Genome-Scale Protein Microarray Comparison of Human Antibody Responses in *Plasmodium vivax* Relapse and Reinfection

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Abstract. Large scale antibody responses in *Plasmodium vivax* malaria remains unexplored in the endemic setting. Protein microarray analysis of asexual-stage *P. vivax* was used to identify antigens recognized in sera from residents of hypoendemic Peruvian Amazon. Over 24 months, of 106 participants, 91 had two symptomatic *P. vivax* malaria episodes, 11 had three episodes, 3 had four episodes, and 1 had five episodes. *Plasmodium vivax* relapse was distinguished from reinfection by a merozoite surface protein-3α restriction fragment length polymorphism polymerase chain reaction (MSP3α PCR-RFLP) assay. Notably, *P. vivax* reinfection subjects did not have higher reactivity to the entire set of recognized *P. vivax* blood-stage antigens than relapse subjects, regardless of the number of malaria episodes. The most highly recognized *P. vivax* proteins were MSP 4, 7, 8, and 10 (PVX_003775, PVX_082650, PVX_097625, and PVX_114145); sexual-stage antigen s16 (PVX_000930); early transcribed membrane protein (PVX_090230); tryptophan-rich antigen (Pv-fam-a) (PVX_092995); apical merozoite antigen 1 (PVX_092275); and proteins of unknown function (PVX_081830, PVX_117680, PVX_118705, PVX_121935, PVX_097730, PVX_110935, PVX_115450, and PVX_082475). Genes encoding reactive proteins exhibited a significant enrichment of non-synonymous nucleotide variation, an observation suggesting immune selection. These data identify candidates for seroepidemiological tools to support malaria elimination efforts in *P. vivax*-endemic regions.

INTRODUCTION

*Plasmodium vivax* malaria affects human populations in Asia, Latin America, and parts of Africa.1,2 *Plasmodium vivax* malaria is conventionally considered to be less of a public health concern than the more lethal malaria parasite *P. falciparum*, which dominates malaria-related mortality predominantly in sub-Saharan Africa.3 The biology of *P. vivax* fundamental differs from *P. falciparum* particularly with regard to how this species maintains itself in human populations, particularly the ability to relapse from the dormant liver forms, the hypnozoite, and its wider tolerance of temperature conditions enabling sporogonic development.3 For these reasons, and because the parasite cannot be propagated in vitro, studies of this form of malaria are neglected. In an era when malaria eradication has been put on the global health agenda,4 an exigent need has emerged to understand detailed aspects of *P. vivax*, including parasite antigen-specific human immune responses and to develop rapid tools to assess transmission on a population level.

Current estimates of the global prevalence of *P. vivax* infection are based on identifying potential regions of transmission using a geo-referenced parasite-prevalence rate combined with biological masking to indicate malaria-compatible transmission zones.5 Quantifying the global burden of *P. vivax* malaria is complicated by the biology of the parasite: *P. vivax* relapse from dormant hypnozoite liver stage over time and space—often asymptomatically—which allows for human migration to disperse infection within an endemic region or reintroduce the parasite into areas where malaria may have been eliminated. The potential range of *P. vivax* transmission is vast, the biology of the parasite complicates incidence and prevalence estimates, and the public health impact of *P. vivax* remains. Regional elimination and global eradication require accurate and population-deployable tools to estimate parasite prevalence and malarial disease incidence.1,2,6

Because determining the presence of malaria parasitemia or exposure is time intensive, often insensitive, and expensive, interest has grown in using serological tools to monitor infection status and transmission dynamics—so-called seroepidemiology. This approach has been particularly useful for malaria7-8 and additionally for vector-borne diseases such as lymphatic filariasis in which mass drug administration campaigns have been carried out.9-14 Antigens for antibody detection have included lysates of in vitro grown *P. falciparum* schizonts8,15-20 and recombinant proteins based on vaccine candidates (circumsporozoite protein, merozoite surface protein 1 [MSP1], and apical membrane antigen-1 [AMA-1]) have been commonly used. By analogy, for seroepidemiological studies of *P. vivax*, recombinant PvMSP1 and PvAMA-1 have been used to determine seroprevalence of antibodies to *P. vivax* in populations of Vanuatu, Solomon Islands.2 More recently, a proof-of-principle array study using 152 predicted asexual-stage proteins was reported in which sera from Korean *P. vivax* malaria patients were analyzed for anti-*P. vivax* antibodies using a wheat germ expression system.21 Recent work from Papua New Guinea—where all four major *Plasmodium* spp. circulate at intense level—has led to the development of focused protein microarrays22 composed of both *P. falciparum* and *P. vivax* recombinant proteins. Because *P. vivax* samples from humans have low parasitemia, and only in limited quantities from non-human primates, seroepidemiology studies using...
P. vivax asexual-stage parasite lysates has only infrequently been done, hence recombinant proteins are essential for studying exposure to P. vivax in endemic populations.

To understand the P. vivax antigens predominantly recognized by the antibody response of naturally infected humans in a low-transmission region, we analyzed the serological reactivity of patients with P. vivax malaria using custom-made protein microarrays composed of asexual-stage antigens predicted by transcriptional profiling\textsuperscript{23,24} and heterologously produced by a prokaryotic cell-free expression system.\textsuperscript{25–27} With the validation of molecular tools to distinguish P. vivax relapses and reinfections that are common in our Amazonian village study population,\textsuperscript{28,29} we compared the level of IgG responses between consecutive episodes of symptomatic P. vivax malaria, in particular, to determine whether naturally acquired antibody responses were boosted by subsequent infection. More generally, we intended to systematically and comprehensively identify P. vivax antigens of potential use for seroepidemiological studies and possibly for identifying vaccine candidates.

MATERIALS AND METHODS

Ethics statement. This study was approved by the following institutional review boards: Ethical Committee of Universidad Peruana Cayetano Heredia, Lima, Peru; Ethical Committee of Asociación Benéfica PRISMA, Lima, Peru; the Directorate of Health of Loreto-Peru; theHumans Research Protection Program of the University of California at San Diego, La Jolla, CA; and the Institutional Review Board of the Johns Hopkins Bloomberg School of Public Health, Baltimore, MD. All participants provided written informed consent and were coded through all study participation. Specimens were also coded before protein microarray analysis.

Study sites. The field activities of this study were carried out from May 2005 to July 2008 in northeastern Peru, in villages near to the city of Iquitos in the province of Maynas, the capital of the Amazon Department of Loreto (map in Ref. 28). Considering the region’s geographical isolation from the rest of Peru, health services within the surrounding areas of Iquitos are relatively good and accessible. Three health posts provide medical services to the study villages described as follows. Santo Tomas health post, located 16 km by road from Iquitos and surrounded by the Nanay River, is a referral health center for three villages: La Unión, 12 de Diciembre, and Santo Tomás, collectively 2,650 inhabitants. San José de Lupa health post, located 10 km from Iquitos is accessible only through the Nanay River and is the referral center for four villages: San Pedro, Santa Rita, Fray Martín, and San José de Lupa, with collectively 1,250 inhabitants. Padrecocha health post, located 6 km from Iquitos is accessible only through the Nanay River and is a referral health post for three villages: San Andrés, Nueva Vida, and Padrecocha, with collectively 1,800 inhabitants.

Blood sampling. Blood samples were collected from patients diagnosed by conventional light microscopy on site at Peruvian Ministry of Health establishments according to national norms. Patients identified as infected with only P. vivax (microscopy only) were invited to participate in the study. At each enrollment site, venous blood was collected in EDTA Vacutainer tubes (Becton Dickinson, Franklin Lakes, NJ) and taken to the field project laboratory where samples were aliquoted and frozen at –20°C. Samples were shipped on dry ice to Universidad Peruana Cayetano Heredia in Lima for molecular diagnostic analysis.

Molecular confirmation of P. vivax infection. DNA was extracted from 200 μL of thawed, anticoagulated whole blood using the Qiagen Blood Kit (Qiagen, Valencia, CA). The diagnosis of P. vivax infections was confirmed in all patients using a genus and species-specific nested polymerase chain reaction (PCR) assay based on an 18S ribosomal RNA gene fragment specific for the genus Plasmodium, as previously reported.\textsuperscript{28,30} A 1,200-bp (base pair) fragment allowed for Plasmodium genus-level identification; identification of P. vivax and P. falciparum species was done using a 120-bp fragment specific for P. vivax and a 205-bp fragment specific for P. falciparum; samples containing P. falciparum or mixed infections were not considered for further analysis, P. malariae or P. ovale were not found.

Molecular genotyping. Genotyping of P. vivax isolates was performed by PCR-restriction fragment length polymorphism (PCR-RFLP) analysis of the P. vivax MSP3α (PvMSP3α) gene as previously described.\textsuperscript{31} Case definition and data analysis. Relapse was defined as identical PvMSP3α PCR-RFLP patterns when primary and subsequent infection parasites were compared. Reinfection was defined as different genotypes present in primary versus subsequent infection parasites by PvMSP3α PCR-RFLP patterns.\textsuperscript{28,29,32,33}

Protein microarray analysis using a P. vivax asexual blood-stage proteome array. A proteome array was designed containing 2,233 P. vivax recombinant proteins, representing 1,936 predicted P. vivax asexual blood-stage proteins and comprised as recently described.\textsuperscript{22} Proteins predicted to be secreted or present on the parasite surface, on the basis of the presence of a secretory signal peptide or transmembrane domains, were annotated as such in PlasmoDB\textsuperscript{34,35} and preferentially included. Additional selection for expression of P. vivax genes included expression microarray evidence for blood-stage expression.\textsuperscript{23,24} Putative cytoplasmic proteins, lacking both signal peptides and transmembrane domains, were also selected (isoelectric point [pI] < 7.6 for P. vivax genes). Plasmodium vivax vir genes were excluded because of their variability. Both single and multi-exon genes were selected. Exons of multi-exon genes were cloned and expressed separately. Furthermore, large genes or exons were further divided into overlapping segments to limit amplicon length between 300 and 3,000 nucleotides. Amplicons were labeled with the exon number and the total number of exons, such as “1o2” for exon 1 of a 2-exon gene. Genes that were further divided into segments were labeled s1, s2, and so forth.

The array was fabricated as previously described.\textsuperscript{36} In brief, target sequences were amplified genes from P. vivax genomic DNA (Sal I strain [MRA-552, MR4]) and cloned into the PXT7 plasmid with a T7 transcription terminator and encoded 5` polyhistidine (HIS) and 3` hemagglutinin (HA) epitopes. Recombinant proteins were expressed by an Escherichia coli cell-free in vitro transcription and translation system (Rapid Translation System 100 High Yield [RTS 100 HY] kits from 5 PRIME, Gaithersburg, MD) according to the manufacturer’s instructions. Proteome arrays were printed as previously described, with each recombinant protein spotted once in each array.\textsuperscript{36} Each array contained 256 negative control spots made with an in vitro transcription–translation master mix without plasmid DNA. Once printed, recombinant protein expression
was verified using anti-polyhistidin (clone His-1; Sigma-Aldrich, St. Louis, MO) and anti-hemagglutinin (clone 3F10; Roche, Indianapolis, IN) monoclonal antibodies, as previously described. All signal intensities were corrected for spot-specific background. A recombinant protein was deemed to be present on the slide if its spot’s mean fluorescence intensity was higher than the mean of the “no DNA” control spots plus two standard deviations.

Overall, 1,470 different P. vivax recombinant proteins (66%) were expressed with both His and HA tags, confirming that the majority of recombinant proteins were fully expressed. These represented 1,328 P. vivax-predicted asexual blood-stage proteins. Furthermore, 1,949 P. vivax recombinant proteins (87%) were expressed with at least one tag suggesting that these recombinant proteins were at least partially expressed.22

**Microarray data analysis.** A reactive protein was defined as a protein that had a signal intensity values > 2-fold the mean of the “no DNA” intensity values for the same sample (i.e., column on the matrix) in at least 10% of the samples in the P.v-infected group, Pv reinfected group or the Pv relapse group. The background-corrected signal intensity values for reactive antigens were log 2 transformed and normalized by subtracting the median of the “no DNA” spots in the log space. t tests were used to identify differentially reactive antigens. The Benjamini–Hochberg (BH) method was used for multiple test correction, which estimates the False Discovery Rate (FDR) and provide corrected P values. Statistical analysis and figure generation was performed in the R environment (www.r-project.org). Paired Student’s t test was used to compare differences in total antibody responses between relapsed and reinfected subjects.

**Analysis of genome-wide P. vivax single nucleotide polymorphisms.** The genes encoding were compared with the four globally represented and annotated P. vivax genomes (parasites from Brazil, India, Mauritania, and North Korea), available at: https://www.broadinstitute.org/annotation/genome/plasmodium_vivax/GenomeDescriptions.html (accessed May 5, 2015).

### RESULTS

**Number of P. vivax malaria episodes.** In the study period, 106 participants were enrolled who had 1–5 episodes of symptomatic light microscope- and PCR-confirmed P. vivax malaria (Table 1, Figure 1). The median age was 24 years, main age was 27 years, and 48% of the subjects were women. Occupation and demographics of the study participants were typical of the region (Table 2).

All infected participants were given standard antimalarial treatment following guidelines from the Peruvian Ministry of Health (chloroquine for 3 days (10 mg/kg on days 1 and 2 and 5 mg/kg on day 3), plus primaquine (0.5 mg/kg/day for 7 days)). Of the 106 subjects, 91 had two episodes, 11 had three episodes, 3 had four episodes, and 1 had five episodes. Using PvMSP3α genotyping, of the recurrent infection episodes, 48 had identical PvMSP3α PCR-RFLP patterns (hereafter referred to as “genotype”) compared with a previous infection leading to classification as relapse; 78 had different genotypes and were classified as reinfection. This classification is limited by the possibility of a subject harboring more than one P. vivax clone and hence overestimates the rate of reinfection compared with relapse. Subjects with P. vivax malaria tended to report more lifetime episodes of malaria than the episodes observed during the study period (Table 1). The average number of self-described malaria lifetime episodes for all participants was 4.8; for relapsing subjects, 4.3; and for reinfection subjects, 5.2.

**Descriptive analysis of serological reactivity to P. vivax antigens using a protein microarray.** Endemic controls were not used for this determination because they have substantial reactivity against P. vivax antigens and therefore are not an

![Number of Plasmodium vivax relapses and reinfections in patient population.](image-url)
appropriate control for the discovery of markers of exposure as shown in the heat map of the reactive antigens (Figure 2). Therefore, differentially reactive antigens in the text indicates results in relation to the negative control group with no history of malaria (N= 18, U.S. residents with no history of malaria). Of the 2,233 P. vivax protein spots (derived from 1,470 genes) on the protein microarray (see Supplemental Table 1 for complete list of arrayed recombinant proteins), 304 proteins spots were reactive when comparing

\[
\text{Table 2}
\]

<table>
<thead>
<tr>
<th>Occupation</th>
<th>Relapses (%)</th>
<th>Reinfections (%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student</td>
<td>23 (48)</td>
<td>25 (32)</td>
<td>48 (38)</td>
</tr>
<tr>
<td>Agriculture</td>
<td>7 (15)</td>
<td>12 (15)</td>
<td>19 (15)</td>
</tr>
<tr>
<td>Homemaker</td>
<td>6 (13)</td>
<td>20 (26)</td>
<td>26 (21)</td>
</tr>
<tr>
<td>Crafting</td>
<td>0 (0)</td>
<td>2 (3)</td>
<td>2 (2)</td>
</tr>
<tr>
<td>Transportation</td>
<td>1 (2)</td>
<td>3 (4)</td>
<td>4 (3)</td>
</tr>
<tr>
<td>Commerce</td>
<td>1 (2)</td>
<td>1 (1)</td>
<td>2 (2)</td>
</tr>
<tr>
<td>Construction</td>
<td>0 (0)</td>
<td>8 (10)</td>
<td>8 (6)</td>
</tr>
<tr>
<td>Unemployed</td>
<td>4 (8)</td>
<td>4 (5)</td>
<td>8 (6)</td>
</tr>
<tr>
<td>Fisherman</td>
<td>4 (8)</td>
<td>2 (3)</td>
<td>6 (5)</td>
</tr>
<tr>
<td>Logging</td>
<td>0 (0)</td>
<td>1 (1)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>&lt; 5 years old</td>
<td>2 (4)</td>
<td>0 (0)</td>
<td>2 (2)</td>
</tr>
<tr>
<td>Total</td>
<td>48 (100)</td>
<td>78 (100)</td>
<td>126 (100)</td>
</tr>
</tbody>
</table>

subject developed a recurrent episode within 28 days after prior treatment. One subject developed a recurrent episode after 29 days but it had a different P.v MSP3α pattern, hence was considered a reinfection for this analysis.

**Paired analysis reveals that relapse was not associated with a greater increase in reactivity than reinfection.** Although looking at the infected, reinfeeted, and relapse groups allowed us to find markers of exposure, there were multiple confounding factors that complicated comparison of the reinfeeted and the relapse groups. One confounder is precise knowledge of previous to P. vivax infections before episode 1 in this study, which would be useful in understanding changes in antibody profile after reinfection versus relapse. The current dataset had 113 subjects for whom samples for episodes one and two were available, of which 73 were defined as reinfection and 40 as relapse. Paired analysis looking at the changes elicited by the second episode for relapse subjects did not show increase after episode 2 compared with reinfection subjects; this latter group appeared to have just as many recognized antigens decreasing at episode 2 as increasing (Figure 4). Comparing the deltas (Second Episode–First Episode for each subject) observed in the two subject groups, the deltas for the reactive antigens in the relapse group were not greater in scope and magnitude than the deltas in the relapse group (Figure 4).

**Enrichment of genetic diversity of genes encoding differentially reactive antigens.** The non-synonymous genetic diversity (π) of genes encoding the set of recognized P. vivax antigens was compared with coding sequences found in the P. vivax genome as a whole. This analysis, using globally representative P. vivax strains from Brazil, India, Mauritania, and North Korea, only included annotated genes; vir gene family members, hypothetical genes, were not included. The set of genes encoding the recognized P. vivax antigens as a whole (combining proteins differentially recognized by both relapse and reinfection patients) had a significantly higher level of single nucleotide polymorphism (SNP) diversity than the rest of the coding genes, as assessed by the Mann–Whitney test (W = 249,177, P = 0.0007472). Genes encoding the set of recognized proteins were significantly more likely to have 1 or more non-synonymous SNPs (W = 249,791, P = 0.006419). In contrast, the level of synonymous SNPs in genes encoding recognized proteins was not significantly different (W = 291,635, P = 0.3948). This analysis suggests that positive immune selection for amino acid polymorphism in these P. vivax antigens has taken place.

**DISCUSSION**

This study is the first large-scale analysis in which immune responses to relapsed versus reinfection of P. vivax infection in a hypoendemic human population were compared. The first major finding was that there was no observable difference in seroreactivity between relapsed versus reinfection P. vivax infections. The second major finding is that we identified a large set of serodiagnostic antigens that have potential utility for seroepidemiological studies of transmission in P. vivax-endemic areas. Third, genome-scale analysis of the diversity of the serodiagnostic antigens recognized by P. vivax-infected subjects suggests that immune selection has led to antigenic changes in the parasite. These results collectively demonstrate that most of the antigens that could lead
FIGURE 2. Protein microarray analysis comparing serological responses of *Plasmodium vivax* relapse vs. reinfection. (A) Key to heat map, indicating color associated with signal intensity (left). Displayed at the left of the heat map are results of uninfected controls from the Iquitos region ("endemic controls"); the middle two panels of the heat map show results of paired, sequential samples from *P. vivax* infection of same subjects comparing total Infected (this category does not distinguish relapse from re-infection) vs. Re-infected; the right two panels of the heat map show results of paired, sequential samples from *P. vivax* infected-subjects that compare total Infected vs. Relapse (based on shared molecular genotyping—see Methods). (B) Protein microarray analysis of sera from first observed episode of *Plasmodium vivax* malaria. Recognized proteins are indicated with a green bars above them on the left side of the figure, where the *P* value is less than 0.05 (corrected for multiple measures by the Benjamini Hochberg test (BH) *P* value). All *P. vivax*-infected (relapse plus reinfection) are indicated by (Pv Inf) and negative controls are non-malaria infected individuals from the USA controls (GCRC, General Clinical Research Center). The full list of recognized proteins is in Supplementary Table 1. (C) Scatter plots with the GCRC mean fold over control (FOC) values on the x-axis, the mean *P. vivax* Infected FOC values on the y-axis and the identity line in red are graphed (Pv antigens with BH *P* values < 0.05 are colored in salmon and the others in cyan). (D) Volcano plots with the log2 (fold difference) on the x-axis and the −log10(BH *P* value) on the y-axis (*P. vivax* antigens with BH *P* values < 0.05 are colored in salmon and the others in cyan) to illustrate the difference in antibody profiles between the groups.
to important antibody responses are not being investigated; and immune responses differ between relapse and reinfection, which has important implications for understanding \textit{P. vivax} epidemiology, transmission, and vaccine development.

Infections by malaria parasites are known to lead to broadly reactive \textit{anti-\textit{Plasmodium}} antibody responses.\textsuperscript{38} How to analyze large-scale antibody responses in key areas of malaria research such as delineating target antigens of protective immunity or how to identify new proteins for seroepidemiological analyses of malaria transmission in endemic regions are important applications of current systems immunology methodologies.\textsuperscript{27} In this study, sera from symptomatically relapsed or reinfeected \textit{P. vivax}-infected subjects in the low-transmission region of the Peruvian Amazon were used to probe genome-scale \textit{P. vivax} protein microarrays.

That the cumulative total antibody response was not greater in reinfection compared with relapsing infection has implications for understanding immunological mechanisms and consequences of relapsing \textit{P. vivax} malaria. Previous studies have suggested that asymptomatic relapse is common in \textit{P. vivax} malaria,\textsuperscript{37} despite the more widely recognized phenomenon of relapse leading to symptomatic infection and the seeking of medical care. The present investigation provides evidence that reinfection resulting in clinical

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Protein & Exon & No. of exons & No. of tm domains & SignalP positive & Molecular weight (Da) & Isoelectric point & Selection criteria & Description \\
\hline
PVX\_114145 & 1 & 1 & 0 & Yes & 52,341 & 4.79 & SE\_secreted & MSP10, putative \\
PVX\_081830 & 2 & 2 & 0 & No & 56,607 & 4.64 & ME\_cytoplasmic & Hypothetical protein \\
PVX\_117680 & 1 & 2 & 0 & No & 128,624 & 5.47 & ME\_cytoplasmic & Hypothetical protein, conserved \\
PVX\_000930 & 1 & 2 & 2 & Yes & 15,068 & 10.46 & ME\_secreted & Sexual stage antigen s16, putative \\
PVX\_007625 & 1 & 1 & 1 & Yes & 54,742 & 4.92 & SE\_secreted & MSP8, putative \\
PVX\_118705 & 1 & 1 & 1 & No & 50,808 & 10.51 & SE\_secreted & Hypothetical protein, conserved \\
PVX\_121935 & 2 & 2 & 2 & Yes & 27,735 & 8.85 & ME\_secreted & Hypothetical protein \\
PVX\_097730 & 1 & 1 & 0 & Yes & 46,332 & 3.25 & SE\_secreted & Hypothetical protein \\
PVX\_110935 & 1 & 1 & 0 & Yes & 42,780 & 3.7 & SE\_secreted & Hypothetical protein \\
PVX\_082650 & 1 & 1 & 0 & Yes & 47,963 & 5.2 & SE\_secreted & MSP7 (MSP7), putative \\
\hline
\end{tabular}
\caption{Top 10 reactive proteins recognized in \textit{Plasmodium vivax} malaria patients}
\end{table}

\textsuperscript{MSP} = merozoite surface protein; \textit{tm} = transmembrane.
symptoms is not associated with an enhanced immune memory-driven antibody response than relapsing symptomatic infection. This observation might be explained in several ways, but raises the possibility that any partially effective immune response to a previous \textit{P. vivax} strain might have been maximized in terms of driving elevations of antibody response. Alternatively, it is also possible that lower parasitemia in relapse compared with reinfection might be associated with a lower antibody response, but the present data are not consistent with this possibility because the parasitemias were only semiquantitatively assessed (1–4+ system) in this study.

An important limitation of this study is the accurate classification of \textit{P. vivax} relapse versus reinfection in patients at continued risk for new infections, an issue addressed in other reports when \textit{P. vivax}-infected subjects leave a malaria-endemic region and experience what can definitively be classified as relapse in a malaria non-endemic place.\textsuperscript{39,40} Our classification of relapse is limited by the possibility that subjects may harbor more than one \textit{P. vivax} clone. Hence our data conservatively underestimate the rate of relapse, and for this reason the lack of difference in antibody responses between relapse and reinfection on a systems level should remain valid. However, there is still no reliable method to differentiate \textit{P. vivax} relapse from reinfection in the endemic setting, an important area for future research.

This protein microarray analysis provides immediate tools to apply to seroepidemiology of malaria with regard to surveillance, control, and elimination. Future work should use these tools to establish the population decay kinetics of antibody responses to different specific antigens, thereby allowing estimates of timing of previous infection. Comparison of \textit{E. coli} to eukaryotic recombinant protein expression systems may be important to improve the performance of such serological assays based on the protein microarray results. Such studies will be important because previous seroepidemiological studies have relied on blood-stage vaccine candidate antigens selected for high titer, immunodominant and sustained antibody responses rather than with regard to seroreactivity in human populations that would diminish over time. The use of

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**Figure 4.** Paired protein microarray analysis comparing changes (indicated as delta) in serological response between episodes 1 and 2 of subjects with \textit{Plasmodium vivax} (Pv) relapse or reinfection, as defined by MSP3α PCR-RFLP. Volcano plots comparing episodes 1 and 2 for reinfection and relapse (A and B, respectively) show log\(_2\) of the fold change on the x axis and the \(-\log_{10}(P\ \text{value})\) on the y axis. (C) Comparison of reinfection to relapse using a volcano plot comparing the deltas for each subject and each antigen with the \(-\log_{10}(P\ \text{value})\) on the y axis. A boxplot of the mean of the deltas is shown. A boxplot of the mean of the deltas (D) illustrates the median and distribution of the mean of the deltas for the relapse group on the left and the reinfection group on the right.
parasite lysates for enzyme-linked immunosorbent assay or immunofluorescent microscopy is not applicable to such studies of decay kinetics because of their heterogeneity and low sensitivity/specificity for inferring previous time of infection. The ideal antigen(s) for determining recent versus remote malaria transmission from mosquitoes to residents of endemic areas would have the properties of being associated with rapid versus sustained decay kinetics.

The P. vivax antigen yielding the most consistently high-intensity reactivity on the protein array was PvMSP10; other top-ranked antigens included MSP7, MSP8 and several hypothetical proteins, and a putatively sexual-stage antigen s16. Antibodies to PvMSP10 have previously been readily detected in humans with P. vivax malaria, and and wheat germ in vitro expression system–expressed protein. Studies with P. falciparum MSP10 demonstrated a lack of cross-reactivity with other MSPs (PMSP-1, -4, -5 and -8), consistent with the 95% specificity for P. vivax infection found for antibodies detected against wheat germ–expressed PvMSP10. No experimental evidence has emerged to date regarding the viability of any Plasmodium spp. MSP10 as a candidate for an asexual blood-stage-based vaccine.

This large-scale analysis of antibody responses to P. vivax infection has identified a large set of serodiagnostic antigens with potential utility for seroepidemiological studies of transmission in endemic areas. This work sets the stage for testing these antigens in well-characterized human populations in diverse malaria-endemic settings around the world and for planning new approaches to malaria vaccine development aimed at the neglected parasite, P. vivax.

Received March 24, 2015. Accepted for publication May 13, 2015.

Financial support: This work was supported by United States Public Health Service grants U19AI089681, D43TW007120, R01AI067727, and K24AI068903 (Joseph M. Vinetz); AI066791, AI095916, and R01AI067727 (Douglas M. Molina, and Xiaowu Liang), all from the U.S. National Institutes of Health.

Conflict of interest: The authors have read the journal’s policy and declare the following potential conflicts: Philip Felgner has an equity interest in Antigen Discovery, Inc., which is developing products related to the research described in this article. In addition, this author serves on the advisory board of ADI and receives compensation for these services. The terms of this arrangement have been reviewed and approved by the University of California in accordance with its conflict of interest policies. Douglas Molina is an employee of Antigen Discovery, Inc. No other author declares a conflict of interest. This does not alter our adherence to ASTMH/AJTMH journal policies on sharing data and materials.

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