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Attractive targeted sugar baits for malaria control in western Kenya (ATSB-Kenya): enrolment characteristics of cohort children and households

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Abstract

Background In western Kenya, a cluster-randomized trial is assessing the impact of attractive targeted sugar baits (ATSBs) on malaria in children enrolled in three consecutive cohorts. Here, characteristics of children and households at enrolment, and factors associated with baseline malaria prevalence are described.

Methods Children aged 1 to < 15 years were randomly selected by cluster (n = 70) from a census database. Cohorts were enrolled in March–April 2022, September–October 2022, and March–April 2023. ATSBs were deployed in March 2022. At enrolment, all participants were tested for malaria by rapid diagnostic test (RDT). After enrolment a household survey was conducted. Household structures were classified as 'improved' (finished walls and roofs, and closed eaves) or 'traditional' (all other construction). A generalized linear mixed model was used to assess factors associated with malaria prevalence.

Results Of 3705 children screened, 220 declined and 523 were excluded, due to plans to leave the study area (n = 392), ineligible age (n = 64) or other reason (n = 67). Overall, 2962 children were enrolled. Bed net use the previous night was more common in children aged 1–4 years (746/777 [96%]) than those aged 5–<15 years (1806/2157 [84%], p < 0.001). Of the 2644 households surveyed (for 2,886 participants), information on house construction was available for 2595. Of these, only 199 (8%) were categorized as 'improved', as most houses had open eaves. While 99% of households owned at least one bed net, only 51% were adequately covered (one net per two household residents). Among 999 children enrolled in the first cohort (baseline), 498 (50%) tested positive by RDT. In an adjusted multivariable analysis, factors associated with RDT positivity included sub-county (Alego-Usonga vs Rarieda, adjusted odds ratio [aOR] 4.81; 95% CI: 2.74–8.45; p < 0.001), house construction (traditional vs improved, aOR 2.80; 95% CI: 1.59–4.95; p < 0.001), and age (5–< 15 vs 1–4 years, aOR 1.64; 95% CI: 1.13–2.37; p = 0.009).

Conclusions In western Kenya, the burden of malaria in children remains high. Most households owned a bed net, but coverage was inadequate. Residents of Alego-Usonga sub-county, those living in traditionally constructed

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households, and older children were more likely to test positive by RDT. Additional tools are needed to effectively control malaria in this area.

Trial registration The ATSB trial is registered under Clinicaltrials.gov NCT05219565

Keywords Attractive targeted sugar baits, Pyrethroid-only long-lasting insecticidal net (LLIN), Malaria parasite prevalence, Western Kenya, Malaria control

Background

In Kenya, substantial progress on malaria control has been achieved over the last 20 years, but malaria continues to be a major public health problem [1]. The epidemiology of malaria in Kenya is heterogeneous, varying widely by geographic region [2]. In western Kenya, the burden of malaria remains high despite distribution of pyrethroid-only long-lasting insecticidal nets (LLINs), targeted indoor residual spraying (IRS), improved malaria case management, and recent introduction of the RTS,S/AS01 malaria vaccine. Widespread resistance to pyrethroid insecticides, inadequate LLIN coverage, changes in vector species composition and behaviours, and increased outdoor biting all challenge the effectiveness of vector control efforts [3–6].

Anopheles gambiae sensu stricto (*s.s.*), *Anopheles arabiensis,* and *Anopheles funestus* are the primary malaria vectors in Kenya, each with their own unique characteristics [7]. *Anopheles gambiae s.s.* and *An. funestus* are both strongly anthropophilic, preferring to feed on humans and rest indoors, while *An. arabiensis* is more versatile with opportunistic feeding habits [8, 9]. Following the scale-up of LLINs and targeted IRS in Kenya, shifts in species composition and behaviours have been observed, with an increase in the relative abundance of *An. arabiensis* driving outdoor biting [4]. More recently, *An. funestus* demonstrating early and late morning biting has emerged as the predominant vector in the counties bordering Lake Victoria in western Kenya [7, 10]. The evolving composition of malaria vectors and shift in peak biting times toward periods when people are less likely to be protected by LLINs pose serious threats to malaria control.

Attractive Targeted Sugar Baits (ATSBs), a novel tool to attract and kill mosquitoes outdoors, have been developed to address these challenges [11]. ATSBs are A4-sized panels containing fruit syrup laced with an insecticide, and are hung in pairs on the outside walls of household structures. ATSBs have the potential to complement bed nets, addressing the gap in vector control interventions. Preliminary entomological field trials and modelling studies suggest that ATSBs can reduce mosquito populations significantly across various transmission intensities, offering a means to further reduce malaria transmission in areas where bed nets and/or IRS have been deployed [12–15]. To further evaluate the epidemiological impact of ATSBs, open-label, cluster-randomized controlled trials have been conducted in Kenya, Mali, and Zambia [16]. In Siaya county, western Kenya, three consecutive cohorts of children aged 1 to < 15 years were enrolled and followed for over two years to assess the impact of ATSBs on malaria. Here, a comprehensive profile of these cohorts and an analysis of factors associated with prevalence of malaria infection in the first cohort of children, enrolled at baseline, are presented. Although Siaya county is a well-researched area, detailed presentation of the enrolment characteristics of study participants and their households provides essential context for understanding subsequent analyses.

Methods

Study setting

The multi-country study protocol for the ATSB trials has been published previously [16]. In western Kenya, the trial is being conducted in Alego-Usonga and Rarieda sub-counties in Siaya County near Lake Victoria (Fig. 1). This region represents a typical rural, equatorial African setting. Rainfall peaks occur twice a year, with the heaviest 'long' rains typically occurring from March to May and 'short' rains falling between October and December. The average temperature in the area ranges between 17 °C and 35 °C and the mean altitude is approximately 1070 m above sea level.

The area is culturally homogeneous with over 95% of the population identifying with the Luo ethnic group. Settlements are dispersed and houses are constructed using mud, cement, or brick, with typically iron sheet or thatch roofs. Clusters of houses form compounds, which include dwellings for the male head of household, his wife (or wives), and sons. These compounds are often located near the households' agricultural fields. Small-scale businesses, subsistence farming and fishing are the primary economic activities for the local community [17].

Malaria is endemic in this region and transmission occurs throughout the year [1, 18]. Standard malaria control measures in the study area include LLINs, treatment with artemisinin-based combination therapy, and intermittent preventive treatment for pregnant women (IPTp). In September 2019, the Kenyan Ministry of Health piloted the introduction of the RTS,S/AS01

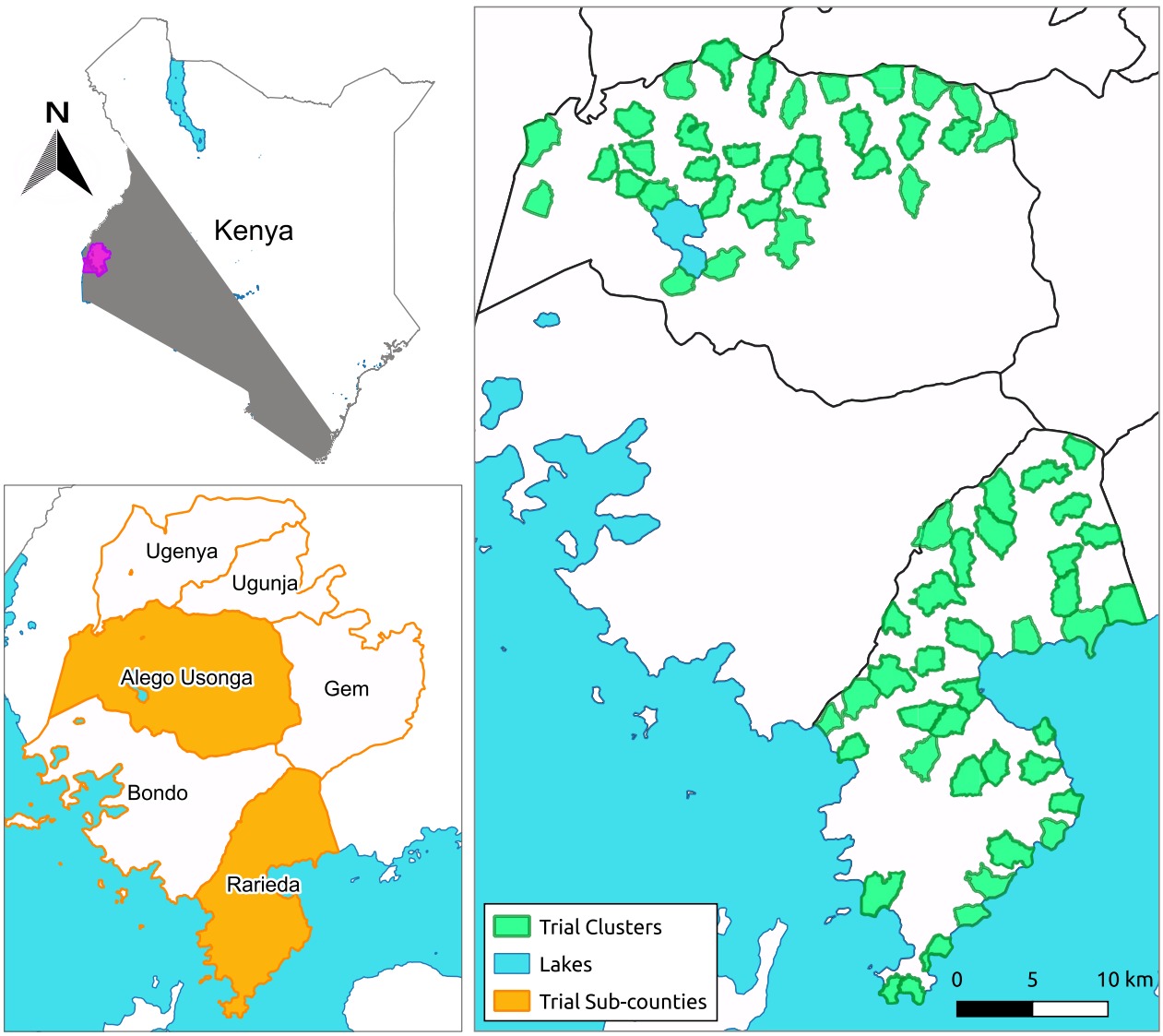

Fig. 1 Map of the study area

vaccine, targeting children aged 5–17 months. Rarieda sub-county was selected as one of initial vaccinating sub-counties, but Alego-Usonga was not included.

Baseline census and clusters

A health and demographic surveillance system (HDSS) has been established in Alego-Usonga and part of Rarieda sub-county (Asembo) [17]. To generate the sampling frame for the cohort study, a baseline census and enumeration of households in Alego-Usonga and Rarieda sub-counties was conducted from December 2020 to March 2021, and was updated in January 2022. All household structures were mapped using a global positioning system (GPS). Using data from the baseline census, 70 clusters were selected for the main trial. Each cluster consists of 1 to 3 contiguous villages, aiming for an optimal size of 100–400 households per cluster.

Main trial cohort recruitment

Three consecutive cohorts were recruited and enrolled in March–April 2022, September–October 2022, and March–April 2023, aiming to ensure high retention of cohort participants and to minimize the risk of loss-to-follow-up. A list of randomly selected children aged 1 to < 15 years was generated from the baseline census list for each cluster to guide recruitment for the three cohorts. A new recruitment list was generated for each of the three cohorts. All children on the recruitment

list were approached by the study team and invited for a screening appointment at a study clinic. Children were included if they met the following selection criteria: (1) age 1 to < 15 years; (2) resident of the household (over the previous four months, and intending to stay for an additional 6–12 months); (3) provision of written informed consent by their parent or guardian; (4) provision of assent by children aged 13–14 years; (5) no evidence of pregnancy; (6) not taking cotrimoxazole prophylaxis; (7) no known sickle cell disease; (8) no contraindication to artemether-lumefantrine; and (9) not currently enrolled in another interventional study or previously enrolled in the ATSB cohort study.

Cohort enrolment procedures

At enrolment, detailed information was gathered on demographics, clinical history, and LLIN ownership and use. Participants were questioned about history of fever within the past 48 h and axillary temperature was measured. A fingerpick blood sample was collected to perform the dual antigen First Response® Combo Malaria Ag (pLDH/HRP2) rapid diagnostic test (RDT) for malaria and dried blood spot collected for future molecular analyses. A presumptive treatment course of artemether-lumefantrine was given to all participants, irrespective of their RDT results, to clear any potential malaria infections. For participants aged < 5 years, information on RTS,S/AS01 vaccination was obtained from the maternal child health booklet. If the booklet was not available, the parent/guardian was asked to provide history of RTS,S/AS01 vaccination, including the number of doses. Information on ownership and use of bed nets was also gathered including whether the child slept under a net the previous night and if so, what time they went to bed (entering the net) and awoke (exiting the net). After enrolment, a household survey questionnaire was administered at the home of cohort participants by study staff. Heads of household, or their designee, provided information on household characteristics, residents, and bed net ownership and use.

Statistical analysis

A straight-line distance to the study clinic from the household was estimated between the centroid of the compound and the study clinic coordinates. A previously established definition was used to categorize household construction [19, 20]. Houses were classified as 'improved' if they had closed eaves, were constructed with synthetic wall materials (including lime, bricks, cement blocks, stone, iron sheets, wood planks, or shingles) and synthetic roof materials (made of iron sheet, cement, or concrete slabs). All other houses, typically with thatched roofs, mud walls, and open eaves, were classified as 'traditional. To estimate household socioeconomic status, principal component analysis (PCA) was used. Variables considered in the analysis included main source of income, source of drinking water, type of toilet, main fuel used, floor, wall, and roof materials, and ownership of key items. The households were ranked by wealth scores obtained from the PCA analysis and were grouped into tertiles to give a categorical measure of socioeconomic position as least poor, poor, and poorest.

ATSBs were first deployed in March 2022. The analysis of factors associated with baseline malaria prevalence, as measured by RDT at enrolment, was restricted to children enrolled into the first cohort. Children enrolled into cohorts #2 and #3, after the deployment of ATSBs, were excluded from this analysis. A generalized linear mixed model (GLMM) was used for the factor analysis. Malaria prevalence as measured by RDT was assumed to follow a Binomial distribution with a random effect to account for the intra-class correlation. Uncertainty was reported as 95% confidence intervals (CI). The likelihood ratio test was used to determine the statistical support for the inclusion of a term in the model. The model with the lowest Akaike information criterion was considered as the most optimal. Factors considered included region, adequate bed net coverage (one net per two household residents), socioeconomic status, house construction, and age and gender of the cohort participant. Data analysis was conducted in R statistical software version 4.3.1 using the 'stats' package for the PCA and 'lme4' package for the GLMM.

Results

Cohort recruitment

Between December 2020 and March 2021, 304,708 residents (125,908 in Alego-Usonga; 178,800 in Rarieda) residing in 192,979 households were enumerated in the baseline census. Of the 4509 children on the recruitment lists for the three trial cohorts, 804 children were unable to be contacted, and 3705 (82%) were screened (Table 1). Of those screened, 220 declined to participate and 523 were excluded, due to plans to leave the study area (n = 392), ineligible age (n = 64) or other reason (n = 67). Considering the populations of children enrolled vs those excluded, there was no significant difference in gender (p = 0.14). However, children who were enrolled were slightly older (median age 8.5 years, interquartile range [IQR]: 4.8, 11.8), than those who were excluded (median age 8.0 years, IQR: 4.0, 12.0; p < 0.001).

Description of cohort participants

In total, 2962 children aged 1 to < 15 years were enrolled in the trial cohorts (Table 2); 1000 in cohort #1, 969 in cohort #2, and 993 in cohort #3. Of these participants,

Table 1 Cohort study enrolment

	Trial cohort overall	Trial cohort 1	Trial cohort 2	Trial cohort 3
Children on recruitment list (N)	4509	1779	1330	1400
Children not contacted	804 (17.8%)	440 (24.7%)	161 (12.1%)	203 (14.5%)
Children screened	3705 (82.2%)	1339 (75.3%)	1169 (87.9%)	1197 (85.5%)
Declined to participate	220 (5.9%)	106 (7.9%)	70 (6.0%)	44 (3.7%)
Reasons declined				
Not interested in the study	102 (46.4%)	45 (42.5%)	42 (60.0%)	15 (34.1%)
No reason stated	103 (46.8%)	54 (50.9%)	24 (34.3%)	25 (56.8%)
Not comfortable with sample collection (blood draws)	6 (2.7%)	4 (3.8%)	1 (1.4%)	1 (2.3%)
Other*	9 (4.1%)	3 (2.8%)	3 (4.3%)	3 (6.8%)
Children excluded	523 (14.1%)	233 (17.4%)	130 (11.1%)	160 (13.4%)
Reasons for exclusion				
No intention to stay in household for the study period	392 (75.0%)	164 (70.4%)	94 (72.3%)	134 (83.8%)
Not of appropriate age (≥ 1y & < 15y at enrolment)	64 (12.2%)	30 (12.9%)	18 (13.8%)	16 (10.0%)
Enrolled in prior ATSB cohort	21 (4.0%)	16 (6.9%)	5 (3.8%)	0 (0.0%)
Confirmed or suspected pregnancy	0	0	0	0
Taking daily cotrimoxazole prophylaxis	33 (6.3%)	14 (6.0%)	10 (7.7%)	9 (5.6%)
Known sickle cell disease	8 (1.5%)	4 (1.7%)	3 (2.3%)	1 (0.6%)
Contraindication to AL	0	0	0	0
Currently enrolled in another interventional study	5 (1.0%)	5 (2.1%)	0 (0.0%)	0 (0.0%)

* *Other reasons: child has previous burn injury (n = 1), twins, declined unless both could participate (n = 1), parent unable to consent (n = 1), child has liver disease, parents uncomfortable (n = 1), child bereaved due to loss of parent (n = 1), child only available on weekends (n = 1), child in grade 8 (n = 2), child in high school (n = 1)*

1411 (48%) were female. Overall, the characteristics of participants enrolled in the three trial cohorts were similar. The median distance from the participant's home to the cohort study clinic was 3.9 km (IQR: 2.3, 5.1). Most eligible children aged 4 years or older were enrolled in school, with only 57 reporting that they had never attended school. Over half of children had completed pre-primary (16%) or primary school (52%), while only 10% had attended secondary school. Nearly all cohort participants were related to the head of household, either as a first-degree (80%) or a second- or third-degree relative (18%); only 43 children were not related to their head of household (Table 2).

Bed net use and sleeping behaviour

Most participants reported sleeping under a bed net the previous night, but net use was higher in children aged 1–4 years (96%) than in older children (84%; $p < 0.001$) (Table 2). Among participants who reported sleeping under a net the previous night, differences in sleeping patterns were observed between younger and older children, with older children aged 5 to < 15 years less likely to sleep under a net in the evening (before 9:00 pm) and early morning hours (3:00 to 6:00 am) than children aged 1–4 years (Fig. 2). Significantly more school-aged children rose before dawn, with 17% (302/1,771) of children aged 5 to < 15 years waking and exiting their nets between 3:00 and 6:00am, compared to only 3% (25/732) of younger children ($p < 0.001$).

RTS,S/AS01 vaccine coverage

During the study period, the RTS,S/AS01 malaria vaccine was administered in Rarieda sub-county, targeting children aged 5–17 months. Of the 461 eligible children under 5 years of age living in Rarieda, vaccination information was available for 436; 5 had missing data on vaccination and 20 missed their first routine visit when vaccination information was collected. Only 126 (29%) had a vaccination card available, and 260 (60%) had received at least one dose of the vaccine. However, only 38 (15%) children were reported to have received all four doses of the vaccine (Table 2). Many caregivers were uncertain about the total number of doses received (n = 125), either because vaccination cards were unavailable during follow-up (n = 108) or lacked the necessary information (n = 17).

Household demographics

A total of 2644 households were surveyed for 2886 (97%) of enrolled cohort participants. More households were located in Rarieda sub-county than in Alego-Usonga (Table 3). Few households were classified as having 'improved' construction (8%), primarily because most houses had open eaves. The median household size was

Table 2 Clinical characteristics of cohort participants at enrolment

Characteristic	Trial cohort overall N = 2962	Trial cohort 1 N = 1000	Trial cohort 2 N = 969	Trial cohort 3 N = 993
Participant gender				
Female	1411 (48%)	491 (49%)	468 (48%)	452 (46%)
Age (years), median (IQR)	8.5 (4.8, 11.8)	8.6 (5.3, 12.0)	8.3 (4.4, 11.8)	8.5 (4.6, 11.5)
Age group				
1 to 4 years	784 (26%)	233 (23%)	276 (28%)	275 (28%)
5 to < 15 years	2,78 (74%)	767 (77%)	693 (72%)	718 (72%)
Distance to enrolling health facility (km), median (IQR)*	3.9 (2.3, 5.1)	3.7 (2.1, 5.1)	3.9 (2.3, 5.1)	4.0 (2.4, 5.2)
Highest school grade completed*				
Not eligible (< 4years)	601 (20%)	178 (18%)	208 (21%)	215 (22%)
Pre-Primary[#]	484 (16%)	169 (17%)	176 (18%)	139 (14%)
Primary	1526 (52%)	527 (53%)	481 (50%)	518 (52%)
Secondary	288 (10%)	104 (10%)	85 (9%)	99 (10%)
Never attended school	57 (1.9%)	22 (2.2%)	18 (1.9%)	17 (1.7%)
Relationship of participant to head of household*				
1st degree relative	2272 (80%)	739 (80%)	760 (81%)	773 (81%)
2nd and 3rd degree relative	516 (18%)	174 (19%)	166 (18%)	176 (18%)
Not related	43 (1.5%)	16 (1.7%)	16 (1.7%)	11 (1.1%)
Slept under a bednet the previous night*				
Children 1–4 years	746 (96%)	217 (96%)	264 (96%)	265 (96%)
Children 5–14 years	1806 (84%)	618 (83%)	577 (83%)	611 (85%)
RTS,S vaccine[φ]				
Children 1–4 years in Rarieda sub-county	461	140	159	162
Received RTS,S vaccine				
Yes	260 (60%)	87 (69%)	85 (56%)	88 (56%)
No	176 (40%)	40 (31%)	67 (44%)	69 (44%)
Number of RTS,S doses				
1	13 (5.0%)	2 (2.3%)	4 (4.7%)	7 (8.0%)
2	18 (6.9%)	3 (3.4%)	4 (4.7%)	11 (13%)
3	66 (25%)	26 (30%)	18 (21%)	22 (25%)
4	38 (15%)	6 (6.9%)	21 (25%)	11 (13%)
Unknown	125 (48%)	50 (57%)	38 (45%)	37 (42%)

[*] *Missing data: distance to enrolling health facility (n = 7), highest school grade completed (n = 6), relationship to head of household (n = 131), slept under a bednet the previous night (n = 28, 7 in Children 1–4 years and 21 in Children 5–14 years)*

[#] *Pre-primary includes pre-primary 1 (PP1), pre-primary 2 (PP2), and nursery*

[φ] *Rarieda sub-county was selected to receive the RTS,S vaccine, which was administered to children aged 5 to 17 months. Of the 461 children aged ≤ 5 years in Rarieda, 436 were asked about RTS,S vaccine uptake (5 had missing data, and 20 had missed visits). Vaccine information for 126 children (29%) was obtained from vaccination cards, while for 310 children (71%), it was obtained verbally*

six people (IQR: 4, 7). Most of the household heads had completed primary education (65%), while only 4% had never attended school. Nearly all households owned at least one bed net (Table 3), however, only half of households were considered adequately covered (one net for every two household residents).

Factors associated with malaria at baseline

Of the 1000 children enrolled in the first cohort, an RDT result was available for 999 participants. Overall, 498 (50%) children were RDT positive (for HRP2, pLDH, or both antigens). Of these, 326 were positive for HRP2 only, 12 for pLDH only, and 160 were positive for both antigens. In an adjusted multivariable analysis, factors associated with RDT positivity included region, house construction, and participant age (Table 4). Region was the strongest predictor, with the odds of malaria infection higher in children residing in Alego-Usonga than those living in Rarieda sub-county (69% vs 37%; adjusted odds ratio [aOR] 4.81, 95% CI 2.74–8.45; p < 0.001). Traditional house construction (aOR 2.80, 95% CI 1.59–4.95; p < 0.001), and older age (aOR 1.64,

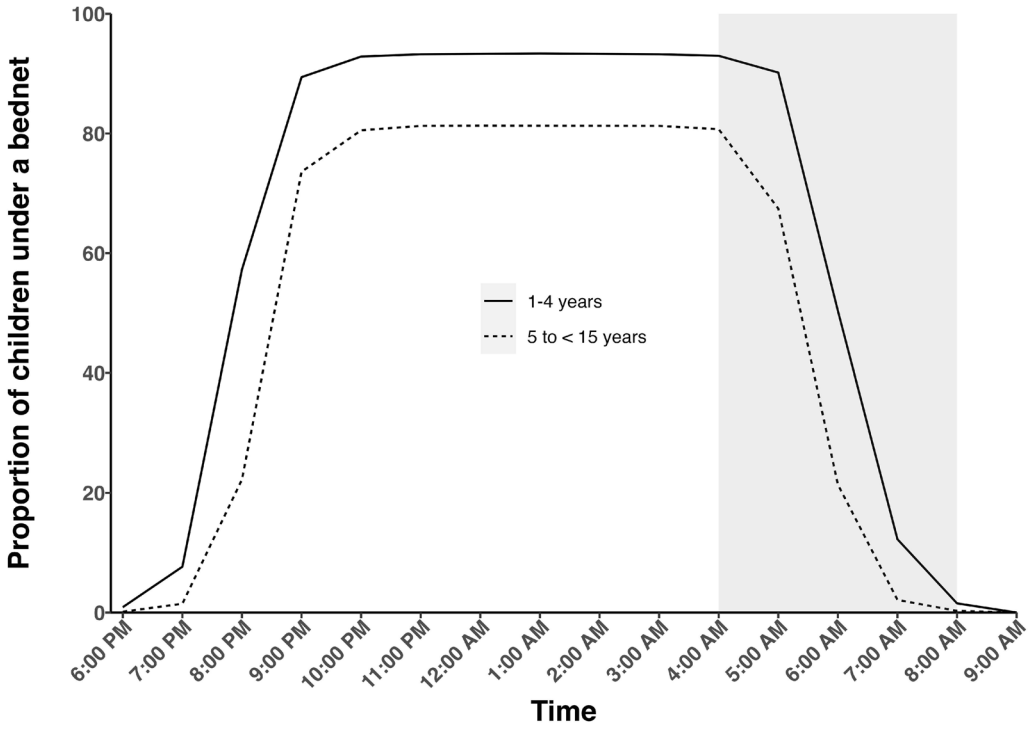

Fig. 2 Proportion of children under a bed net. There were 2552/2962 (746/784 aged 1–4 years and 1806/2178 aged 5 to < 15 years) participants who slept under a bed net last night. Of those, 2503 (732 aged 1–4 years and 1771 aged 5 to < 15 years) had information on time in and out of a bed net

95% CI 1.13–2.37; p = 0.009), were other significant factors.

Discussion

Despite nearly two decades of intensified control efforts in western Kenya [18, 21], the burden of malaria in children from Siaya County remains high. Significant geographic variation in malaria prevalence was found in this study, ranging from 37% in Rarieda sub-county to 69% in Alego-Usonga, highlighting the substantial heterogeneity in malaria burden within the study area. Alego-Usonga has a rice plantation and an oxbow lake, with surrounding papyrus swamps that provide stable mosquito habitats which potentially explains the heterogeneity observed. Additionally, higher *An. funestus* density in Alego-Usonga compared to Rarieda exposes the population in this area to a much greater transmission potential (unpublished data). Bed net coverage remains suboptimal, and school-aged children were significantly less likely to sleep under a net than younger children, as previously reported [21, 22]. Residence in Alego-Usonga, traditional household construction, and older age were independently associated with a higher odds of malaria infection at baseline in cohort children.

LLINs are a key element of the malaria control strategy in western Kenya. The Kenya government provides LLINs through mass distribution campaigns conducted every three years, supplemented by routine distribution through antenatal care and child welfare clinics, aiming for universal coverage [1]. The Ministry of Health distributed LLINs in June 2021 and the study team delivered additional LLINs in August 2021 and October 2022. Despite these efforts, only half of households in the study area were considered adequately covered by LLINs approximately 1–2 years following the initial LLIN campaign, highlighting the challenges of ensuring universal coverage and net attrition [23, 24]. Limited net durability, suboptimal LLIN use practices, dynamic vector behaviours, and widespread pyrethroid resistance in mosquito vectors contribute to lack of LLIN effectiveness [10, 25–28]. To maximize the benefits of LLINs, strategies to ensure high LLIN coverage and use should be implemented, including distribution of adequate numbers of LLINs during campaigns.

Residual malaria transmission persists despite the widespread use of bed nets and targeted implementation of IRS [29, 30], prompting the World Health Organization to call for new vector control tools, including ATSBs [31]. Mosquitoes, both male and female, seek out sources

Table 3 Household demographics

Characteristic	Trial cohort overall	Trial cohort 1	Trial cohort 2	Trial cohort 3
Participants surveyed	2886 (97%)	954 (95%)	956 (99%)	976 (98%)
Households surveyed	2644	953	843	848
Region				
Rarieda	1567 (59%)	585 (61%)	487 (58%)	495 (58%)
Alego-Usonga	1077 (41%)	368 (39%)	356 (42%)	353 (42%)
House construction*†				
Improved	199 (7.7%)	86 (9.3%)	61 (7.3%)	52 (6.2%)
Traditional	2396 (92%)	842 (91%)	770 (93%)	784 (94%)
Household residents, median (IQR)*	6 (4, 7)	5 (4, 7)	6 (4, 7)	6 (5, 7)
Educational attainment of head of household*				
Higher	158 (6.1%)	54 (5.8%)	58 (7.0%)	46 (5.5%)
Secondary	648 (25%)	229 (25%)	207 (25%)	212 (25%)
Primary	1677 (65%)	607 (65%)	535 (64%)	535 (64%)
Never attended school	112 (4.3%)	38 (4.1%)	31 (3.7%)	43 (5.1%)
Socioeconomic index in terciles*¶				
Least poor	875 (34%)	307 (34%)	303 (37%)	265 (32%)
Poor	849 (33%)	293 (32%)	255 (31%)	301 (36%)
Poorest	851 (33%)	316 (34%)	267 (32%)	268 (32%)
Bednet*				
Household owns at least one bednet	2558 (99%)	912 (98%)	822 (99%)	824 (99%)
Adequate bednet coverage (1 net per 2 residents)	1332 (51%)	500 (54%)	444 (53%)	388 (46%)

* *Missing data: house construction (n = 49), household residents (n = 49), educational attainment of head of household (n = 49), socioecomic index (n = 69), household owns at least one bednet (n = 49), adequate bednet coverage (n = 49)*

† *House type was defined as improved houses if they had closed eaves, finished wall materials which included: lime, bricks, cement blocks, stone, iron sheet and wood planks or shingles and finished roof materials which included: iron sheet, cement and concrete slab. All other houses, typically with thatched roofs, mud walls, and open eaves, were classified as traditional*

¶ *Socioeconomic index was defined using the following indicators: main source of income, access to improved drinking water, toilet, fuel, improved housing based on floor, wall, roof, ownership of any livestock (goats, cattle, sheep, poultry, donkeys and pigs), ownership of the following items: plough, motorbike, bicycle, car, tractor, engine boat, rowing boat, mattress, mobile phone, radio, vcr dvd, sofa, lantern, television, fridge, solar panel*

of liquid and sugar using chemical attractants. ATSBs exploit this behaviour by attracting mosquitoes to a toxicant-laced sugar solution, effectively killing them [32]. This attract-and-kill strategy has been shown to reduce vector populations, even in sugar-rich environments [12]. In Mali, proof-of-concept studies using ATSBs containing dinotefuran showed promising results in reducing malaria vector populations [15, 33]. Modelling studies, based on Mali's results [15, 33], suggest that deploying ATSBs could result in a 30% or greater decrease in malaria case incidence and parasite prevalence compared to universal vector control coverage alone (standard of care). Further evidence of the impact of ATSBs on epidemiological and entomological endpoints will be generated in the ongoing Phase III trials of ATSBs in Kenya, Zambia, and Mali [16, 34].

In high transmission settings, school-aged children have consistently been shown to have the highest burden of malaria infection [35, 36]. In this study, school-aged children had a higher odds of malaria infection than younger children. Older children were also more likely to go to sleep late and to rise early, and were less likely to report using LLINs the previous night, increasing their potential exposure to mosquito bites. A shift in the biting patterns of *An. funestus*, the predominant vector in the study area, with peak biting activity occurring between 06:00 and 07:00 when children are preparing for school could also increase malaria risk for school-aged children [10]. In endemic areas, school-aged children are often asymptomatic carriers of malaria parasites, serving as major contributors to the infectious reservoir for onward malaria transmission [37, 38]. Reducing malaria infection in school-aged children will benefit individual children and may protect the whole community by reducing transmission [39, 40]. To effectively control malaria in this region, additional tools such as ATSB are needed to potentially provide added protection for school-aged children.

This study has several limitations. First, the estimates of malaria prevalence were based on RDT, which may have either underestimated (due to limited sensitivity resulting in false negative tests, particularly for low density

Table 4 Malaria prevalence by RDT prior to ATSB intervention using mixed effect model

Characteristic	RDT positive[¶]	Crude OR (95% CI)	P-value	Adjusted OR (95% CI)	P-value
Overall†	498/999 (49.8%)				
Age group					
1 to 4 years	102/233 (43.8%)	1		1	
5 to < 15 years	396/766 (51.7%)	1.65 (1.17, 2.33)	0.004	1.64 (1.13, 2.37)	0.009
Gender					
Female	247/490 (50.4%)	1		1	
Male	251/509 (49.3%)	1.00 (0.75, 1.33)	0.99	0.86 (0.63, 1.17)	0.35
Region					
Rarieda	221/596 (37.1%)	1		1	
Alego-Usonga	277/403 (68.7%)	4.24 (2.57, 7.02)	< 0.001	4.81 (2.74, 8.45)	< 0.001
House construction*					
Improved	30/87 (34.5%)	1		1	
Traditional	435/841 (51.7%)	2.83 (1.65, 4.86)	< 0.001	2.80 (1.59, 4.95)	< 0.001
Socioeconomic index in terciles*					
Least poor	147/306 (48.0%)	1		1	
Poor	155/294 (52.7%)	1.16 (0.80, 1.69)	0.066	1.29 (0.87, 1.89)	0.15
Poorest	155/316 (49.1%)	0.75 (0.51, 1.09)		0.89 (0.60, 1.32)	
Adequate net coverage (1 net per 2 residents)*					
Yes	247/500 (49.4%)	1		1	
No	218/428 (50.9%)	1.29 (0.95, 1.75)	0.10	1.23 (0.90, 1.68)	0.20

[¶] There were 999/1000 in trial cohort 1 included in this analysis as 1 participant had missing RDT results

† Total RDT positive, 326 were positive for HRP2 only, 12 for pLDH only, and 160 were positive for both antigens

*Missing data: house construction (n = 71 participants), adequate net coverage (n = 71 participants), and socioeconomic index (n = 83 participants)

infections), or overestimated (due to false positive tests from persistent HRP2 antigenaemia) the true prevalence of infection [41, 42]. Second, only 999 children enrolled in the first cohort were included in the factor analysis due to the deployment of ATSBs in the study area. The impact of ATSBs on malaria incidence and prevalence will be assessed during trial follow-up, and reported separately. Third, assessment for bed net coverage and use was done through self-report, rather than direct observation, potentially resulting in an overestimation of net coverage, and limiting our ability to determine whether bed nets were LLINs. Fourth, 804 children on the recruitment list were not contact for screening, primarily due to migration out of the study area, boarding school attendance, enrolment in schools outside the study area, or (for Cohort 1 only) because they were on a second supplementary recruitment list and were not needed to reach our target sample size. When comparing gender and age, there was no significant differences between the children who were not contacted and those who were contacted for screening. Fifth, RTS,S/AS01 vaccination was not included as a factor in our analysis of baseline malaria prevalence. While vaccination could have been an important determinant of baseline malaria prevalence, the risk of potential bias from excluding this factor is low, given that few children had reported receiving the vaccination in Cohort 1 (87 with only 29 confirmed by vaccination card).

Conclusions

The burden of malaria in western Kenya remains high. Although most households own at least one LLIN, only half were adequately covered by LLINs. Residents of Alego-Usonga sub-county, those living in traditionally constructed households, and older children were at highest risk of malaria infection. Currently deployed malaria control tools, including pyrethroid-only LLINs are insufficient to control malaria in this area. Strategies to maximize the effectiveness of LLINs, and additional tools such as ATSBs, are needed to intensify malaria control in western Kenya.

Abbreviations

ATSB	Attractive targeted sugar baits
LLIN	Pyrethroid-only long-lasting insecticidal net
RDT	Rapid diagnostic test
IRS	Indoor residual spraying
IPTp	Intermittent preventive treatment for pregnant women
HDSS	Health and demographic surveillance system
GPS	Global positioning system

PCA	Principal component analysis
GLMM	Generalized linear mixed model
CI	Confidence intervals
IQR	Interquartile range

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Author contributions
EO, FOtK, and AMS conceived of the trial, with input from DPM, JJ, MJD, and SK. EO, FOtK, and AMS designed the study, developed the procedures, and drafted the protocol with DPM, ML, JJ, WO, WN, KO1, BS and MC. CO, KO1, WN, and BS led the field activities and data collection, with oversight from SGS and FOtK, and support from JS and JRG. AK, DPM, FA, and OT managed the data, and AK led the data analysis, with support from ML. KO2 coordinated sample collection, processing, and storage. AK and SGS interpreted the data and drafted the manuscript, with input from ML and DPM. All authors reviewed the manuscript and gave permission for publication. AK, the corresponding author, has full access to all the data in the study and has final responsibility for the decision to submit for publication.

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Availability of data and materials
The datasets used to generate the results reported here will be made publicly available after the main trial results are published but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The trial was approved by the Kenya Medical Research Institute Scientific Ethics Review Unit (KEMRI SERU: 4189), by the Institutional Review Board of the US Centers of Disease Control and Prevention (IRB: 00008118) and Liverpool School of Tropical Medicine Research Ethics Committee (LSTM REC: 21-027). Written informed consent was sought from the parent/guardian. Additional assent was obtained for children aged 13- < 15 years in the cohort study.

Consent for publication
This study was published with the consent of the KEMRI Director General.

Competing interests
The authors declare no competing interests.

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