

RESEARCH

Open Access



# Background malaria incidence and parasitemia during the three-dose RTS,S/AS01 vaccination series do not reduce magnitude of antibody response nor efficacy against the first case of malaria

Griffin J Bell<sup>1\*</sup>, Stephaney Gyaase<sup>2</sup>, Varun Goel<sup>3</sup>, Bright Adu<sup>4</sup>, Benedicta Mensah<sup>4</sup>, Paulin Essone<sup>5</sup>, David Dosoo<sup>2</sup>, Musah Osei<sup>2</sup>, Karamoko Niare<sup>6</sup>, Kenneth Wiru<sup>2</sup>, Katerina Brandt<sup>3</sup>, Michael Emch<sup>1,3</sup>, Anita Ghansah<sup>4</sup>, Kwaku Poku Asante<sup>2</sup>, Tisungane Mvalo<sup>7,8</sup>, Selidji Todagbe Agnandji<sup>5,9</sup>, Jonathan J Juliano<sup>1,10†</sup> and Jeffrey A Bailey<sup>6†</sup>

## Abstract

**Background** RTS,S/AS01 has been recommended by WHO for widespread implementation in medium to high malaria transmission settings. Previous analyses have noted lower vaccine efficacies in higher transmission settings, possibly due to the more rapid development of naturally acquired immunity in the control group.

**Methods** To investigate a reduced immune response to vaccination as a potential mechanism behind lower efficacy in high transmission areas, we examine initial vaccine antibody (anti-CSP IgG) response and vaccine efficacy against the first case of malaria (to exclude the effect of naturally acquired immunity) using data from three study areas (Kintampo, Ghana; Lilongwe, Malawi; Lambaréné, Gabon) from the 2009–2014 phase III trial (NCT00866619). Our key exposures are parasitemia during the vaccination series and background malaria incidence. We calculate vaccine efficacy (one minus hazard ratio) using a cox-proportional hazards model and allowing for the time-varying effect of RTS,S/AS01.

**Results** We find that antibody responses to the primary three-dose vaccination series were higher in Ghana than in Malawi and Gabon, but that neither antibody levels nor vaccine efficacy against the first case of malaria varied by background incidence or parasitemia during the primary vaccination series.

**Conclusions** We find that vaccine efficacy is unrelated to infections during vaccination. Contributing to a conflicting literature, our results suggest that vaccine efficacy is also unrelated to infections before vaccination, meaning that control-group immunity is likely a major reason for lower efficacy in high transmission settings, not reduced immune

<sup>†</sup>Jonathan J Juliano and Jeffrey A Bailey Contributed Equally.

\*Correspondence:  
Griffin J Bell  
bell@unc.edu

Full list of author information is available at the end of the article



© The Author(s) 2023. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>. The Creative Commons Public Domain Dedication waiver (<http://creativecommons.org/publicdomain/zero/1.0/>) applies to the data made available in this article, unless otherwise stated in a credit line to the data.

responses to RTS,S/AS01. This may be reassuring for implementation in high transmission settings, though further studies are needed.

**Keywords** Vaccine, Africa, Geographic information system, GIS, Immunology, Delayed Malaria, Rebound Malaria

## Background

Malaria remains a public health challenge, with 241 million cases in 2020 despite the increasing implementation of control measures such as artemisinin combination therapies, insecticide-treated bed nets, and indoor residual spraying [1]. RTS,S/AS01, a vaccine recently recommended for widespread implementation by the World Health Organization (WHO), is a newly available tool to reduce this burden. RTS,S, administered with the adjuvant AS01, is a pre-erythrocytic vaccine targeting the circumsporozoite protein (CSP) of *Plasmodium falciparum*. Overall efficacy of the vaccine in phase III trials was modest, resulting in a 36.3% reduction in the incidence of clinical malaria over a median of 4 years in children aged 5–17 months across 11 sites in sub-Saharan Africa [2]. Efficacy varied between study areas, with areas of higher malaria transmission having lower vaccine efficacy, but with more cases averted [2]. Understanding the reasons for efficacy heterogeneity is critical for the implementation of the current vaccine and the development of the next generation of malaria vaccines.

Various theories attempt to explain the geospatial heterogeneity in RTS,S/AS01 vaccine efficacy [3]. “Delayed” malaria, combined with the development of immunity from natural infections over time in the control group, is one explanation [4, 5]. In the RTS,S/AS01 group, initial protection afforded by the vaccine wanes over time, essentially “delaying” malaria infections. In the control group, lack of initial protection results in malaria infection and the development of immunity at rates corresponding to background malaria transmission intensity. Since efficacy is a function of the ratio of incidences in the RTS,S/AS01 and control groups, greater naturally acquired immunity in the control group reduces RTS,S/AS01 efficacy, without necessarily changing the protection RTS,S/AS01 provides to vaccinated individuals. In higher transmission areas, more frequent natural infections result in faster development of protection in the control group over time. Since the protection afforded by RTS,S/AS01 wanes over time, it can even fall below the protection afforded to the control group during later periods of follow-up in high transmission areas (resulting in temporary negative vaccine efficacy, previously referred to as “rebound malaria”) [5, 6].

However, lower efficacies in higher transmission settings have elicited hypotheses that children in endemic regions experience immune modulation mediated through infections before or during vaccination (three doses over three months) resulting in lower immune

responses. Two analyses of phase II data and one of phase III data found support for this hypothesis [7–9]. Potential mechanisms can be drawn from results identifying that RTS,S/AS01 induced fewer functional antibodies in older children with greater malaria exposure and suggesting that malaria infection prior to vaccination could result in worse T helper cell responses to vaccination [7, 8, 10]. Further, *P. falciparum* can modulate the immune response upon infection, resulting in the depletion of T cells and altering the functional characteristics of B cells, potentially reducing the immune response to vaccination [11–14]. Infections with other pathogens (such as helminths) concurrently with vaccination can reduce the immune response and efficacy of other malaria vaccines, [15, 16] so it’s possible that concurrent malaria infection would have a similar effect [17]. Conversely, natural malaria infections expose children to a wider diversity of non-vaccine strains and antigens [18] resulting in broader antibody breadth that has been associated with protection against malaria [19, 20]. In support of this, studies have predicted and shown that malaria vaccines that add additional antigens outperform their fewer-antigen counterparts [21, 22].

Here, we evaluated the impact of malaria infections, before or during vaccination, on RTS,S/AS01 antibody response and efficacy. From three phase III trial sites in Gabon, Ghana, and Malawi, we obtained longitudinal malaria infection data and baseline and post-vaccination anti-circumsporozoite antibody levels. Further, we obtained parasitemia counts during the three-dose vaccine schedule. We used ecological data at the individual, household, and neighborhood levels to estimate the background malaria transmission intensity as a proxy for pre-vaccination infections.

It is vital that we understand the specific mechanisms through which malaria transmission intensity does, or does not, alter the impact of RTS,S/AS01. With this understanding, we can improve implementation and design interventions to supplement RTS,S/AS01 vaccination where necessary.

## Methods

### Study population and design

Study participants included in this analysis were children (5–17 months) enrolled in the 2009–2014 phase III trial of RTS,S/AS01 in Kintampo, Ghana; Lilongwe, Malawi; and Lambaréné, Gabon. The details of the parent study can be found elsewhere [2]. Briefly, this was a randomized, double-masked, controlled clinical trial, which was

stratified by age group (children 5–17 months and infants 6–12 weeks) and evaluated the efficacy of three- and four-dose regimens of RTS,S/AS01. In the three-dose regimen, RTS,S/AS01 was administered monthly, while the four-dose regimen added a booster dose around 18 months after the third dose. The primary outcome in the phase III trial was clinical malaria, defined as blood film microscopy measuring  $>5000$  parasites per microliter and a fever within the previous 24 h. Malaria surveillance was passive, except for 14, 16, and 18 months after the booster.

#### **Development of naturally acquired immunity in the control group**

The development of naturally acquired immunity in the control group was a cause of reduced vaccine efficacy in high-incidence areas in the phase III trial of RTS,S/AS01 [5, 6]. When calculating vaccine efficacy in this analysis, we include only the first post-vaccination case of clinical malaria, to exclude the impacts of the development of naturally acquired immunity in the control group.

#### **Primary exposures: background malaria incidence and parasitemia during the vaccination series**

Background malaria incidence was estimated using our previously described method [5] which predicts malaria incidence using household locations and ecologic modeling. Briefly, we partitioned the data for phase III trial infants (6–12 weeks) who received the control vaccine into training and test datasets to fit a random forest model to estimate the relationship between 28 ecological variables (also detailed elsewhere [5]) and malaria incidence. Using the model fit, we can predict the malaria incidence for individual children (5–17 months). Though the actual malaria incidence experienced by the children in the time period between birth and vaccination likely does not map perfectly to this prediction, we theorize that a high positive correlation between the two makes predicted background malaria incidence a good proxy.

Parasitemia during the vaccination series was measured directly by microscopy during passive surveillance in between the first and third dose of RTS,S: any individual which had a blood film microscopy with visible parasites ( $>0$  parasites per microliter) was considered to be infected.

#### **Anti-CSP antibody response**

Anti-CSP antibody (IgG against the NANP repeat region) levels, which were associated with protection at the time of the trial, were previously measured using standardized enzyme-linked immunosorbent assays (ELISA) on the day of the first dose and one month after the third dose of RTS,S/AS01 [23]. Antibody data were collected for the first ~200 enrolled children at each site. To determine

whether background malaria incidence influenced the anti-CSP antibody response to the RTS,S/AS01 vaccine, we fit a linear regression model with the outcome being either the natural log or untransformed antibody levels (whichever enabled the residuals to be approximately normally distributed, evaluated with a Quantile-Quantile plot, at the pre- and post- vaccine series timepoints). The covariates were vaccination status (RTS,S/AS01 or control) and the predicted malaria incidence, as well as an interaction term between the two covariates. We also adjusted for the child's age at the third dose; this age was set to the median when estimating from regression outputs. In case of any other differentiating study area characteristics besides background malaria incidence, we fit an additional model where we adjusted for study area and included an interaction term between study area and vaccine group. The functional form of the malaria background incidence covariate was assessed by comparing Akaike information criterion (AIC) values. To determine whether infections during vaccination influenced the anti-CSP antibody response, we fit a linear regression model with antibody levels as the outcome and parasitemia during the vaccination series (dichotomous: ever  $>0$  parasites per microliter) as the main exposure. Covariates and functional forms were treated in the same manner as the model for background malaria incidence.

#### **Efficacy and time to first malaria case**

To calculate the efficacy of RTS,S/AS01 against the first case of malaria depending on background malaria incidence and parasitemia during the vaccination series, we fit a Cox proportional hazards (CPH) model. The time period was bounded by the date of the third vaccine and the earliest date among the first case of malaria, loss to follow-up, receipt of the fourth dose of RTS,S/AS01, or study end. Those with non-malaria outcomes were considered to be censored. Main covariates included vaccination status (RTS,S/AS01 or control), predicted background malaria incidence, and whether parasitemia during the initial 3-dose vaccination series period was observed. Interaction terms between treatment and background incidence as well as treatment and parasitemia were included. We used repeated measures (six-month intervals) to allow for the effect of time on vaccine protection: an interaction term between time and treatment was included and we accounted for the repeated measures in standard error calculations. We also adjusted for the child's age at the third vaccination; this age was set to the median when estimating from model outputs. Efficacy was calculated as one minus the hazard ratio for vaccination. Functional forms of background incidence were assessed using AIC.

Finally, we fit an accelerated failure time (AFT) model to estimate the impact of vaccination on the time to the

first case of malaria. Censoring was conducted in the same manner as in the CPH model and we assumed the outcome followed a log-logistic distribution. Our covariates in the AFT model were the same as the CPH model. The functional form of background incidence was assessed using AIC.

### Sensitivity analysis

We conducted a sensitivity analysis detailed in the supplemental materials by replacing our predicted background incidence values with average transmission intensity values from the Malaria Atlas Project over 2009–2014 [24]. We repeated the relevant analysis with these values, including describing the relationship between transmission intensity and post-vaccination antibody response, as well as the CPH model.

## Results

### Study population

In total, 2,427 children were included in this analysis, 992 from Ghana, 771 from Malawi, and 664 from Gabon (Table 1). Children (5–17 months) were oldest at primary vaccine series completion in Ghana (median 461 days) and youngest in Gabon (385 days). The estimated background malaria incidence was highest in Ghana. Though

median background incidences were low in Malawi and Gabon, Malawi had more variation with a proportion of higher values. GPS coordinates were missing in 134 (20.2%) of the children from Gabon and thus we were unable to estimate their individual exposure (background malaria incidence value). Age at vaccination was missing in 31 total children (1.3%).

Parasitemia during the vaccination series occurred in 23.2% of children in Ghana compared to less than 5% in Malawi and Gabon. Of these infections, one was detected on the same day as the first dose, 185 were detected in between the first and second doses, 26 were detected on the same day as the second dose, and 120 were detected in between the second and third doses. Median parasitemia in these infections was 24,528 (IQR: 2,628–121,173) in Ghanaian children, compared to 15,377 (IQR: 1,803–82,062) in Malawian children and 6,706 (IQR: 1,400–40,682) in Gabonese children.

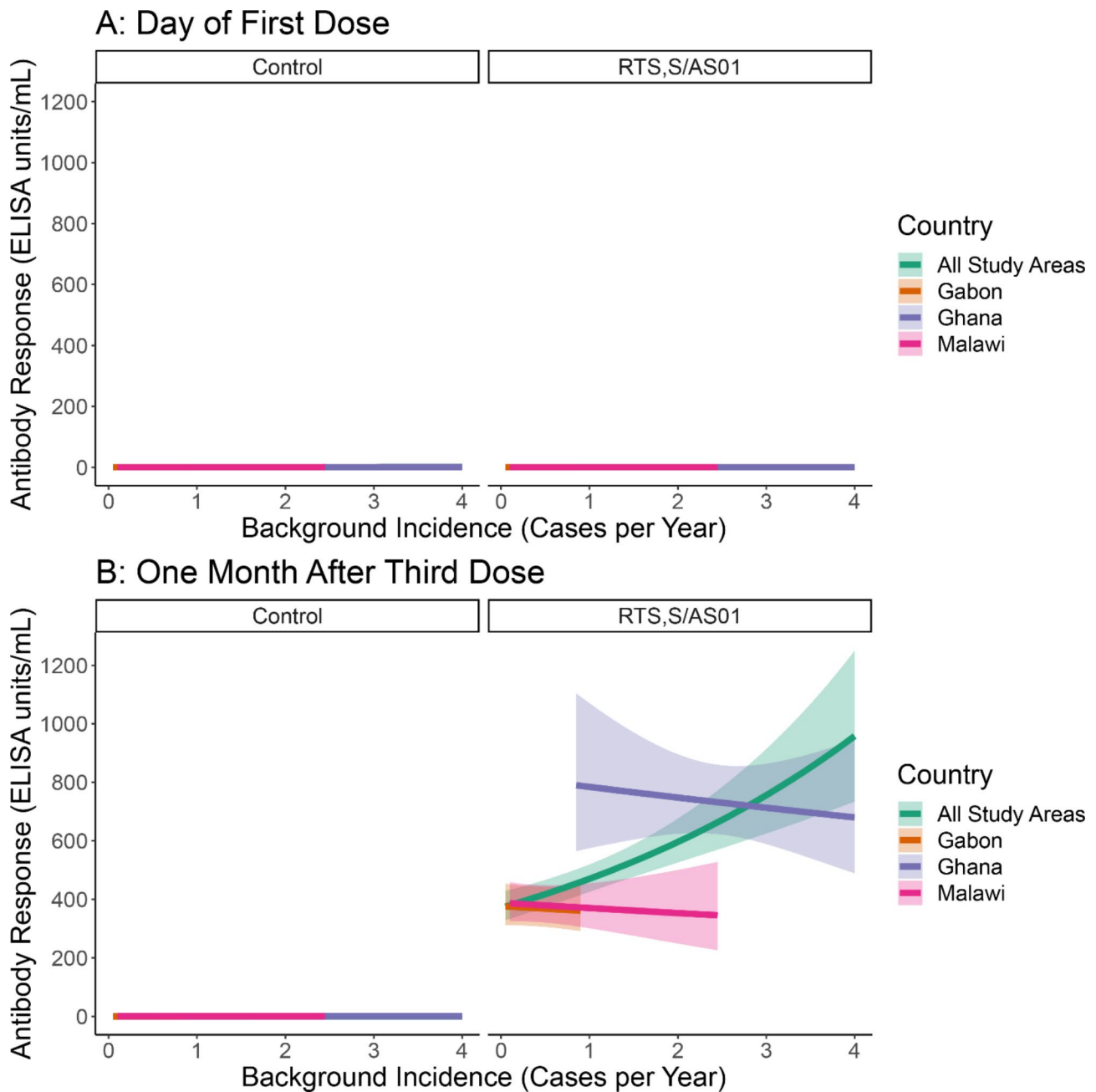
### Anti-CSP antibody response

Antibody data were available for 641 children (220 Ghana, 213 Malawi, 208 Gabon). On the day of vaccination with the first dose of RTS,S/AS01 or a control vaccine, participant anti-CSP levels were below 1.0 ELISA units/ml, regardless of background malaria incidence (Fig. 1A). One month after the third dose, those who received the control vaccine maintained low antibody levels, regardless of background malaria incidence, while those who received the three-dose RTS,S/AS01 vaccine series had greatly increased antibody levels (Fig. 1B). Among those who received RTS,S/AS01, antibody level was positively associated with background incidence: at 0.25 cases per person-year (CPPY), antibodies were estimated to be 393.8 ELISA units/ml and at 3 CPPY, antibodies were estimated to be at 755.8 ELISA units/ml. However, after study area stratification, we found no statistically significant relationship between background incidence and antibody response in the RTS,S/AS01 group ( $p=0.82$ ). Higher antibody responses and background incidences in Ghana were driving the positive correlation in the unstratified model (Fig. 1B, Supplemental Figs. 1 and 2). Controlling for background incidence, the antibody response to RTS,S/AS01 was higher in Ghana compared to the other sites. Older age at the third dose was negatively associated with antibody response before ( $p=0.02$ ) and after ( $p<0.01$ ) controlling for the study area. Our sensitivity analysis found a statistically significant positive relationship between malaria transmission intensity and 1-month post-vaccination antibody response ( $p=0.02$ ), which remained but became statistically insignificant after study area stratification ( $p=0.48$ ) (Supplemental Figs. 3 and 4).

Parasitemia during the vaccination series did not increase antibody levels in the control group one month

**Table 1** Characteristics of the Phase III Trial Children (5–17 months)

Variable	Categorical: N (%), Numerical: Median (IQR)		
	Ghana (N = 992)	Malawi (N = 771)	Gabon (N = 664)
Sex			
Female	483 (48.7%)	383 (49.7%)	307 (46.2%)
Male	509 (51.3%)	388 (50.3%)	357 (53.8%)
Age at Vaccination Series Completion (Days)			
Median (IQR)	461 (333.5, 539)	411.5 (316, 502.75)	385 (270.5, 495.5)
Min - Max	216–724	211–700	197–636
Missing	9	9	13
Vaccine Status			
RTS,S/AS01 (4 dose)	332 (33.5%)	253 (32.8%)	218 (32.8%)
RTS,S/AS01 (3 dose)	330 (33.3%)	263 (34.1%)	223 (33.6%)
Control	330 (33.3%)	255 (33.1%)	223 (33.6%)
Estimated Background Malaria Incidence (Cases per Person-Year)			
Median (IQR)	2.30 (1.69, 2.81)	0.24 (0.18, 0.32)	0.30 (0.15, 0.50)
Min - Max	0.85–4.45	0.08–2.47	0.04–0.92
Missing	4	1	134
Parasitemia during the Vaccination Series			
Yes	230 (23.2%)	37 (4.8%)	26 (3.9%)
No	762 (76.8%)	734 (95.2%)	638 (96.1%)

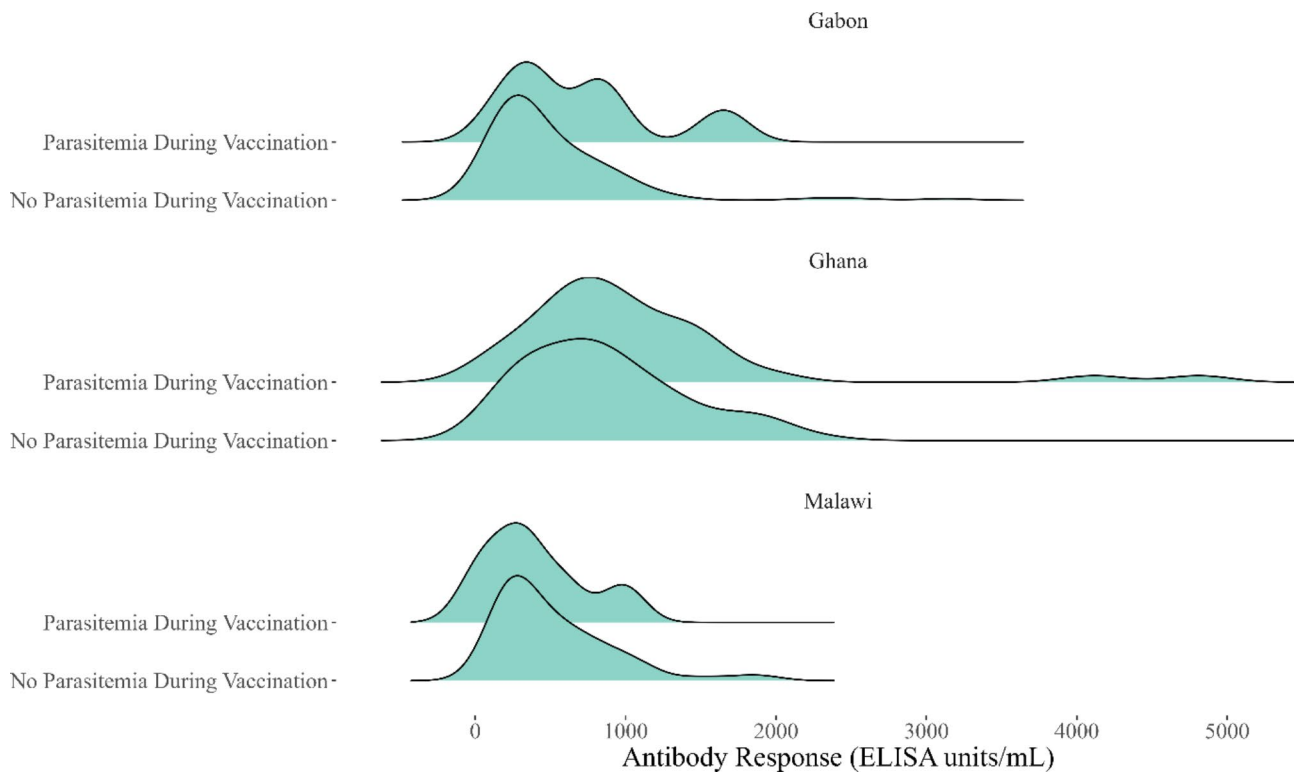


**Fig. 1** Anti-CSP Antibody Response by Background Incidence, All Study Areas and Study Area Adjusted (**A**: Pre-Vaccination, **B**: One Month Post-Vaccination) (**A**) Children have a very low anti-circumsporozoite protein (CSP) antibody response on the day of the first vaccine dose (**B**) One month after vaccination, children in higher incidence areas have higher antibody responses to RTS,S/AS01 vaccination. This positive relationship disappears when adjusting for study area. Antibody responses were elevated in Ghana, the highest incidence study area

after the third dose: levels were near zero regardless of parasitemia. Those without parasitemia during RTS,S/AS01 vaccination developed lower antibodies levels, though this observed difference could have reasonably been generated by chance ( $p=0.24$ ). This difference remained statistically insignificant after stratification by study area ( $p=0.68$ ) (Fig. 2).

**Efficacy and time to first malaria case**

In our CPH model, RTS,S/AS01 efficacy waned over time (Fig. 3). Evidence was weak that efficacy against the first case of malaria varied by background incidence or parasitemia during the three-dose vaccination series. Our sensitivity analysis found very similar results (Supplemental Fig. 5). Similar results were found using the AFT model, implying that the vaccine delayed the first case of malaria equally across background incidences, on the



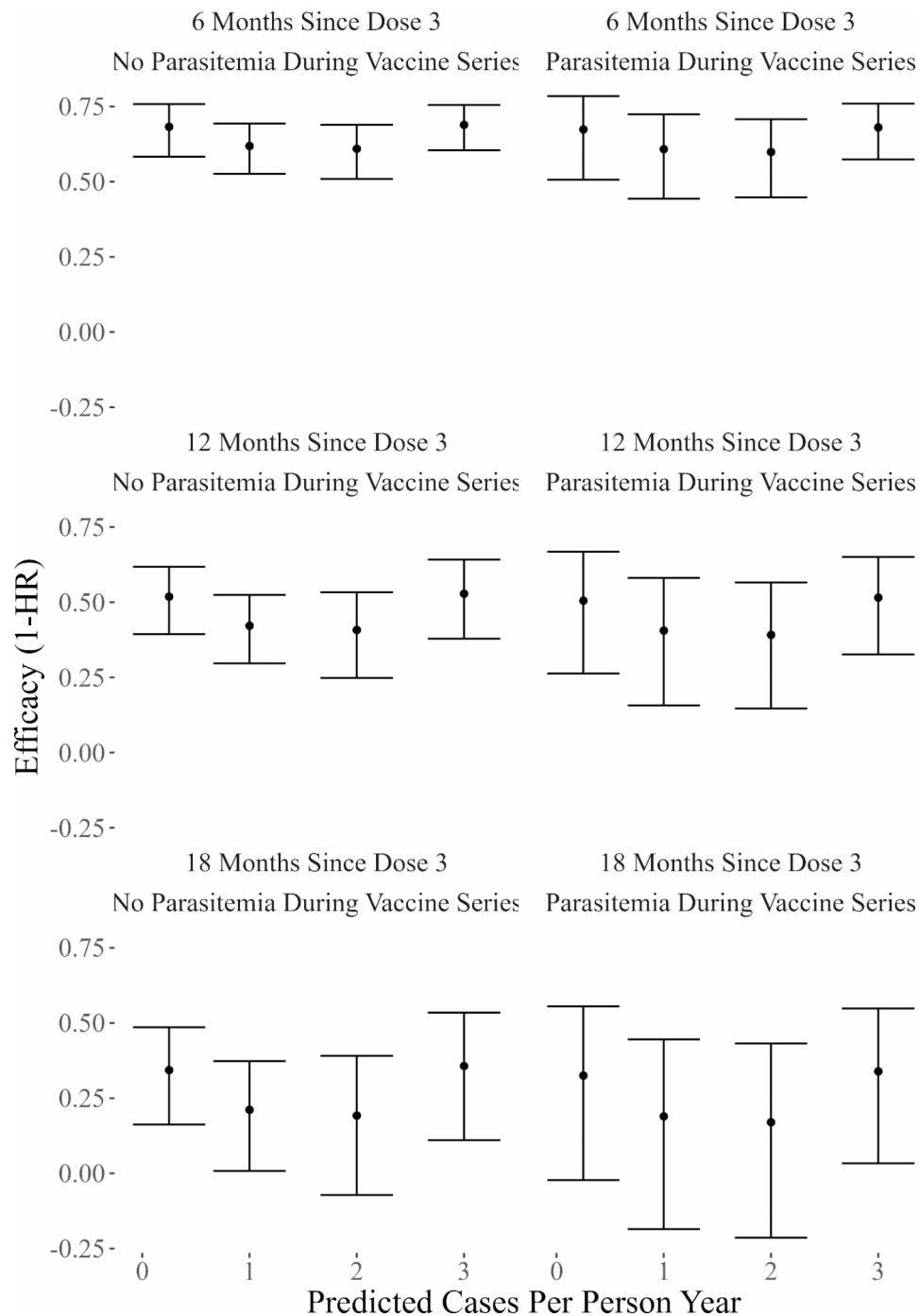
**Fig. 2** Density Plots of Anti-CSP Antibody Response (One Month Post-Vaccination) in the RTS,S/AS01 Group

ratio scale (Supplemental Fig. 6). Age did not impact vaccine efficacy in a statistically significant manner ( $p=0.47$ ) when an interaction term was considered, thus, the interaction term was not included. A breakdown by site for the CPH model can be viewed in Supplemental Fig. 7, however, no meaningful differences were observed.

## Discussion

Following the phase III trial of RTS,S/AS01, multiple hypotheses were formed to explain the lower efficacy in higher malaria transmission areas [3]. One such hypothesis was that infections before and during RTS,S/AS01 vaccination reduce vaccine efficacy due to a lower immune response to vaccination. Based on transmission intensity modeling at the household level, our findings challenge this hypothesis. We found that both antibody response and efficacy against the first case of malaria were practically unrelated to background malaria incidence and parasitemia during vaccination. Our sensitivity analysis found a statistically insignificant positive relationship between transmission intensity and antibody response, though it found no impact on vaccine efficacy against the first case of malaria. Antibody response was highest in Kintampo, Ghana, possibly for reasons other than transmission intensity, such as host differences [25]. The observation of higher antibody responses in higher incidence areas that disappears after study-site-stratification is an example of Simpson's paradox.

The existing literature is divided on whether infections before and during RTS,S/AS01 vaccination impact vaccine protection. One between-site study in Kintampo, Ghana and Manhica, Mozambique found that post-vaccination antibody levels were positively associated with previous clinical malaria episodes and pre-vaccination antibody levels [18]. An analysis of all phase III trial sites found that higher baseline anti-CSP antibody levels were associated with higher anti-CSP antibody levels post-vaccination in children (5–17 months) [23]. However, this effect was reversed in the infants (6–12 weeks), possibly related to the presence of maternal antibodies. Additionally, malaria exposure trains the immune system to hyper-respond to the stimulation of TLR2, potentially increasing anti-CSP antibody levels in higher transmission areas [26]. Higher anti-CSP antibody levels are correlated with increased RTS,S/AS01 vaccine efficacy in both high and low transmission settings [23, 27]. Other studies draw opposite conclusions. One between-site analysis found that RTS,S/AS01 efficacy was higher when malaria exposure before vaccination was lower, which the authors claimed was in line with the overall phase II and III trial findings that vaccine efficacy was lower in higher transmission sites [2, 9, 28]. However, the main trial result can be largely explained by the faster development of naturally acquired protection in the unvaccinated in higher incidence areas, not because of reduced protection from RTS,S/AS01 [4, 5]. The authors also correctly



**Fig. 3** Efficacy Against the First Case of Malaria Over Time, Background Incidence, and Cases During Vaccination

acknowledge a major limitation in their study, that the greatest predictor of future malaria infection is past malaria infection [9]. When the authors controlled for confounding by transmission intensity (using study area as a proxy), associations between prior clinical malaria episodes and antibody response were reduced or lost [9]. Finally, a phase IIb study in Mozambique which used biomarkers as a proxy for malaria exposure found that

complement-fixing antibodies were less readily induced in older (12–24 months) children with higher malaria exposure, though disentangling age and malaria exposure was difficult in this study [7].

Our analysis has multiple strengths. First, evidence for the natural acquisition of immunity being delayed in the vaccine compared to the control group (resulting in delayed malaria cases) being largely responsible

for lower efficacy in high transmission in areas is strong, [5, 6, 29, 30] and we intentionally filter out this effect by concentrating on antibody response to vaccination and the first malaria infection post-vaccination. Additionally, our vaccine efficacy calculations corroborate our vaccine antibody response results. Further, we used intrasite environmental data in order to model household-level malaria background incidence, improving upon studies that use study area as a proxy. This is especially important in sites with intrasite heterogeneity in transmission intensity. We also include a sensitivity analysis using more established transmission intensity estimates. This study also has limitations. First, we use background incidence as a proxy for infections before vaccination and this analysis would be improved if we had actual data on pre-vaccination infections. This is a problem throughout the existing literature: we could not find a study that directly measured pre-vaccination infections. Second, we rely on passive surveillance of malaria, so we may have missed some first cases or infections during vaccination, and our background incidence model (described elsewhere [5]) may underestimate background incidence in areas with lower healthcare access. Third, only one child had detected parasitemia on the date of first vaccination with RTS,S/AS01, and infection status on this date could be a key determinant of vaccine response. Fourth, we consider here only the quantity of the anti-CSP antibody response. Previous research has shown that RTS,S vaccine efficacy is related to qualitative differences such as antibody isotypes [31]. Thus, focusing only on the size of the IgG anti-CSP NANP response may omit important correlates of protection against malaria. Finally, other mechanisms not considered in this paper may also link transmission intensity to reduced vaccine efficacy, such as pathogen dose magnitude [32].

## Conclusions

Our results suggest that the lower RTS,S/AS01 efficacy in higher malaria transmission areas may be largely due to delayed malaria and the development of naturally acquired immunity in the control group, and not due to infections before or during vaccination which led to reduced immune responses. However, the literature remains divided over the influence of infections before vaccination on RTS,S/AS01 efficacy, with each published study (including ours) suffering from various important limitations. A future study that directly measures infections before vaccination is needed to elucidate the influence of such infections on RTS,S/AS01 efficacy. The roles of delayed malaria and the development of immunity in control group, however, have a strong evidence base in the current literature. During the widespread rollout of RTS,S/AS01, it may be sensible to concentrate our energy

on combating delayed malaria later in follow-up in order to maximize vaccine impact in high transmission areas.

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12879-023-08699-7>.

**Supplemental Figure 1:** Distribution of MTI values within and across study sites using a) our original predicted values b) *Plasmodium falciparum* incidence rate and c) *Plasmodium falciparum* infection prevalence among 2-10 year olds. **Supplemental Figure 2:** Anti-CSP Antibody Response by Study Area (1 Month Post-Vaccination). **Supplemental Figure 3:** Anti-CSP Antibody Response by Transmission Intensity, All Study Areas and Study Area Adjusted (A: 1 Month Pre-Vaccination, B: 1 Month Post-Vaccination) using *Plasmodium falciparum* incidence rate per person per year. **Supplemental Figure 4:** Anti-CSP Antibody Response by Transmission Intensity, All Study Areas and Study Area Adjusted (A: 1 Month Pre-Vaccination, B: 1 Month Post-Vaccination) using *Plasmodium falciparum* infection prevalence among 2-10 year olds. **Supplemental Figure 5:** Efficacy Against the First Case of Malaria Over Time, Transmission Intensity, and Cases During Vaccination using *Plasmodium falciparum* incidence rate. **Supplemental Figure 6:** Multiplier Effect of RTS,S/AS01 Vaccination on the Time to First Case of Malaria A higher multiplier implies a greater delay until the first case of malaria (e.g. a multiplier of 2 where the control group experiences their first case of malaria in 100 days will extend the time to the first case to 200 days). The null value is 1. **Supplemental Figure 7:** Efficacy Against the First Case of Malaria Over Time, Transmission Intensity, and Cases During Vaccination, Stratified by Study Area.

## Acknowledgements

Not applicable.

## Authors' contributions

GJB and VG wrote the manuscript text, conducted the analysis, and prepared the figures. GB, SG, BA, BM, and PE planned the analysis. JJJ and JAB supervised analysis. ME, AG, KPA, TM, and STA took mentorship roles and were involved in data collection. DD, MO, and KW were involved in data collection. All authors reviewed the manuscript.

## Funding

This research is supported by NIH grant 1R01AI137410-01.

## Notes

AS01 is a trademark owned by or licensed to the GSK group of companies.

## Data availability

Phase III trial data are available upon reasonable request from GlaxoSmithKline (GSK), and ecological data used to build the malaria transmission intensity model are publicly available. Contact the corresponding author for more information: bell@unc.edu.

## Declarations

### Ethics approval and consent to participate

This is a secondary analysis of phase III clinical trial data (NCT00866619). The trial protocol was approved by the ethical review board at each study center and partner institution and by the national regulatory authority in each country and the trial was undertaken in accordance with the provisions of the Good Clinical Practice Guidelines.

### Consent for publication

Not applicable.

### Competing interests

The authors declare no conflicts of interest. GlaxoSmithKline Biologicals SA was provided the opportunity to review a preliminary version of this manuscript for factual accuracy, but the authors are solely responsible for final content and interpretation.

**Author details**

<sup>1</sup>Department of Epidemiology, Gillings School of Global Public Health, University of North Carolina, Chapel Hill, NC 27599, USA

<sup>2</sup>Kintampo Health Research Centre, Kintampo, Ghana

<sup>3</sup>Carolina Population Center, University of North Carolina, Chapel Hill, NC 27599, USA

<sup>4</sup>Noguchi Memorial Institute for Medical Research, University of Ghana, Legon, Ghana

<sup>5</sup>Centre de Recherches Médicales de Lambaréné, Lambaréné, Gabon

<sup>6</sup>Department of Pathology and Laboratory Medicine, Brown University, Providence, RI 02912, USA

<sup>7</sup>University of North Carolina Project, Lilongwe, Malawi

<sup>8</sup>Department of Pediatrics, School of Medicine, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA

<sup>9</sup>Institute of Tropical Medicine, University of Tübingen, Tübingen, Germany

<sup>10</sup>Division of Infectious Diseases, School of Medicine, University of North Carolina, Chapel Hill, NC 27599, USA

Received: 30 May 2023 / Accepted: 11 October 2023

Published online: 23 October 2023

**References**

- Organization WH. Others. World malaria report 2021. 2021; Available from: <https://apps.who.int/iris/bitstream/handle/10665/350147/9789240040496-eng.pdf?sequence=1>.
- Efficacy and safety of RTS, S/AS01 malaria vaccine with or without a booster dose in infants and children in Africa: final results of a phase 3, individually randomised, controlled trial. *Lancet*. 2015;386(9988):31–45.
- Bell GJ, Agnandji ST, Asante KP, Ghansah A, Kamthunzi P, Emch M et al. Impacts of Ecology, Parasite Antigenic Variation, and Human Genetics on RTS,S/AS01e Malaria Vaccine Efficacy. *Current Epidemiology Reports* [Internet]. 2021; <https://doi.org/10.1007/s40471-021-00271-8>.
- Greenwood B, Zongo I, Dicko A, Chandramohan D, Snow RW, Ockenhouse C. Resurgent and delayed Malaria. *Malar J*. 2022;21(1):77.
- Bell GJ, Goel V, Essone P, Dosoo D, Adu B, Mensah BA et al. Malaria Transmission Intensity Likely Modifies RTS, S/AS01 Efficacy Due to a Rebound Effect in Ghana, Malawi, and Gabon. *J Infect Dis* [Internet]. 2022; <https://doi.org/10.1093/infdis/jiac322>.
- Tinto H, Otieno W, Gesase S, Sorgho H, Otieno L, Liheluka E, et al. Long-term incidence of severe Malaria following RTS,S/AS01 vaccination in children and infants in Africa: an open-label 3-year extension study of a phase 3 randomised controlled trial. *Lancet Infect Dis*. 2019;19(8):821–32.
- Kurtovic L, Agius PA, Feng G, Drew DR, Ubbillos I, Sacarlal J, et al. Induction and decay of functional complement-fixing antibodies by the RTS,S Malaria vaccine in children, and a negative impact of Malaria exposure. *BMC Med*. 2019;17(1):45.
- Feng G, Kurtovic L, Agius PA, Aitken EH, Sacarlal J, Wines BD, et al. Induction, decay, and determinants of functional antibodies following vaccination with the RTS,S Malaria vaccine in young children. *BMC Med*. 2022;20(1):289.
- Ubbillos I, Ayestaran A, Nhabomba AJ, Dosoo D, Vidal M, Jiménez A, et al. Baseline exposure, antibody subclass, and Hepatitis B response differentially affect Malaria protective immunity following RTS,S/AS01E vaccination in African children. *BMC Med*. 2018;16(1):197.
- Moncunill G, Mpina M, Nhabomba AJ, Aguilar R, Ayestaran A, Sanz H, et al. Distinct helper T cell type 1 and 2 responses Associated with Malaria Protection and Risk in RTS,S/AS01E vaccinees. *Clin Infect Dis*. 2017;65(5):746–55.
- Wykes MN, Horne-Debets JM, Leow C-Y, Karunarathne DS. Malaria drives T cells to exhaustion. *Front Microbiol*. 2014;5:249.
- Fu Y, Ding Y, Wang Q, Zhu F, Tan Y, Lu X, et al. Blood-stage Malaria parasites manipulate host innate immune responses through the induction of sFGL2. *Sci Adv*. 2020;6(9):eay9269.
- Horne-Debets JM, Faleiro R, Karunarathne DS, Liu XQ, Lineburg KE, Poh CM, et al. PD-1 dependent exhaustion of CD8 + T cells drives chronic Malaria. *Cell Rep*. 2013;5(5):1204–13.
- Illingworth J, Butler NS, Roetynck S, Mwacharo J, Pierce SK, Bejon P, et al. Chronic exposure to Plasmodium Falciparum is associated with phenotypic evidence of B and T cell exhaustion. *J Immunol*. 2013;190(3):1038–47.
- Nouatin O, Mengue JB, Dejon-Agobé JC, Fendel R, Ibáñez J, Ngoa UA, et al. Exploratory analysis of the effect of helminth Infection on the immunogenicity and efficacy of the asexual blood-stage Malaria vaccine candidate GMZ2. *PLoS Negl Trop Dis*. 2021;15(6):e0009361.
- Su Z, Segura M, Stevenson MM. Reduced protective efficacy of a blood-stage Malaria vaccine by concurrent nematode Infection. *Infect Immun*. 2006;74(4):2138–44.
- Cunnington AJ, Riley EM. Suppression of vaccine responses by Malaria: insignificant or overlooked? *Expert Rev Vaccines*. 2010;9(4):409–29.
- Dobaño C, Ubbillos I, Jairoce C, Gyan B, Vidal M, Jiménez A, et al. RTS,S/AS01E immunization increases antibody responses to vaccine-unrelated Plasmodium falciparum antigens associated with protection against clinical Malaria in African children: a case-control study. *BMC Med*. 2019;17(1):157.
- Rono J, Osier FHA, Olsson D, Montgomery S, Mhoja L, Rooth I, et al. Breadth of anti-merozoite antibody responses is associated with the genetic diversity of asymptomatic Plasmodium falciparum Infections and protection against clinical Malaria. *Clin Infect Dis*. 2013;57(10):1409–16.
- Chaudhury S, MacGill RS, Early AM, Bolton JS, King CR, Locke E, et al. Breadth of humoral immune responses to the C-terminus of the circumsporozoite protein is associated with protective efficacy induced by the RTS,S Malaria vaccine. *Vaccine*. 2021;39(6):968–75.
- Sklar MJ, Maiolatesi S, Patterson N, Sedegah M, Limbach K, Teneza-Mora N, et al. A three-antigen Plasmodium Falciparum DNA prime-adenovirus boost Malaria vaccine regimen is superior to a two-antigen regimen and protects against controlled human Malaria Infection in healthy malaria-naïve adults. *PLoS ONE*. 2021;16(9):e0256980.
- Bustamante LY, Powell GT, Lin Y-C, Macklin MD, Cross N, Kemp A, et al. Synergistic Malaria vaccine combinations identified by systematic antigen screening. *Proc Natl Acad Sci U S A*. 2017;114(45):12045–50.
- White MT, Verity R, Griffin JT, Asante KP, Owusu-Agyei S, Greenwood B, et al. Immunogenicity of the RTS,S/AS01 Malaria vaccine and implications for duration of vaccine efficacy: secondary analysis of data from a phase 3 randomised controlled trial. *Lancet Infect Dis*. 2015;15(12):1450–8.
- Hay SI, Snow RW. The Malaria Atlas Project: developing global maps of Malaria risk. *PLoS Med*. 2006;3(12):e473.
- Nielsen CM, Vekemans J, Lievens M, Kester KE, Regules JA, Ockenhouse CF. RTS,S Malaria vaccine efficacy and immunogenicity during Plasmodium falciparum challenge is associated with HLA genotype. *Vaccine*. 2018;36(12):1637–42.
- Schrum JE, Crabtree JN, Dobbs KR, Kiritsy MC, Reed GW, Gazzinelli RT, et al. Cutting Edge: Plasmodium Falciparum induces trained innate immunity. *J Immunol*. 2018;200(4):1243–8.
- White MT, Bejon P, Olotu A, Griffin JT, Riley EM, Kester KE, et al. The relationship between RTS,S Vaccine-Induced antibodies, CD4 + T cell responses and Protection against Plasmodium falciparum Infection. *PLoS ONE*. 2013;8(4):e61395.
- Bejon P, White MT, Olotu A, Bojang K, Lusingu JPA, Salim N, et al. Efficacy of RTS,S Malaria vaccines: individual-participant pooled analysis of phase 2 data. *Lancet Infect Dis*. 2013;13(4):319–27.
- Olotu A, Fegan G, Wambua J, Nyangweso G, Leach A, Lievens M, et al. Seven-year efficacy of RTS,S/AS01 Malaria vaccine among young African children. *N Engl J Med*. 2016;374(26):2519–29.
- Olotu A, Fegan G, Wambua J, Nyangweso G, Awuondo KO, Leach A, et al. Four-year efficacy of RTS, S/AS01E and its interaction with Malaria exposure. *N Engl J Med*. 2013;368(12):1111–20.
- Dobaño C, Sanz H, Sorgho H, Dosoo D, Mpina M, Ubbillos I, et al. Concentration and avidity of antibodies to different circumsporozoite epitopes correlate with RTS, S/AS01E Malaria vaccine efficacy. *Nat Commun*. 2019;10(1):1–13.
- Langwig KE, Gomes MGM, Clark MD, Kwitny M, Yamada S, Wargo AR, et al. Limited available evidence supports theoretical predictions of reduced vaccine efficacy at higher exposure dose. *Sci Rep*. 2019;9(1):3203.

**Publisher's Note**

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.