RESEARCH ARTICLE

Functional antibodies against *Plasmodium falciparum* sporozoites are associated with a longer time to qPCR-detected infection among schoolchildren in Burkina Faso [version 1; referees: awaiting peer review]

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Abstract

**Background:** Individuals living in malaria-endemic regions develop naturally acquired immunity against severe malarial disease, but it is unclear whether immunity that affects the establishment of infections develops following continuous natural exposure.

**Methods:** We cleared schoolchildren in Burkina Faso of possible sub-patent infections and examined them weekly for incident infections by PCR. Plasma samples collected at enrolment were used to quantify antibodies to the pre-erythrocytic-stage antigens circumsporozoite protein (CSP) and liver stage antigen. Sporozoite gliding inhibition by naturally acquired antibodies was assessed using *Plasmodium falciparum* NF54 sporozoites; hepatocyte invasion was assessed using the human HC-04 hepatoma cell line and NF54 sporozoites. The associations between these functional pre-erythrocytic immunity phenotypes and time to PCR-detected infection were studied.

**Results:** A total of 51 children were monitored; the median time to first detection of infection by PCR or development of clinical symptoms was 28 days. Anti-CSP antibody titres showed a strong positive association with sporozoite gliding motility inhibition (P<0.0001, Spearman’s ρ=0.76). *In vitro* hepatocyte invasion was inhibited by naturally acquired antibodies (median invasion inhibition, 19.4% [IQR 15.2-40.9%]), and there was a positive correlation between gliding and invasion inhibition (P=0.02, Spearman’s ρ=0.60). Survival analysis indicated longer time to infection in individuals displaying higher-than-median sporozoite gliding inhibition activity (P=0.01).
Conclusions: In summary, functional antibodies against the pre-erythrocytic stages of malaria infection are acquired in children who are repeatedly exposed to *Plasmodium* parasites. This immune response does not prevent them from becoming infected during a malaria transmission season, but might delay the appearance of blood stage parasitaemia and consequently needs to be considered in the evaluation of malaria vaccines.

Keywords
malaria, sporozoites, antibodies, immunity, sterilizing, pre-erythrocytic, liver-stage
Introduction
The most advanced malaria vaccine, RTS,S (trade name, Mosquirix), induces immune responses that target \textit{P. falciparum} circumsporozoite protein (CSP) and thereby the pre-erythrocytic stages of malaria\(^1\). Alongside the RTS,S subunit vaccine, several other pre-erythrocytic stage vaccines are under development, based on subunit or whole-parasite vaccination\(^2\text{-}^4\). Vaccination with the attenuated sporozoite vaccine PISPZ resulted in a protective efficacy of \(~48\%\), as quantified by differences in time to first positive blood smears in malaria-experienced adults in Mali\(^5\). The results of this and other vaccine trials and the efficient immunisation of malaria-naive individuals with multiple infected mosquito bites while receiving chloroquine\(^6\) contrast with the limited epidemiological evidence of naturally acquired functional immunity to \textit{Plasmodium} pre-erythrocytic stages. Individuals living in malaria-endemic regions can develop naturally acquired immunity against severe malaria disease and death\(^7\text{-}^9\), but it is unclear whether immunity that prevents or reduces infection incidence develops following natural exposure\(^7\). The high incidence of blood-stage re-infection after effective anti-malarial treatment in adults living in malaria-endemic regions suggests that sterilizing immunity does not develop even after years of repeated infection\(^10\text{-}^11\). Similarly, cohort studies that have analysed the relationship between age and risk of \textit{P. falciparum} infection showed no evidence for complete protection against infection and conflicting evidence on whether naturally acquired immunity can result in a different time to patentcy\(^2\text{-}^4\text{-}^11\). One of the most detailed studies on this topic reported clear negative associations between age and the risk of clinical malaria or microscopy-detected malaria infection, but similar times to PCR-detected infection for all age groups. The study concluded no or very limited evidence for an age-dependent acquisition of immunity that protects from infection\(^11\).

Given the interest in pre-erythrocytic vaccines, studies are needed to understand natural protective immune responses that target sporozoite and liver-stages of malaria infection. Here, we determine the associations between responses affecting sporozoite gliding motility, hepatocyte invasion and malaria infection risk assessed by weekly quantitative PCR (qPCR) in a cohort of schoolchildren from Burkina Faso exposed to intense malaria transmission.

Results
Study population and follow-up
Of the 58 school-aged children who were recruited and received treatment at enrolment, 6 were PCR-positive 3 weeks after dihydroartemisinin-piperaquine (DHA-PQ) administration and were not eligible to continue follow-up. One child who was only followed for one routine visit, when no infection was detected, and who withdrew from the study, did not have immune responses quantified and was not included in this analysis.

Parasitological and immunological data from the remaining 51 intensively followed children were analysed (Table 1). Every week these study participants were screened for incident infections. All but one study participant had \textit{P. falciparum} parasites detected by \textit{18S} qPCR during follow-up. Malaria infection caused clinical disease in 43/50 children. One child developed symptomatology suggestive of malaria, but no parasites were detected in samples collected before and during the clinical episode; data from this child were censored after the onset of symptoms. The median time from confirmation of the absence of parasites (i.e. 3 weeks after anti-malarial treatment) to infection detection by nested PCR or onset of symptoms was 28 days; one child who did not have parasites detected by field PCR was not included in this calculation. Similarly, the median time to parasite detection by \textit{18S} qPCR was 30 days. In Figure \textit{1}, both the times of first \textit{18S} qPCR positive result and, if applicable, of development of clinical disease are presented for all study participants.

Sporozoite-specific IgG and IgM antibodies in malaria-exposed children
Malaria antigen-specific antibodies to pre-erythrocytic antigens CSP, liver stage antigen (LSA-1) and asexual lysate were determined in naturally exposed children and malaria-naive European donors by ELISAs. Antibody titres to the CSP pre-erythrocytic antigen were on average low in naturally exposed children and not significantly different from malaria-naive donors (Figure \textit{2A}, \(P=0.11\); non-parametric tests were used for all comparisons), while LSA-1 antibody levels were significantly higher in malaria-exposed children compared to malaria-naive donors (Figure \textit{2B}, \(P=0.006\)). As expected, asexual blood stage-specific antibody titers in naturally exposed children were higher compared to malaria-naive donors (Figure \textit{2C}, \(P<0.0001\)). In addition to antigen-specific assays, IgG and IgM antibodies

### Table 1. Study population.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of individuals</td>
<td></td>
</tr>
<tr>
<td>Screened and parasite-free by microscopy</td>
<td>58</td>
</tr>
<tr>
<td>Persisting parasites post-treatment</td>
<td>6</td>
</tr>
<tr>
<td>Consent withdrawn</td>
<td>1</td>
</tr>
<tr>
<td>Monitored</td>
<td>51</td>
</tr>
<tr>
<td>Age in years, median (IQR)</td>
<td>7.1 (5.7–8.1)</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
</tr>
<tr>
<td>Female, % (n)</td>
<td>37.2 (n=19)</td>
</tr>
<tr>
<td>Reported bed net use, % (n)</td>
<td>51.0 (26)</td>
</tr>
<tr>
<td>Haemoglobin levels at the beginning of follow-up*, median (IQR)</td>
<td>11.9 (11.3–12.5)</td>
</tr>
<tr>
<td>Haemoglobin types</td>
<td></td>
</tr>
<tr>
<td>AA</td>
<td>70.6 (36)</td>
</tr>
<tr>
<td>AC</td>
<td>21.6 (11)</td>
</tr>
<tr>
<td>AS</td>
<td>5.9 (3)</td>
</tr>
<tr>
<td>SS</td>
<td>2.0 (1)</td>
</tr>
<tr>
<td>Total number of weekly surveillance visits</td>
<td>222</td>
</tr>
<tr>
<td>Weekly visits/participant, median (IQR)</td>
<td>4 (2–6)</td>
</tr>
</tbody>
</table>

*First weekly visit. IQR, interquartile range.
recognizing *Plasmodium* sporozoites were quantified using fluorescently labelled anti-IgG and anti-IgM antibodies by flow cytometric analysis. Whole sporozoite-specific IgG and IgM antibody levels in the study participants were significantly higher than in malaria-naive donors (Figure 2D, E, P=0.02 and 0.004 for IgG and IgM, respectively). Strong correlations between sporozoite-specific IgG and IgM antibodies (Figure S1A in Extended data), P=0.0005, Spearman’s ρ=0.75), and between CSP-IgG antibody levels and whole sporozoite-specific IgG antibodies (Figure S1B in Extended data, Spearman’s ρ=0.83, P<0.0001) were also observed.

Naturally acquired antibodies in children neutralize *in vitro* sporozoite gliding motility

The neutralizing activity of naturally acquired antibodies against sporozoite motility was determined in an *in vitro* assay. Sporozoites pre-treated with PBS showed an average gliding trail surface of 7,392 (95% confidence interval [CI] 4,151-9,388) pixels. To characterize the effect of human plasma on sporozoite gliding motility that is independent of naturally acquired immunity, sporozoites were incubated in the presence of plasma from malaria-naive individuals (n=5) and showed an average gliding trail surface of 1,427 (95% CI 646.6-2,207) pixels, which is considerably larger than the gliding trail surface of sporozoites incubated with 30 μg/ml of a monoclonal anti-CSP antibody, our positive control, 141 (95% CI 71.9-225.4) pixels.

Plasma from the majority of cohort participants reduced *in vitro* sporozoite gliding motility with a median gliding inhibition of 59.6% (IQR 27.8-77.0%); incubation of sporozoites with plasma from three participants resulted in lower gliding trail surfaces than the positive control. We defined two groups: one with poor gliding inhibition (individuals whose plasma inhibited less than 20% of sporozoite gliding motility, N=8) and the other with strong gliding inhibition (more than 80% gliding inhibition, N=8). The first group had similar gliding trail surface (median, 1,353; IQR, 1,311.7-1,639.2) compared to malaria-naive donors (median 1605.7, IQR 824.3 - 1,652) (Figure 2F), whilst strong gliding inhibitors had a median trail surface of 186.2 (IQR 9.4 - 208.6), which was significantly lower compared to malaria-naive donors (Figure 2F, P<0.01). *In vitro* gliding inhibition did not correlate with LSA-1 IgG antibody levels (P=0.11, Spearman’s ρ=0.23), but correlated with CSP-specific IgG antibodies (Figure S2A in Extended data, P<0.0001, Spearman’s ρ=0.76), whole sporozoite-specific IgG (Figure S2B in Extended data, P<0.0001, Spearman’s ρ=0.81) and IgM antibodies (Figure S2C in Extended data, P=0.01, Spearman’s ρ=0.61). While sporozoite-specific IgG and IgM antibody levels of poor gliding inhibitors did not significantly differ from malaria-naive adults, sporozoite-specific antibody levels of strong gliding inhibitors were significantly higher compared to poor gliding inhibitors (Figure S2D in Extended data, P<0.0001 and P=0.004 for IgG and IgM antibodies, respectively) and malaria-naive adults (Figure S2D, E in Extended data, P<0.0001 and P=0.0006 for IgG and IgM antibodies, respectively). This suggests that quantitative differences in measured immune responses might explain variation in these functional phenotypes.

**Antibodies in malaria-exposed children neutralize *in vitro* sporozoite infectivity of hepatocytes**

The inhibitory effect of naturally acquired antibodies on *in vitro* sporozoite invasion of hepatocytes was also assessed in a selected number of samples shown to inhibit gliding motility strongly (n=8) or poorly (n=8). *In vitro* invasion was inhibited by naturally acquired antibodies (median invasion inhibition, 19.4% [IQR, 15.2-40.9%]), and plasma from children categorized as strong
Figure 2. Naturally acquired pre-erythrocytic antibody levels and their functionality against sporozoite infectivity in vitro. Malaria antigen-specific antibody levels in children from Burkina Faso (n=51) and European malaria-naive adults (n=9) to the pre-erythrocytic antigens (A) circumsporozoite protein (CSP), (B) liver-stage antigen-1 (LSA-1), and (C) asexual lysate as an internal control were determined by ELISAs and expressed as arbitrary units (AU). The amount of (D) IgG and (E) IgM antibodies recognizing sporozoites was determined by flow cytometry and shown as the geometric mean fluorescence intensity (MFI). To this end, P. falciparum NF54 sporozoites were pre-treated with 10% heat-inactivated plasma from children from Burkina Faso (n=17) and malaria-naive adults (n=8) and stained with fluorescently labelled antibodies against IgG and IgM antibodies. (F) The gliding motility of P. falciparum NF54 sporozoites, pre-treated with plasma from children from Burkina Faso (n=51) and malaria-naive adults (n=5), was determined by in vitro gliding motility assays. Gliding trail length of sporozoites incubated with plasma from malaria-naive donors (n=5) or naturally exposed children who were poor (n=8) or strong (n=8) inhibitors of gliding motility are shown. (G) The percent hepatocytes invaded by P. falciparum NF54 sporozoites pre-treated with plasma from children from Burkina Faso (n=16) who were shown to be either poor (n=8) or strong (n=8) gliding inhibitors and malaria-naive adults (n=9) was determined by in vitro invasion assays in human hepatoma cells. Comparisons between multiple groups were tested with Kruskal-Wallis test with Dunn’s multiple comparison post hoc test.

gliding inhibitors (see previous section) also prevented hepatocyte invasion more effectively compared to malaria-naive donors (Figure 2G, P<0.001). There was a positive correlation between gliding and invasion inhibition (Figure S3A in Extended data14, P=0.02, Spearman’s ρ=0.60), suggesting that in vitro gliding inhibition by naturally acquired antibodies might serve as a good surrogate for in vitro hepatocyte invasion inhibition. As with gliding inhibition, sporozoite invasion inhibition correlated positively with sporozoite-specific IgG (Figure S3B in Extended data14, P=0.004, Spearman’s ρ=0.71) and CSP-specific IgG antibodies (Figure S3D in Extended data14, P=0.002, Spearman’s ρ=0.76), but not with LSA-1-specific IgG antibodies (P=0.08, Spearman’s ρ=0.48). In contrast, sporozoite-specific IgM antibody levels did not correlate with invasion inhibition (Figure S3C in Extended data14, P=0.14, Spearman’s ρ=0.42).

Evidence of natural risk-modifying pre-erythrocytic immunity

For each immunological assay, ELISA or sporozoite gliding motility assays, children were categorized in two groups: participants with high antibody responses (or high sporozoite gliding inhibition activity) were those with assay values higher than the study population median (Figure 3A); children considered to have low antibody responses or low sporozoite gliding inhibition capacity had values lower than the median. Based on this categorization, study subjects with high CSP responses and those whose plasma inhibited sporozoite gliding movement acquired blood-stage P. falciparum infection (qPCR-based parasitaemia ≥ 0.1 parasites/μl) later compared to children with lower CSP responses and less efficient gliding inhibitory activity (Figure 3B; P=0.05 and P=0.01 for CSP responses and
sporozoite gliding inhibition, respectively). High anti-LSA-1 antibody levels, on the other hand, did not influence time to infection ($P=0.31$). Blood-stage immunity, i.e. high response in the asexual stage lysate assay, was also associated with longer time to PCR-detected infection (Figure 3C, $P=0.005$). We repeated these analyses excluding children with haemoglobin S and haemoglobin C mutations, as these conditions might influence both immunity$^{15}$ and parasite carriage$^{16,17}$. Despite the limited number of individuals included in this analysis ($n=36$), similar results were obtained ($P=0.01$ for both CSP and asexual stage lysate assays and $P=0.05$ for the sporozoite gliding inhibition assay). Additional analyses (Extended data$^{18}$) show that functional responses against pre-erythrocytic stages were also associated with infection risk when different parasite density thresholds are used to define infection.

Since children with high CSP responses were more likely to have high antibody responses to asexual blood stage parasite lysate compared to low CSP responders (60% versus 38.5%, respectively; $P=0.12$), multivariate Cox models were fit to assess the mutually adjusted effects of these immune responses on time to infection detection (Table 2). While the relationship between

![A](image)

**Figure 3.** Effects of immune responses against liver- and blood-stage antigens on malaria infection risk. To assess the effect of immune responses on infection risk, children were classified based on whether the results of their assays were higher or lower than the study population median (see Results); in (A), vertically aligned cells represent the same participant, and orange cells indicate that assay results are higher than the median. In (B), Kaplan-Meier curves for children with high and low circumsporozoite protein (CSP) responses and gliding inhibition (GI) phenotypes are presented; in (C), curves for participants categorized based on their responses to asexual stage antigens (AL) are shown.

![B](image)

![C](image)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hazard ratio</th>
<th>95% CI</th>
<th>P-value</th>
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<tr>
<td><strong>Model I</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High CSP response</td>
<td>0.62</td>
<td>0.34–1.15</td>
<td>0.13</td>
</tr>
<tr>
<td>High response to asexual stage lysate</td>
<td>0.49</td>
<td>0.27–0.89</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Model II</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>High gliding inhibition activity</td>
<td>0.55</td>
<td>0.29–1.01</td>
<td>0.06</td>
</tr>
<tr>
<td>High response to asexual stage lysate</td>
<td>0.52</td>
<td>0.29–0.94</td>
<td>0.03</td>
</tr>
</tbody>
</table>

CI, confidence interval; CSP, circumsporozoite protein.
anti-CSP responses and time to malaria infection was not statistically significant in a model that also included results of the asexual stage lysate assay, higher inhibition of in vitro sporozoite gliding motility remained associated with protection against falciparum infection after adjustment for blood-stage immunity (hazard ratio, 0.55; 95% CI, 0.29–1.01).

Discussion
In this longitudinal study in Burkina Faso, we analysed the associations between functional immune responses against pre-erythrocytic stages of malaria and the incidence of qPCR-detected infections in children aged 5–10 years. We observed that (i) schoolchildren develop antibody responses that can interfere with sporozoite motility and infectivity in vitro, and (ii) those children with antibodies that more efficiently reduced in vitro sporozoite gliding motility remained uninfected for longer periods of time. Our epidemiological data together with the in vitro data provide evidence that there is partial immunity that influences individual level infection incidence.

Sterile protection against malaria can be readily demonstrated in human and animal experimental models, but not following natural malaria exposure. Field studies showed conflicting evidence on whether naturally acquired immunity can result in delays to patency and showed no evidence for sterile immunity completely preventing the appearance of parasites in the blood stream of exposed individuals. We selected children aged 5–10, who have limited blood stage immunity (a potential confounder when studying pre-erythrocytic immunity) compared to semi-immune adults, and who allow repeated blood sampling compared to toddlers. Since submicroscopic infections are prevalent in the area, we used a curative dose of antimalarials to clear possible sub-patent infections and, upon confirmation that children were parasite-free at the start of the transmission season, assessed the infection incidence by sensitive molecular assays. Our finding that 98% of the cohort became infected with P. falciparum within 3 months confirms the high force of infection in the area.

Consistent with previous sero-epidemiological studies, our results indicate that antibodies to P. falciparum sporozoite and liver-stage antigens are acquired following natural exposure. Antibody titres to the CSP antigen were on average low in our cohort and not significantly different from malaria-naïve donors. These low titres could be related to the timing of the study recruitment (prior to the transmission season after ~7 months of very low malaria exposure) and may also be influenced by repeated blood-stage infection in our cohort, which may have suppressed immune responses against the pre-erythrocytic stages. To assess the contribution of pre-erythrocytic humoral immunity to protection, previous studies have related antibodies at baseline with time-to-infection after parasite clearance with antimalarials. A significant challenge in these studies is that both protective immunity and cumulative exposure increase with age, and so it is often unclear whether measured responses mediate protection or are merely a marker of past exposure. In an attempt to move beyond indirect epidemiological associations, we explored functional anti-sporozoite immunity by assessing the ability of plasma to inhibit sporozoite gliding motility and hepatocyte invasion and related these in vitro phenotypes to field findings. We observed that CSP IgG antibodies showed a strong positive association with sporozoite gliding motility inhibition. It has been demonstrated that Plasmodium parasites use the system of adhesion-based motility, gliding, to actively penetrate host cells, and that the invasive ability of sporozoites is directly associated with their motility. In agreement with these findings, the data presented here suggest that in vitro gliding inhibition by naturally acquired antibodies may be a useful surrogate marker for in vitro hepatocyte invasion. In an immuno-epidemiological study undertaken in Indonesia, hepatocyte invasion inhibition was associated with higher anti-CSP antibody titres. In our cohort, subjects with high CSP responses (i.e. higher than the study population median) and those whose plasma more efficiently inhibited sporozoite gliding movement developed P. falciparum infection later compared to children with lower responses. To our knowledge, this is one of the first studies to show that there are functional antibodies against pre-erythrocytic malaria stages in malaria-exposed children.

Our study has several limitations. We observed that high responses in the asexual stage lysate assay with unknown functionality were also associated with longer time to infection. We thus cannot rule out a supportive role for asexual antibody responses in the observed associations. We believe it is likely that the functionally important pre-erythrocytic antibody responses that we quantified here are acquired alongside anti-blood-stage antibodies. In addition, a recent study in the same geographical area demonstrated that heterogeneity in mosquito exposure contributes considerably to heterogeneity in parasite inoculation risk. In the current study, we used delayed time to blood-stage infection as a simplistic indicator of partial protection, which fails to take into account variation in exposure. In an ideal approach, we would have been able to quantify malaria exposure at an individual level, which may involve linking of blood meals in household-caught mosquitoes to household occupants and determining sporozoites in the salivary glands of these mosquitoes. Measuring exposure at individual level in such an approach will help to shed further light on pre-erythrocytic immunity in naturally exposed individuals. With respect to discriminating between pre-erythrocytic and blood-stage immunity, a valuable but laborious approach would be to examine the observed relationships in a larger cohort that allows stratification based on similar blood stage immunity but different levels of pre-erythrocytic immunity at baseline and that provides sufficient power to detect weaker associations. Another limitation of our study is that we were only able to determine humoral responses. Cellular responses to pre-erythrocytic stages have been implicated in malaria protection in multiple studies. It is conceivable that by quantifying both antibody and cellular responses we would be able to better define natural immunological phenotypes associated with differential malaria risk.

In summary, in our cohort of children, anti-CSP antibodies were strongly associated with in vitro sporozoite gliding inhibition and hepatocyte invasion inhibition. Children with functional anti-sporozoite antibody responses had a longer time to P. falciparum infection compared to children with lower functional responses, suggesting that these in vitro assays are
relevant to understand natural protection. The partial protection (i.e., delay in infection) observed in our study does not prevent individuals from becoming infected during an entire transmission season, but reduces infection incidence and consequently needs to be considered in epidemiological studies aiming to understand malaria risk heterogeneity and in malaria vaccines trials. Identifying host or parasite factors linked to these functional immunological phenotypes and characterizing how these phenotypes change with cumulative exposure to malaria parasites will help the understanding of why natural immunity against pre-erythrocytic stages is incomplete.

Methods

Study design

This study was performed from June to December 2015 in the village of Balonghin in the Saponé health district, Burkina Faso, which is exposed to intense and seasonal P. falciparum transmission. Written informed consent was provided by the parent or guardian of each child. The study was approved by the ethics committees of the London School of Hygiene and Tropical Medicine (reference number 9008) and the Ministry of Health in Burkina Faso (reference number 2015-3-053). Children aged 5–10 years with haemoglobin levels above 8 g/dl and no Plasmodium parasites detected by microscopy were eligible. DHA-PQ was used to clear sub-microbial infections. At 3 weeks (20–22 days) after treatment, finger-prick blood samples were collected to ensure parasite negativity by nested PCR prior to formal enrolment into the cohort. Citrated plasma samples were collected before treatment using citrated vacutainer cell preparation tubes (CPT vacutainers, Becton Dickinson), stored at -80°C and used for malaria-antigen-specific IgG ELISAs and sporozoite assays. Peripheral blood mononuclear cells (PBMC) were also collected, but were lost due to the inability to maintain liquid nitrogen supplies during civil unrest in Ouagadougou. Following enrolment, participants were examined during weekly visits, when finger-prick samples were collected for P. falciparum nested PCR that was performed within 48 hours. Following parasite detection, finger-prick blood samples were collected every day for 1 week, and every week afterwards, up to 35 days after parasite detection. Study participants were closely monitored for the development of malaria symptoms. Artemether-lumefantrine was given upon the detection of symptoms or 35 days after initial detection of infection by nested PCR, whichever came first. For the current analyses, only the time between parasite detection and sporozoite assays. Peripheral blood mononuclear cells (PBMC) were also collected, but were lost due to the inability to maintain liquid nitrogen supplies during civil unrest in Ouagadougou. Following enrolment, participants were examined during weekly visits, when finger-prick samples were collected for P. falciparum nested PCR that was performed within 48 hours. Following parasite detection, finger-prick blood samples were collected every day for 1 week, and every week afterwards, up to 35 days after parasite detection. Study participants were closely monitored for the development of malaria symptoms. Artemether-lumefantrine was given upon the detection of symptoms or 35 days after initial detection of infection by nested PCR, whichever came first. For the current analyses, only the time to first infection detection was used and related to baseline immunological assays.

Molecular analyses

Nucleic acids from 100μl whole-blood samples stored in RNAprotect Cell Reagent were extracted using MagNAPure LC automatic extractor (Total Nucleic Acid Isolation Kit—High Performance, Roche Applied Science) and used for qPCR targeting 18S rRNA. Genomic DNA from the same extraction was used to test for human haemoglobinopathies haemoglobin S and C.

Parasite culture and generation of P. falciparum-infected mosquitoes

As source of sporozoites, Anopheles stephensi mosquitoes were infected by standard membrane feeding on P. falciparum NF54 gametocyte cultures. Salivary glands from infected mosquitoes were dissected, collected in Leibovitz culture medium (Lonza) without serum (supplemented with 1% penicillin-streptomycin and 1% L-glutamine for in vitro gliding motility assays), and homogenized in a homemade glass grinder. The number of sporozoites was counted in a Bürker-Türk counting chamber using phase contrast microscopy.

Human hepatoma HC-04 cell line

The HC-04 human hepatoma cell line acquired through MR4 as part of the Biodefense and Emerging Infectious Diseases Research Resources Repository (BEI Resources). Hepatoma cells (referred to as hepatocytes) were cultured in Dulbecco’s Modified Eagle Medium (DMEM/Ham’s F-12 nutrient mixture medium (GIBCO) supplemented with 10% heat-inactivated fetal bovine serum (FBS, GIBCO), 1% glutamine and 1% penicillin/streptomycin (GIBCO) at 37°C in an atmosphere of 5% CO₂.

Enzyme-linked immunosorbent assays and sporozoite opsonization assays

Levels of antibodies were determined to circumsporozoite protein (CSP: full-length P. falciparum NF54 CSP with repeats, produced in E. coli by Gennova Biopharmaceuticals Ltd., Pune, India), LSA-1 (LSA-NRC construct expressed in E. coli) and asexual lysate using previously reported standardized enzyme-linked immunosorbent assays (ELISAs) in naturally exposed children (n=51) and malaria-naïve European donors (n=9). Antibody levels were calculated in relation to the positive control (hyperimmune plasma pool from Tanzania) that was set at 100 arbitrary units (AU) using Auditable Data Analysis and Management System (ADAMSEL, version 1.1).

Recognition of whole sporozoites by naturally acquired IgG and IgM antibodies was determined by an in vitro flow-cytometry-based antibody opsonization assay that was presented in detail elsewhere. Flow cytometric analysis was performed with a LSRII flow cytometer (BD BioSciences); data analysis by FlowJo software (version 10.0.8, Tree Star).

Malaria-naive donors are healthy malaria-naïve European volunteers who participated in CPS-immunization trial (immunization of malaria-naïve human volunteers under chloroquine prophylaxis with sporozoites delivered by mosquito bites) at the Radboud University Medical Center (Nijmegen, The Netherlands). Written informed consent was obtained from these individuals including for their samples to be stored and used in additional immunological experiments. Pre-immunization samples collected before the CPS-immunization were used for analysis of malaria antigen-specific antibody levels.

In vitro sporozoite gliding motility assay

Prior to in vitro sporozoite assays, plasma aliquots were heat-inactivated for 30 minutes at 56°C, centrifuged at 13,000 rpm for 5 minutes at room temperature and kept at 4°C. Flat-bottom optical-bottom 96-well plates with cover glass base were incubated overnight at 4°C with an anti-CSP monoclonal antibody (produced at Radboudumc Nijmegen, Netherlands) 3SP2; 5 μg/ml in PBS). Following incubation, wells were washed twice with 150 μl/well PBS, blocked for 20 minutes at room temperature.
with 100 μl/well Leibovitz medium (Lonza) supplemented with 1% penicillin-streptomycin (GIBCO), 1% L-glutamine (GIBCO) and 10% heat-inactivated FBS (GIBCO). *P. falciparum* NF54 sporozoites (100 μl) were pre-incubated with citrated samples (70 μl; 40% final concentration) for 30 minutes at room temperature and added to each well in triplicate (50 μl/well) at a concentration of 10,000 sporozoites/well. Sporozoites were allowed to glide for 90 minutes at 37°C, 98% humidity, 93% N₂, 4% CO₂ and 3% O₂. Wells were washed thrice with 100 μl/well PBS and gliding trails were fixed for 15 minutes at room temperature with 4% paraformaldehyde (Affymetrix). Following fixation, wells were washed thrice with 100 μl/well PBS and blocked with 150 μl/well 10% FBS/PBS for 20 minutes at room temperature. Subsequently, gliding trails were stained for 1 hour at room temperature with 50 μl/well 5 μg/ml biotinylated anti-CSP monoclonal antibody (anti-CSP 3SP2 antibodies were produced at Radboudumc, Nijmegen, the Netherlands), followed by a wash step (thrice with PBS) and a 1 hour incubation at room temperature with 50μl/well 10 μg/ml streptavidin-Alexa Fluor-594 (Life Technologies) diluted in 10% FBS in PBS. Subsequently, wells were washed thrice with 100 μl/well PBS and stored in 150 μl/well PBS at 4°C in the dark until analysis. Gliding trails were imaged automatically with the BioTek Cytation 8 cell imager (25 images per well at 200x magnification) and images were analysed automatically by FIJI software (under ImageJ version 2.0.0-rc-68/1.52h) with Otsu’s thresholding. Results were plotted in GraphPad Prism version 5.03. The number of pixels present on a stitched image made from 25 individual pictures taken per well is a measure of the amount of shed CSP in that particular well and therefore, differences in the number of pixels can be interpreted as differences in sporozoite gliding trail surface.

**In vitro** sporozoite infectivity assay of a human hepatoma cell line

Neutralization of *P. falciparum* sporozoite hepatocyte invasion by naturally acquired antibodies was assessed in a flow-cytometry-based *in vitro* invasion assay, as previously described. Flow cytometric analysis was performed with a Gallios (Beckman Coulter) flow cytometer and data were analysed with FlowJo software (version 10.0.8, Tree Star). The percentage of CSP-positive hepatocytes was first corrected for background reactivity by subtracting the background (uninfected HC-04 cells in the presence of 3SP2-Alexa Fluor-488 antibody). The percent invasion inhibition was expressed relative to control IgG.

**Statistical analysis**

For analysis of *in vitro* sporozoite data, comparisons between two (controls versus field samples) or multiple groups were performed using Mann-Whitney U-test and Kruskal-Wallis test followed by Dunn’s test between two groups, respectively. The associations between immune responses and malaria infection risk were assessed using survival analysis methods. Log-rank test was used to compare times to infection incidence for individuals with different values of immune phenotypes. Cox survival models were fit to assess the effect of pre-erythrocytic immunity after adjustment for blood-stage immunity; the proportional hazards assumption was tested using Schoenfeld residuals. In these analyses, study participants were considered to have high or low responses (binary explanatory variables) based on the study population median (see Figure S4 in Extended data). The first scheduled weekly visit or intensive follow-up visit when parasitaemia of at least 0.1 parasites per μl was detected by 18S qPCR was considered the time of infection incidence. This threshold of parasitaemia was chosen to minimize false-positive results. In the supplemental material, sensitivity analyses were included that used different cut-offs of 18S qPCR-based density to determine infection positivity. Stata 14 (StataCorp LP, Texas, USA) and GraphPad Prism software (version 5, GraphPad Software Inc., California, USA) were used for statistical analysis. P<0.05 was considered statistically significant.

**Data availability**

**Underlying data**

The main dataset relating to the field study contains individual level data and identifying information on participants; as such, this dataset is stored under restricted access and not available through an open-access repository. Requests from researchers to access these data for pooled or meta-analysis should be addressed to the corresponding author (teun.bousema@radboudumc.nl). However, the dataset used in the survival analysis has been de-identified and is available from the Dryad repository, along with raw ELISA results and sporozoite gliding data. DOI: https://dx.doi.org/10.5061/dryad.n1m33qq.

Data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication).

**Extended data**

The results of sensitivity analyses (see Results section) and Figures S1-4 are available from the Dryad repository.

**Figure S1.** Correlation analyses of naturally acquired sporozoite-specific IgG and IgM antibodies. (A) Scatter plot of sporozoite-specific IgG and IgM antibodies targeting *P. falciparum* NF54 sporozoites is shown (n=17). (B) Correlation analysis for *P. falciparum* NF54 sporozoite-specific and CSP-specific IgG antibodies as determined by ELISAs is shown.

**Figure S2.** Antibody specificity and *in vitro* gliding inhibition by naturally acquired antibodies. (A). Scatter plot of *in vitro* gliding inhibition and CSP-specific IgG antibodies as determined by ELISAs is shown (n=51). Samples selected for additional invasion experiments had either poor (orange) or strong (green) gliding inhibitory activity. Correlation analysis for sporozoite-specific (B) IgG or (C) IgM antibodies and *in vitro* gliding inhibition by naturally acquired antibodies was conducted with samples from 17 children. Recognition of *P. falciparum* NF54 sporozoites by sporozoite-specific (D) IgG and (E) IgM antibodies from naturally exposed children (n=17) or malaria-naïve adults (n=8) was shown as the geometric mean fluorescent intensity (MFI) and divided in subgroups: malaria-naïve adults (black), poor (orange) versus strong gliding inhibitors (green). Correlation analyses were conducted with Spearman correlation analysis. Comparisons between multiple groups were tested by Kruskal Wallist test.
Figure S3. Inhibition of in vitro sporozoite invasion of hepatocytes by antibodies from children in Burkina Faso. Gliding motility and invasion of *P. falciparum* NF54 sporozoites pre-treated with plasma from children from Burkina Faso and malaria-naïve adults was determined by in vitro gliding motility and invasion assays in human hepatoma cells. (A) Scatter plot of in vitro gliding and invasion inhibition by naturally acquired antibodies is shown. Additionally, correlation analyses of the percent invasion inhibition with whole sporozoite-specific (B) IgG, (C) IgM antibodies or (D) CSP-specific IgG antibodies is shown. Children whom had poor or strong neutralizing effect on sporozoite infectivity are shown in orange and green circles, respectively.

Figure S4. Distribution of immune phenotypes. The distributions of log$_{10}$-transformed antibody responses (x-axes) against CSP, LSA-1 and asexual blood stage lysate (AL) are presented in panels (A), (B) and (C). The y-axes in these panels represent the percentages of study population with various levels of responses. In (A) and (B), one and seven individuals had undetectable responses and, to be included in this figure, were assigned response values equivalent to half of the lower limit of detection. In (D), the results of gliding assays are presented: the left plot presents the distribution of log$_{10}$-transformed sporozoite gliding surface; the right plot shows gliding inhibition (y-axis) for each study participant (different bars; x-axis). The median gliding inhibition (59.6%) was used to define high and low inhibition in the survival analysis.

References


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