

INTRODUCTION

Plasmodium vivax is the second most prevalent human malaria parasite worldwide and accounts for approximately 80% to 90% of cases in Asia, Oceania, and Latin America.1 The emergence of drug-resistant P. vivax isolates2 is associated with severe and fatal malaria.2,3 Also, the limitation of our understanding of P. vivax epidemiology has caused problems in elimination programs, particularly in countries where this parasite is prevalent. Therefore, all these factors highlight the need for considering P. vivax in control measures to reduce vivax malaria burden.

P. vivax initiates erythrocyte invasion through expression of several surface and apical organelles on the merozoite that binds to erythrocyte surface proteins.4,5 One of the well-characterized ligand–receptor interactions involves the Duffy binding protein (DBP), which is required for junction formation during merozoite invasion to the host cell.5,6 Duffy-negative individuals are naturally protected against clinical P. vivax malaria,7 because invasion by the parasite is dependent on binding to the Duffy antigen receptor for chemokines (DARC).8 However, recent reports have described the transmission of P. vivax to a Duffy-negative population in Kenya, suggesting that P. vivax could have alternative invasion pathways, although it is rare and no other means of invasion have been identified.9,10 Thus, the P. vivax DBP (PvDBP) represents one of the most promising subunit vaccine candidate antigens against the asexual stages of the parasite for reducing or eliminating the blood stages from malaria parasites and their pathological outcomes.

The PvDBP is a type I membrane protein (140 kDa) that belongs to a family of homologous Duffy binding–like erythrocyte binding proteins (DBL–EBP) located within the micronemes of merozoite4–11 and is characterized by a functionally conserved cysteine-rich region.5–11 This cysteine-rich region in region II (PvDBP-II) was identified as the domain binding to DARC on the erythrocyte surface12,13 that includes cysteines 5 to 8,14,15 Critical binding motifs in PvDBP-II have been mapped to a region between amino acids 291 and 460.14 Although the cysteine and some other hydrophobic amino acid residues are conserved in the binding motif, other amino acid residues are highly polymorphic16–18 and this diversity varies geographically from region to region.16,18–20

After natural exposure to P. vivax infection, individuals residing in malaria-endemic areas develop antibodies that block binding of DBP to DARC-positive erythrocytes.21 It has been hypothesized that polymorphisms in PvDBP-II arose from immune selection16,18–22 so that the frequency of non-synonymous mutations exceeds that of synonymous mutations in PvDBP-II. These polymorphic regions represent B- and/or T-cell epitopes recognized by the host immune response that might inhibit protective immunity against DBP. Therefore, assessment of the level of genetic diversity of Pvdbp-II between and within populations from distinct geographic regions and also its effect on naturally acquired immunity must be considered for vaccine development.

Antibody responses to PvDBP have been shown in endemic populations of P. vivax infection in Papua New Guinea,23,24 Brazil,25–28 and Colombia.29 In addition, different studies suggested that stronger humoral and cellular immune responses to PvDBP-II develop progressively with increasing age,2,22,24,29 showing a boosting effect that was likely because of repeated exposures to the infection.28 Also, the anti-PvDBP-II antibodies in populations living in areas endemic for P. vivax could block PvDBP-II ligand DARC-positive erythrocytes21–23 and inhibit erythrocyte invasion in vitro.20,22

As shown by several studies, selection of an antigen for vaccination requires a detailed understanding of natural immune responses elicited by the protein from different malaria-endemic regions with various epidemiology, and the result of similar studies from one malaria-endemic region cannot be extrapolated to other areas of malaria-endemic regions in the world.30 Therefore, the current investigation was designed,
for the first time, to evaluate naturally acquired antibodies to the two variant forms of PvDBP-II antigen (DBP-I and -VI) in malaria-infected individuals living in hypoendemic areas in Iran in the Middle East region. Moreover, the association between level and avidity of anti–PvDBP-II immunoglobulin G (IgG) with host age and exposure was evaluated. The development of vaccine and other novel interventions strategies for controls requires a better understanding of naturally acquired immune response; hence, the result of this study could possibly contribute to current efforts on vaccine development against *P. vivax* for elimination of malaria in vivax-endemic regions.

**MATERIALS AND METHODS**

**Study area and subjects.** This study was performed in the tropical southeastern region of Chabahar district in Sistan and Baluchistan province, Iran. In this area, malaria is hypoendemic to mesoendemic, and transmission is unstable, with seasonal fluctuations occurring throughout the year with two peaks: first peak from May to August with *P. vivax* as the predominant species and second peak from October to November when both *P. falciparum* and *P. vivax* infections are recorded. The burden of malaria declined gradually over the last few years from 15,712 total cases in 2007 to 6,122 in 2009 because of applying different malaria control tools in these areas. In this region, most of the patients are adults and may experience several infections by *P. falciparum* and/or *P. vivax* with clinical symptoms. There is no record of severe malaria or death because of malaria in Iran.

In this investigation, 85 subjects (male = 64, female = 21; mean age = 26.14 years) with patent malaria as negative controls for all assays. Before blood collection, informed consent was obtained from adults or parents/legal guardians of children who were participants in this study. This study was approved by the Ethical Review Committee of Research of Pasteur Institute of Iran. The diagnosis of vivax malaria was made by microscopic examination of blood smears stained with Giemsa staining in the study areas. From all subjects, 5 mL venous blood were collected for both *P. vivax* DNA detection and serum collection. After transferring to the main laboratory in Tehran, all blood samples were again analyzed for *P. vivax* DNA by nested polymerase chain reaction (PCR) amplification as described previously, and the results were used to confirm the microscopy detection.

**Expression and purification of recombinant PvDBP-II.** In this study, the most prevalent (PvDBP-VI; 41.8%) and least prevalent (PvDBP-I; 7.3%) types of PvDBP-II strains were considered as antigens (Table 1). The PvDBP-II variants (PvDBP-I and -VI), corresponding to 594–1,764 bp Sal-I sequences with GenBank accession numbers EU860428.1 and EU860433.1, were cloned and expressed in *Escherichia coli* M15 as His-tag fusion using pQE30 vector (Qiagen, Hilden, Germany).

Briefly, overnight culture of *E. coli* M15 pQE30–PvDBP-II was grown in Luria broth (pH 7.2) containing ampicillin (100 μg/mL) and kanamycine (25 μg/mL) with shaking (150 rpm) at 37°C. Expression of PvDBP-VI was induced with 1 mM Isopropyl beta thiogalactopyranoside (IPTG) (Sigma-Aldrich Co., USA) when cell density of the culture reached an optical density (OD at 600 nm) of 0.6–0.7. The culture was further grown for 4 hours, and the *E. coli* cells were harvested by centrifugation and kept at −80°C until use. Both PvDBP-II variants were expressed in inclusion bodies; therefore, the cell pellets were dissolved in denaturation buffer containing 6 M guanidine thiocyanate, 20 mM Tris·HCl, 500 mM NaCl, 20 mM imidazole, and 1 mM phenylmethanesulfonylfluoride (PMSF), pH 7.9. The cells were lysed by ice sonication (Ultraschallprozessor, Deutschland, Germany) with 10 cycles, each consisting of 20-second pulses with 20-second intervals. The bacterial lysate was centrifuged at 14,000 × g at 4°C for 30 minutes. The supernatant was incubated with Ni²⁺–nitrilotriacetic acid agarose resin (Ni–NTA Agarose; Qiagen) at 4°C for 2 hours, and the resin was packed into a column and washed with a 10-column volume of wash buffer (6 M urea, 20 mM Tris-HCl, 500 mM NaCl, and 30 mM imidazole, pH 7.9). The bound protein was eluted with elution buffer containing 8 M urea, 30 mM thiocyanate, 20 mM Tris·HCl, 500 mM NaCl, 20 mM imidazole, and 1 mM phenylmethanesulfonylfluoride (PMSF), pH 7.9.

**Table 1:** Frequency distribution of *P. vivax* DBP-II variant antigens identified in malaria-endemic areas of Iran

<table>
<thead>
<tr>
<th>Insertion</th>
<th>475</th>
<th>503</th>
</tr>
</thead>
<tbody>
<tr>
<td>306 308 371</td>
<td>384</td>
<td>385</td>
</tr>
<tr>
<td>Sal-I</td>
<td>F</td>
<td>R</td>
</tr>
<tr>
<td>DBP-I (7.3%)</td>
<td>(TTG)</td>
<td>(AGG)</td>
</tr>
<tr>
<td>DBP-II (1.8%)</td>
<td>S</td>
<td>G</td>
</tr>
<tr>
<td>DBP-III (16.4%)</td>
<td>E</td>
<td>G</td>
</tr>
<tr>
<td>DBP-IV (7.3%)</td>
<td>K</td>
<td>M</td>
</tr>
<tr>
<td>DBP-V (5.4%)</td>
<td>K</td>
<td>I</td>
</tr>
<tr>
<td>DBP-VI (41.8%)</td>
<td>G</td>
<td>H</td>
</tr>
<tr>
<td>DBP-VII (3.6%)</td>
<td>G</td>
<td>(GGT)</td>
</tr>
<tr>
<td>DBP-VIII (1.8%)</td>
<td>R</td>
<td>K</td>
</tr>
<tr>
<td>DBP-VIII (14.5%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
developed with o-phenylediaminedihydrochloride–H₂O₂ (OPD; Sigma-Aldrich Co., USA) and stopped with 2N sulfuric acid. The reaction was stopped with 2N H₂SO₄, and the OD was recorded at 490 nm by the use of a microplate reader (Biotech, USA). To detect subclasses of human IgG, was selected and added to duplicate wells of all the tested samples multiplied by 100. All AI values less than 30% were considered as low-avidity antibodies, values between 30% and 50% were intermediate-avidity antibodies, and values greater than 50% were considered as high-avidity antibodies.37

Statistical analysis. A database was created with SPSS 16.0 for Windows (SPSS Inc., USA). The Spearman’s correlation test was used to correlate antibody levels in PvDBP-I and -VI variants and also, antibody level and AI with age and exposure. In addition, differences in the proportions of positive sera for IgG and different subclasses were assessed using the χ² test. In all tests, P values < 0.05 were considered significant.

RESULTS

Antibody response to PvDBP-II antigen. The PvDBP-II variants (DBP-I and -VI) were expressed in E. coli in a soluble form, and the purified proteins were analyzed by SDS-PAGE and had a molecular mass of ~45 kDa. Total IgG antibody responses to these recombinant proteins were analyzed in 85 individuals (aged 5 to 75 years; median = 22 years) with patent P. vivax infection.

In this study, the prevalence of anti–PvDPB-II IgG responses in our population was not statistically different for both PvDBP-I and -VI variant antigens (31.76% each, cut-off = 0.5 each, mean OD₉₀ = 0.94 and OD₉₀ = 0.92, respectively, P > 0.05; χ² test) (Figure 1 and Table 2). This prevalence was also unrelated to variant frequencies (PvDBP-I, 7.3%; PvDBP-VI, 41.8%) in the examined population (Table 2). Moreover, analysis of the antibody responses to PvDBP-I and -VI showed high (8.23% and 7%), medium (16.47% and 15.3%), and low (7.05% and 9.41%) positive as well as negative (68.2%) each, responses, respectively (Figure 2). None of the sera from healthy individuals (control group) contained IgG antibodies to PvDBP-II, which confirms the specificity of the present results. However, a significant correlation was found for
ISOTYPE COMPOSITION AND AVIDITY OF ANTI-PvDBP

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Prevalence (percent positive) and OD mean values of IgG and subclass-specific responses to PvDBP-II variants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haplotypes</td>
<td>IgG</td>
</tr>
<tr>
<td>PvDBP-I</td>
<td>0.940 ± 0.206 (31.8)</td>
</tr>
<tr>
<td>Cut-off</td>
<td>0.5</td>
</tr>
<tr>
<td>PvDBP-VI</td>
<td>0.92 ± 0.170 (31.8)</td>
</tr>
<tr>
<td>Cut-off</td>
<td>0.5</td>
</tr>
</tbody>
</table>

SD = standard deviation. The cut-off values are determined as mean plus 3 SD of the antibody levels in control groups. No significant difference was observed in the proportion of IgG and IgG subclasses responses to PvDBP-I and -VI (P > 0.05; χ² test). There was a significant correlation of the mean ODs of IgG, IgG1, and IgG3 with PvDBP-I and -VI variant antigens (IgG, r = 0.957, P < 0.0001; IgG1, r = 0.788, P < 0.0001; IgG3, r = 0.351, P = 0.001; Spearman’s correlation test).

The levels of IgG to PvDBP-I and -VI variants (r = 0.957, P < 0.0001; Spearman’s correlation test).

The avidity of IgG, IgG1, and IgG3 anti-PvDBP-II antibodies were similar in patients (40.8% high-, 40.8% intermediate-, and 18.5% low-avidity IgG, IgG1, and IgG3 against both antigens (Table 3). The avidity of antibodies for high- or intermediate-avidity for each variant was mostly detected in positive sera (Table 3). The avidity of antibodies for high- or intermediate-avidity antibodies were mostly detected in positive sera (Table 3). 7.3%) prevalent variant antigens did not differ significantly in the level of IgG (P = 0.007; Spearman’s correlation test) (Table 4).

Exposure and age-dependent IgG1 and IgG3 response. The proportions of anti-PvDBP-II IgG-positive subjects increased with exposure to malaria transmission (Figure 2). The highest IgG seroreactivity against PvDBP-I and -VI was found among 14 of 32 (43.75%) with long-term exposure (more than two P. vivax infections) to malaria (Figure 2). The group who had experienced a single P. vivax infection (first exposure) had very low response to both variants (24.5%). Significant correlations were found in the level of IgG (r = 0.362, P = 0.001; r = 0.354, P = 0.001) and IgG1 (r = 0.411, P < 0.0001; r = 0.312, P = 0.004) antibodies to PvDBP-I and -VI with exposure to the disease, respectively. Moreover, no correlation was found in the level of IgG3 antibody to PvDBP-I and -VI with exposure to the disease (P > 0.05; Spearman’s correlation test) (Table 4).

Furthermore, a significant correlation was found in the level of IgG antibody response to PvDBP-I and -VI with age (r = 0.289, P = 0.007; r = 0.331, P = 0.002, respectively; Spearman’s correlation test). However, in the case of IgG1 and IgG3, no significant correlation was found between the antibody response to PvDBP-I and -VI with age (P > 0.05; Spearman’s correlation test) (Table 4).

DISCUSSION

The goal of developing PvDBP-II vaccine against blood stages of P. vivax is to elicit an antibody response that inhibits the adhesion of this parasite ligand to its erythrocyte receptor and thereby, abrogate merozoite invasion. However, the presence of a highly polymorphic sequence in this antigen interferes with its use in vaccine development. Therefore, understanding the nature of this polymorphism present in PvDBP-II among P. vivax isolates as well as an immunoenepidemiological study on various populations with a different genetic background are key features for vaccine development. In the present investigation, after our previous study on the level of PvDBP-II polymorphisms among Iranian P. vivax populations, naturally acquired immune responses to the two PvDBP-II variants (DBP-I and -VI) were analyzed in the individuals living in the same study areas.

In this study, about 32% of the individuals from a low malaria-endemic region displayed specific antibodies to PvDBP-II, which is consistent with an unstable malaria transmission region such as Colombia (40%). Also, the prevalence of responders to high (PvDBP-VI, 41.8%) and low (PvDBP-I, 7.3%) prevalent variant antigens did not differ significantly (P > 0.05; χ² test). Although the PvDBP-I variant differed from PvDBP-VI by 9 amino acids at various residues (Table 1), these amino acid substitutions did not alter the protein’s function.

Table 1.

<table>
<thead>
<tr>
<th>Exposure</th>
<th>IgG</th>
<th>IgG1</th>
<th>IgG3</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>+++</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>++++</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 2. Patterns of total IgG, IgG1, and IgG3 responses to two PvDBP-II variant antigens in Iranian individuals who were infected with P. vivax isolate. Ages are given in years. Exposures to malaria are shown as single exposure (−) and more than one exposure (+). Antibody reactivity of each sample is measured using ELISA. Cut-off values are 0.5 for IgG, 0.26 for IgG1, and 0.24 and 0.23 for IgG3 responses to PvDBP-I and -VI variants, respectively. The OD mean values for IgG, IgG1, and IgG3 responses have been divided into four groups: • high positive responses (OD > 1), ● medium positive responses (0.8 ≤ OD ≤ 1), ○ low positive responses (cut-off < OD < 0.8), and □ negative responses (OD < cut-off).
antibody binding capacity. Therefore, it seems that the majority of our individuals might have antibodies against both PvDBP-II variants. Nevertheless, recognition of both variant types by examined individuals might not be surprising, because both strains that exist in the population and individuals are likely to have been exposed to both variants. Therefore, additional study is needed to clarify the protective nature of these antibodies to different variants of PvDBP-II.

Furthermore, in the present investigation, the significant percentage of non-responders in all age groups suggests that the PvDBP is a poor immunogen. One explanation could be the presence of cysteine-rich content in PvDBP-II, and as a consequence, the antigen is poorly processed, which may account for the reduced frequency of antibody in individuals. In addition, poorly immunogenic PvDBP-II might be because of the fact that some conformational epitopes could not be properly represented in the recombinant PvDBP-II produced in this study.

To understand the immune responses to malaria, both patterns of the subclasses antibodies and evaluation of the avidity of antibody (functional affinity) are important. In the present investigation, the prevalence of IgG1 but not IgG3 antibodies seems to predominate in the patent *P. vivax* infection. No IgG2 and IgG4 antibodies to PvDBP-II variant antigens were detected among examined samples. Also, there was heterogeneity in IgG1 and IgG3 recognition that might be related to either different epitopes in PvDBP-II antigen, recognized by these two IgG subclasses, or short half-life of IgG3 antibody in the serum sample. Moreover, the investigation of the quality of anti-PvDBP-II IgG in studied individuals showed that a significant proportion of individuals (81%) had high- and intermediate-avidity antibodies. In fact, high-quality antibody is one of the important factors involved in preventing and protecting against infections as well as preventing severe disease in malaria infections. This is the first study with qualitative features of antibody responses to the PvDBP-II variant antigen, and the data support the rational development of an effective blood-stage vaccine based on this antigen.

In malaria-endemic regions, individuals have experienced a variable number of previous episodes of clinical malaria; therefore, individuals who had been infected multiple times with malaria should exhibit higher frequency of antibodies against PvDBP-II than those who had been infected one time. However, the serologic responses of residents in vivax malaria-endemic regions did show a positive correlation with exposure and host age, as shown in the previous studies. This result suggests a possible boosting of the PvDBP-II antibody response because of accumulated age-related exposure. In addition, our present results showed that exposure and age represent key determinants of the quantitative nature of the IgG response to PvDBP-II. One explanation could be that PvDBP-II is expressed in small quantities for a limited time in late schizogony, and it is localized intracellularly in micronemes but is not released until erythrocyte attachment. Therefore, the host immune system seems to have little opportunity to recognize and produce an efficient antibody response, because the invasion process may take less than 1 minute to be completed. However, to efficiently block the binding of *P. vivax* merozoites to its ligand on erythrocytes, antibodies directed against PvDBP would need to be in abundant amounts and also have high binding rates and affinities. Therefore, there is a possibility that exposure to very low parasitemias, which occur in low-endemic malaria areas such as those areas in the present study, may be poorly effective in inducing anti-PvDBP antibody. This may explain why, in the studied population, a long-term exposure to *P. vivax* parasite with a certain level of parasitemia has occurred for the subjects to acquire high-level anti-PvDBP antibodies.

In conclusion, our results add additional information to the available data on the characteristics of naturally acquired antibodies to PvDBP-II antigen in populations who were exposed to *P. vivax* in an area of unstable and hypoendemic malaria transmission. Affinity maturation and age-dependent responses to PvDBP-II implicate this molecule as being partially involved in acquired immunity to *P. vivax* in an unstable malaria region; this region could be challenging to address with vaccine development strategies against *P. vivax* parasites. Further studies are needed to clarify whether naturally acquired antibodies to PvDBP-II variant antigens in Iranian malaria patients have the ability to block erythrocyte cytoadherence to DBP.

### Table 3

Prevalence of the high, intermediate, and low avidity of IgG, IgG1, and IgG3 antibodies to PvDBP-II variants in individuals with patent *P. vivax* infection

<table>
<thead>
<tr>
<th>Antigens</th>
<th>Total IgG (%)</th>
<th>HAI</th>
<th>IAI</th>
<th>LAI</th>
<th>IgG (%)</th>
<th>HAI</th>
<th>IAI</th>
<th>LAI</th>
<th>IgG3 (%)</th>
<th>HAI</th>
<th>IAI</th>
<th>LAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>PvDBP-I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AI ± SD</td>
<td>9/23 (39.1)</td>
<td>12/23 (52.2)</td>
<td>2/23 (8.7)</td>
<td>3/8 (37.5)</td>
<td>5/8 (62.5)</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AI ± SD</td>
<td>95.3 ± 8.8</td>
<td>41.8 ± 6.25</td>
<td>16.45 ± 1.2</td>
<td>71.3 ± 11.7</td>
<td>45.1 ± 6.1</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AI ± SD</td>
<td>9/25 (36%)</td>
<td>12/23 (52.2)</td>
<td>2/23 (8.7)</td>
<td>3/8 (37.5)</td>
<td>4/8 (50)</td>
<td>1/8 (12.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Avidity index (AI) was calculated by the ratio of the OD value of urea-treated samples to untreated samples multiplied by 100. An AI value less than 30% was considered as low-avidity antibodies, between 30% and 50% was intermediate-avidity antibodies, and greater than 50% was high-avidity antibodies. HAI = high-avidity index; IAI = intermediate-avidity index; LAI = low-avidity index; SD = standard deviation. A significant correlation was observed between AI for IgG and IgG1 and the two variant antigens (r = 0.717, P < 0.001 and r = 0.567, P = 0.005, respectively; Spearman’s correlation test).

### Table 4

Correlation analysis of IgG, IgG1, and IgG3 antibody responses in two PvDBP-II variants with host age and exposure

<table>
<thead>
<tr>
<th>Age</th>
<th>Exposure</th>
<th>Correlation coefficient</th>
<th>P value</th>
<th>Correlation coefficient</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IgG (I)</td>
<td>0.164</td>
<td>0.058</td>
<td>0.932</td>
<td>0.009</td>
<td>0.739</td>
</tr>
<tr>
<td>IgG (VI)</td>
<td>0.135</td>
<td>0.044</td>
<td>0.004</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>IgG1 (I)</td>
<td>0.177</td>
<td>0.017</td>
<td>&lt;0.0001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>IgG1 (VI)</td>
<td>0.312</td>
<td>0.037</td>
<td>0.004</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>IgG3 (I)</td>
<td>0.354</td>
<td>0.037</td>
<td>0.009</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>IgG3 (VI)</td>
<td>0.312</td>
<td>0.037</td>
<td>0.009</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The P value denotes the Spearman’s correlation coefficient test. P value < 0.05 was considered significant. 1 = PvDBP-I; 1 = PvDBP-VI; r = correlation coefficient.
Received January 1, 2011. Accepted for publication March 9, 2011.

Acknowledgments: We are grateful for the hospitality and generous collaboration of Zahedan University of Medical Sciences and thank the staff of the Public Health Department, Sistan and Baluchistan province, Chabahar district for their assistance in collecting blood samples from the field. We also express our sincere thanks to the patients in Chabahar for their participation in this study. We also thank Mrs. M. Saffari for editing the manuscript.

Financial support: This work was financially supported through Research Grant No. 264 from Pasteur Institute of Iran (to S.Z.).

Authors’ address: Sedigheh Zakeri, Laleh Babacekhoo, Akram Abouie Mehrizi, Maryam Abbasi, and Navid Dinparast Djadid, Malaria and Vector Research Group (MVRG), Biotechnology Research Center (BRC), Pasteur Institute of Iran, Tehran, Iran, E-mails: zakeris@pasteur.ac.ir, lamid21@yahoo.com, abouie@gmail.com, abast313@gmail.com and navid@pasteur.ac.ir.

Reprint requests: Sedigheh Zakeri, Malaria and Vector Research Group (MVRG), Biotechnology Research Centre (BCR), Pasteur Institute of Iran, PO Box 1316943551, Tehran, Iran, E-mails: zakeris@pasteur.ac.ir and zakeris@yahoo.com.

REFERENCES


