

RELATIONSHIP BETWEEN THE INTENSITY OF EXPOSURE TO MALARIA PARASITES AND INFECTION IN THE USAMBARA MOUNTAINS, TANZANIA

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Abstract. The relationship between exposure to *Plasmodium falciparum* malaria and parasite density and prevalence was studied in six communities along an altitude transect. Prevalence of parasitemia in children decreased by 5% for every 100 meter increase in altitude from 82% in the lowlands at 300 meters to 12% in the highlands at 1,700 meters. This decrease in prevalence corresponded to a 1,000-fold reduction in transmission intensity. The ability to suppress parasite density and prevalence with age increased proportionally with increasing transmission intensity when transmission rates were higher than 0.1 infective bites per year, but developed after 2–3 years of age, regardless of transmission intensity. However, at transmission rates less than 0.1 infective bites per year, prevalence remained similar in all age groups. We propose that both exposure-dependent acquired immunity and age-dependent acquired immunity regulate parasite prevalence and density and suggest that transmission control will not hinder the development of protective anti-parasite immunity.

INTRODUCTION

To assess the impact of malaria transmission intensity on human health and to predict the potential gains from reducing transmission, it is important to understand the relationship between intensity of transmission and disease. This is not a simple relationship and it has been suggested that reductions in transmission intensity might even have an adverse long-term impact on malaria morbidity and mortality by hindering the acquisition of protective immunity.^{1,2} Reduced levels of antibodies against sporozoites and variant surface antigen, the latter being important for acquired immunity, have been reported after introduction of bed nets.^{3,4} Similar studies have reported both increased and decreased levels of protective antibodies against merozoites antigens in children and pregnant women after bed nets were introduced, and suggested an effect of age.^{5,6} Others have argued that acquired immunity is largely age dependent and thus independent of the level of exposure, so that any reduction in transmission would be expected to be beneficial.⁷ Exposure-dependent acquired immunity can be interpreted as an increasing ability to recognize strain-specific *Plasmodium falciparum* antigens as the immune system is presented to different strains through repeated infections with time.⁸ If this is correct, the long-term effect of reducing transmission through vector control would reduce immunity to such an extent that prevalence of infection, or densities of parasites, in older age groups would increase compared with pre-control levels. In this scenario, one would expect an accumulated increase in crude prevalence rates, despite a decrease in young children.⁹

Others have interpreted the age-specific prevalence rates as an effect of age itself rather than accumulated exposure. It is suggested that the mechanism responsible for age-dependent acquired immunity is a maturation of the immune system at older age groups, allowing a strain transcending immunity after a limited number of infections with *P. falciparum*.^{10,11} Thus, according to the hypothesis of an age-dependent acquired immunity, a reduction in transmission will not result in an increased prevalence in older age groups. Rather, it will

postpone a proportion of the infections to older age groups with a more mature immune system.

To predict long-term effects of different types of interventions it is therefore important to understand the nature of acquired immunity to malaria. The greater the contribution of age-dependent acquired immunity, the greater the advantage of reducing transmission because exposure is shifted to older immune-competent individuals. Short-term intervention projects are not expected to show the potential long-term effect of reduced immunity because the immunity acquired before the intervention is expected to last for years under the reduced intensity of transmission. Thus, the immediate reductions in parasitologic parameters observed in short-term intervention trials may not be sustainable. It is therefore important to assess the long-term effects of reduced transmission intensity. This can be achieved by prolonging intervention trials for years.^{12–14} Here we used an alternative ecologic approach and compared malaria indices in six communities differing only in malaria transmission intensity. Using this ecologic approach, we quantified the relationship between transmission intensity and infection rates, spleen enlargement, and density of infections in children and adults. It can be difficult to distinguish the effects of age and accumulated exposure because these are linked. However, by examining villages with different transmission intensities, we were able to analyze the separate effects of age and transmission because similar age groups will have different accumulated exposure in the different villages. Functional immunity is likely to consist of several different mechanisms working together to reduce disease and death by controlling and tolerating the different stages of the parasites and their interaction with the human body. However, this study focuses specifically on the ability to control parasitemia. The six study communities were situated along a transmission transect ranging from holoendemic malaria in the lowlands resulting from 91 infective bites per person per year to hypoendemic malaria caused by an estimated 0.03 infective bites per person per year in the highlands of the Usambara Mountains in Tanzania.¹⁵ These communities reflect the range of malaria endemicity experienced across much of the African continent. This field study appears to be the first to simultaneously investigate the relationship between transmission intensity, age, spleen rates, parasite rates, and parasite densities at all age

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groups over the full range of endemicity from holoendemic to hypoendemic transmission levels.

MATERIALS AND METHODS

Study area. Six villages were surveyed along an altitude transect in the West Usambara Mountains in northeastern Tanzania (Table 1), approximately 100 km inland from the port of Tanga. The villages are densely populated, ranging from 500 to more than 1,000 individuals, but the villages are often separated into a few well-defined clusters. Environmental and entomologic parameters and malaria parasite strains for the six villages have been described in detail previously.¹⁵⁻¹⁷

Selection of study households. A geographically defined cluster of houses containing up to 1,000 people was selected in each village. All households in each cluster were numbered approximately one year before the survey. Four to six months before blood sampling, all study households were visited by a member of the survey team, and family members interviewed in Swahili about their age and residence status. Householders were given a unique identification number, including people not living in the village during this registration period, but locally considered to be members of the household. All persons registered were invited for the survey.

Malariometric data. Registered households were given written invitations by a village assistant specifying the members of the households to be surveyed the following day during the survey in November and December 1996. Once identified, subjects were questioned about whether they had spent one or more nights outside the village in the previous month and if they had taken any antimalarials in the previous two weeks. Subjects were palpated in a horizontal position for presence of enlarged spleen by the same medical doctor throughout the survey. Blood was obtained from all subjects by finger prick, and thin and thick blood smears were prepared on glass slides. Slides were stained with Geimsa and 100 fields examined for asexual *P. falciparum* parasites at 1000× magnification. Positive slides were counted against 200 leukocytes.

Data analysis. For graphic presentations, the populations were grouped for age-specific calculations in the following nine age intervals adapted from the World Health Organization:¹⁸ children < 2 years of age, children 2-4 years of age, juveniles 5-9 years of age, adolescents 10-14 years of age, young adults 15-19 years of age, and four adult groups 20-29, 30-39, 40-59, and > 60 years of age. Densities were calculated as geometric mean densities of positive samples (positive

samples in 100 fields examined) using the equation $GM = \text{antilog}_{10}(\sum \log_{10}(x_i + 1)/n) - 1$, where x_i = number of parasites per 200 leukocytes and n = is the number of slides. Prevalences were calculated as the ratio of positive samples (at least one parasite seen in 100 fields examined). Counts were converted to asexual parasites per microliter of blood assuming an average concentration of 8,000 leukocytes/ μ L of blood.

Prevalence of enlarged spleen defined as a Hacketts size $\geq 1^{19}$ was calculated among palpated subjects. The relationship between altitude and infection rates in children < 10 years of age and the relationship between annual number of infective bites and infection rates in children < 10 years of age was assessed with linear regression.

Two logistic regression models were developed: one on prevalence of asexual *P. falciparum* parasites and one on prevalence of enlarged spleen. A linear relationship between the logit transformed prevalence and the predictive variables were visually examined by plotting the relationship using the ksm smoothing procedure (Stata version 7.0; Stata Corporation, College Station, TX). \log_{10} (annual number of infective bites), the square root of age, the interaction term of the product of square roots of age, the \log_{10} (annual number of infective bites), overnight stays, and antimalarial use were entered as predictive variables in both models. Data were clustered at the village level, and to avoid underestimating the variance, we used a random effect model, Proc NL MIXED (SAS System version 8; SAS Institute, Cary, NC) with villages as random effect, assuming the random effects to be normally distributed. Parameters were entered in the above order in a manual stepwise forward logistic procedure. A parameter was included in the model if it significantly (at the 5% level) reduced the deviance compared with a model without the parameter. The assumption of normally distributed random effects was visually confirmed in the final model by plotting the predicted random effects in a normal probability plot using the UNIVARIATE procedure (SAS Institute). To quantify the effect of age in each village, we used the two resulting models excluding both the \log_{10} (annual number of infective bites) and the interaction term, and estimated the odds ratio of increasing age village by village. Confidence intervals (95%) for the odds ratios were calculated in all logistic models from the more robust, but less sensitive, Wald statistics. This means that the confidence interval of the beta estimate of a variable may include zero, although the variable is significantly improving the model according to the likelihood statistics (deviance).

Parasite densities were log transformed and analyzed with linear regression (Proc GLM, SAS) for each village with square root transformed age as predictor. Wald statistics was used to determine if the predictor variable was significantly improving the model at the 5% level.

Ethics. Informed consent was obtained from all adult participants and from the legal guardians of all minors. All subjects with malaria were offered appropriate treatment free of charge. In addition, all subjects were offered treatment of minor ailments or admitted to a health facility free of charge. Ethical approval for this study was provided by the Medical Co-ordinating Committee of the National Institute for Medical Research in Tanzania and registered at the Tanzania Commission for Science and Technology as No 95-217-CC, 96-264-ER-95-121 and 98-005-ER-95-21.

TABLE 1

Geographic and entomologic characteristics of six study villages along an altitude transect in the Usambara Mountains, Tanzania

Village	Altitude (meters)	Annual infective bites*	Location
Kwameta	300	91	5° 06.6' S, 38° 29.1' E
Magundi	600	9.7	5° 05.3' S, 38° 28.3' E
Kwamhanya	800	1.7	5° 03.5' S, 38° 27.6' E
Bagamoyo	1,000	1.8	5° 04.0' S, 38° 26.5' E
Balangai	1,400	0.08	4° 55.6' S, 38° 27.7' E
Milungui	1,700	0.03	4° 45.3' S, 38° 21.3' E

* Bødker and others.¹⁵

RESULTS

A total of 3,833 (82.7%) of the 4,636 residents were examined during the survey, which included almost every resident present during the 3–4-day survey period. Some attending the survey refused either finger prick or palpation. Good slides and spleen recordings were obtained from 75.1% and 79.6%, respectively, of the resident populations.

We found very different patterns of malaria in the closely situated villages along the altitude transect from 300 meters to 1,700 meters. The prevalence of asexual *P. falciparum* parasitemia in children < 10 years of age decreased with increasing altitude in a linear fashion, with 5% fewer children infected for every 100-meter increase in altitude ($R^2 = 0.96$, $P < 0.001$). This can be represented by the equation $P. falciparum$ prevalence (%) = $99.1 - (0.05 \times \text{altitude in meters})$.

The relationship of prevalence of infection in children < 10 years of age and the estimated annual number of infective bites could conveniently be described as a log-linear relationship ($R^2 = 0.92$, $P = 0.002$) by the equation¹⁵ $P. falciparum$ prevalence (%) = $47.8 + (19.7 \times \log_{10} \text{number of infective bites per year})$.

This indicates that for every 10-fold increase in transmission intensity, an additional 20% of the children are infected with malaria, within the range of prevalence observed along the transect (Figure 1). However, these regression coefficients are dependent on age and therefore only apply to this specific age group. Infective mosquitoes were not collected in the two highest villages. The numbers of infective bites in these two villages are therefore estimates based on the observed human biting rate in the villages, and the proportion of infective mosquitoes observed at 800–1,000 meters.¹⁵

Overall, the six villages showed an initial increase in both

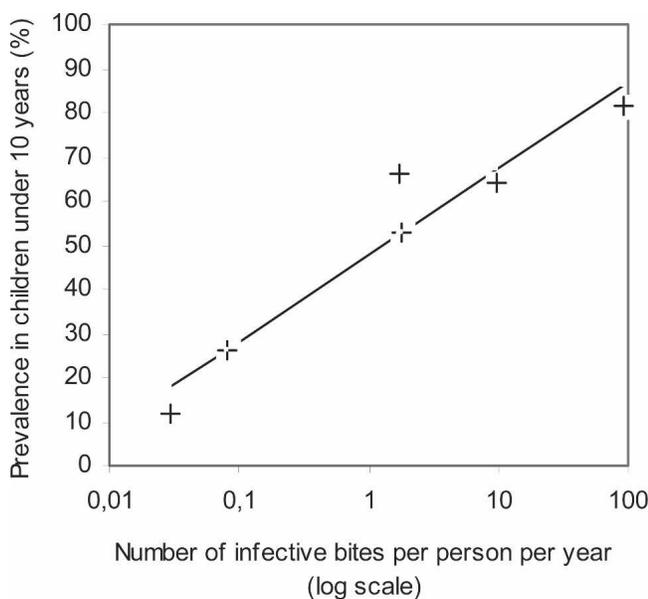


FIGURE 1. Relationship between annual number of infective mosquito bites per person and the prevalence of *Plasmodium falciparum* in children less than 10 years of age. A 10-fold increase in transmission intensity increases the prevalence of infections by 19.7% of the children. The transmission intensity is shown on a \log_{10} scale. The six villages are connected with a linear regression line. This regression does not adjust for age and clustering at the village level.

prevalence of *P. falciparum* infections and enlarged spleen with age in the first approximately two years of life, followed by a decrease with age (Figures 2 and 3). We analyzed the decrease in prevalence of infections and spleen enlargement with age in those more than two years old. Logistic regression, which allowed for clustering of the data at village level, showed a significant overall effect of transmission intensity and age and a significant interaction between transmission intensity and age for both prevalence of *P. falciparum* infections and prevalence of enlarged spleen (Table 2). The analysis of parasite rate and parasite density showed a log-linear relationship between transmission intensity and the probability of both infection and enlarged spleen. Both analyses identified a square root relationship between age and the probability of infection or enlarged spleen. We also identified a significant interaction between the square root transformed age and the log-transformed transmission intensity. This means that the reduction in prevalence with age is more rapid in younger age groups and levels off with age, and that the reduction in prevalence with age is more rapid at high transmission intensities than low ones. Since the identified interaction of age and transmission intensity is the product of age and exposure, we interpret the interaction as a measure for accumulated exposure. Thus, the analysis found that the probability of both infection and enlarged spleen was affected by the transmission intensity in the village, the accumulated exposure of the person, and the age of the person. The identified effect of age is adjusted for the effect of accumulated exposure in the analysis and therefore an effect of age itself. The odds ratios of age were remarkably similar in both models. Both analyses show that the impact of transmission intensity decreases with age, resulting in fairly similar prevalences in all villages in those 25–30 years of age, regardless of the transmission intensities. At no age group were the villagers better off at higher transmission intensities in terms of infections or enlarged spleens. We examined the effect of age on the probability of infection or enlarged spleen by analyzing the same data set village by village. Each village was analyzed with a simple logistic regression model adjusting for overnight stays outside the village and recent drug use. We identified

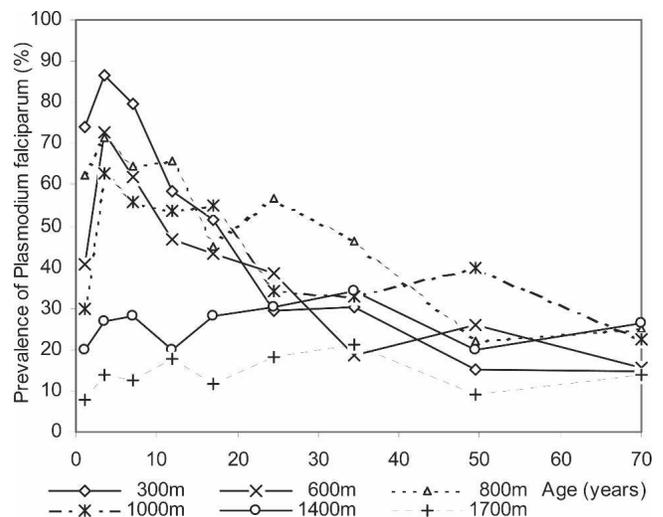


FIGURE 2. Prevalence of asexual *Plasmodium falciparum* infection at different ages in six villages at different altitudes.

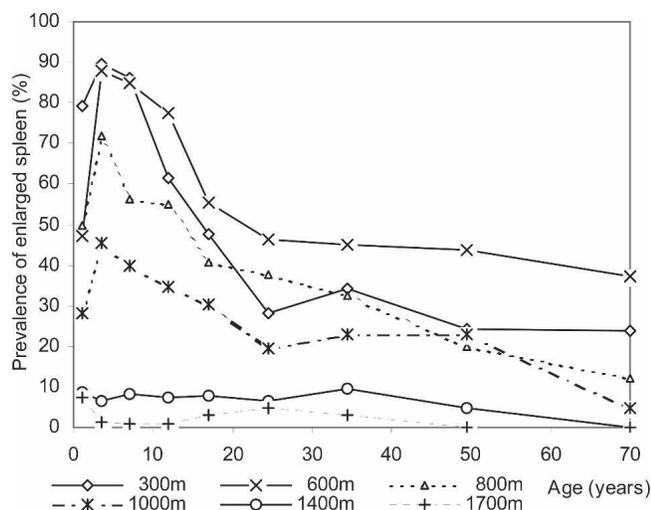


FIGURE 3. Mean ratio of enlarged spleen at different ages in six villages at different altitudes.

two main patterns, which were similar for both the probability of infection and the probability of enlarged spleen. The first pattern found in the four lowest villages with transmission rates higher than one annual infective bite showed a sharp decrease in parasite rates and enlarged spleen rates with age above two years (Table 3). In contrast, in the two highland villages with low transmission intensities < 0.1 infective bites annually, the probability of being infected or having enlarged spleens was similar at all ages. The odds ratios of age for each village were again remarkably similar in the models for parasite prevalence and the models for prevalence of enlarged spleens (Table 3).

High-density infections, defined as densities $> 5,000$ parasites/ μL of blood, decreased from 16.1% of infected children < 10 years of age in the lowland village to 7.9%, 13.3%, 7.0%, 2.0%, and 0.4%, respectively, with increasing altitude (χ^2 for trend = 40.2, degrees of freedom = 5, $P < 0.001$). Only 12 of 2,279 adults and children ≥ 10 years of age had infections of more than 5,000 parasites/ μL of blood.

The density of parasitemia peaked in those less than five years of age in the four villages where transmission was greatest, but the geometric mean densities were fairly similar in all four villages for each age group. In these villages the densities rapidly decreased with age (Figure 4). In the two highland

villages, there was much less variation in mean parasitemias with age. Linear regression on log-transformed density of infections in each village showed that density of infections decreased significantly with age in the four villages with the highest transmission intensity (Table 4). No significant decrease in density of infection was found in the two low transmission villages. However, for all age groups the highland populations had lower mean densities when infected than did people living in the four villages with greatest transmission. High-density infections ($> 5,000$ parasites/ μL of blood) were largely confined to children. The patterns seen with densities of infection thus reflect the pattern observed with prevalence of infection, with a large variation with age in the younger age groups, followed by fairly similar densities in older age groups and with no apparent advantage of high exposure at any age from two years to old age.

DISCUSSION

The level of malaria endemicity along the six village altitudinal transect in the Usambara mountains decreased from holoendemicity in the lowland village to mesoendemicity or to hypoendemicity in the two highest villages depending on whether endemicity was classified according to parasite rates or to prevalence of enlarged spleens.^{20,21}

The decreasing risk of infection with increasing altitude results in a simple linear relationship between altitude and prevalence in children less than 10 years of age, with 5% fewer of the children being infected for every 100-meter increase in altitude. The slope of the relationship is age-dependent and thus only valid for this specific age group.

According to estimates of the number of infective bites annually recorded in the previous year,¹⁵ holoendemic malaria was associated with 90 infective bites annually, hyperendemic malaria with 10–2, mesoendemic malaria with 2–0.1, and hypoendemic malaria with ≤ 0.1 infective bites per year.^{15,21} However, this is probably an oversimplification of the levels of exposure required for the different levels of malaria because the seasonality of transmission differs in villages at different altitudes and the highland areas have the potential for large inter-annual variation as a result of unstable short rains in the warm season.^{15,22}

The relationship between transmission intensity and parasite prevalence in children less than 10 years of age was best described by a log-linear relationship, in which the proportion

TABLE 2

Results of two logistic regression analysis with parasite prevalence ($n = 3,256$) and prevalence of enlarged spleen ($n = 3,450$) as outcome*

Parameter	P.f. infection					Enlarged spleen				
	Odds ratio	95% CI		df	P	Odds ratio	95% CI		df	P
		Lower	Upper				Lower	Upper		
Constant	1.65	1.03	2.64	5	< 0.025	0.91	0.41	2.02	5	0.75
Log_{10} (annual number of infective bites)	3.69	2.46	5.54	5	< 0.001	6.85	3.43	13.69	5	< 0.001
Square root of age	0.78	0.74	0.83	5	< 0.001	0.75	0.69	0.81	5	< 0.001
Interaction of log_{10} (annual infective bites) and square roots of age	0.82	0.78	0.87	5	< 0.001	0.86	0.80	0.92	5	< 0.001
Staying outside village (Y/N)	1.25	0.92	1.70	5	< 0.001	1.36	0.97	1.90	5	< 0.001
Intake of antimalarial drugs (Y/N)	0.85	0.62	1.18	5	< 0.001	1.14	0.80	1.62	5	< 0.001
Random effects				5	< 0.001				5	< 0.001

* Subjects younger than two years were not included in analysis. Confidence intervals (CIs) are based on Wald statistics and P values are based on log-likelihood statistics. P.f. = *Plasmodium falciparum*; df = degrees of freedom; Y/N = yes/no.

TABLE 3

Result of six logistic regression analysis of the relationship between infection and square roots of age and six similar analysis of the relationship between enlarged spleen and square root of age*

Village altitude (meters)	Annual infective bites	P.f. infection					Enlarged spleen				
		Odds ratio	95% CI		df	P	Odds ratio	95% CI		df	P
			Lower	Upper				Lower	Upper		
300	91	0.51	0.44	0.60	389	< 0.001	0.57	0.51	0.65	465	< 0.001
600	9.7	0.65	0.58	0.72	524	< 0.001	0.65	0.59	0.72	610	< 0.001
800	1.7	0.67	0.59	0.77	336	< 0.001	0.64	0.56	0.73	364	< 0.001
1,000	1.8	0.77	0.71	0.85	587	< 0.001	0.73	0.66	0.82	583	< 0.001
1,400	0.08	1.00	0.92	1.10	736	1	0.92	0.78	1.09	752	> 0.25
1,700	0.03	0.99	0.88	1.12	624	0.75	0.94	0.67	1.32	624	1

* The impact of age is significant and decreasing with age in villages with transmission more than 2 infective bites annually. Parasite prevalence or prevalence of enlarged spleen showed no correlation with age in two low-transmission villages. Subjects less than two years of age was not included in the analysis. Confidence intervals (CIs) are based on Wald statistics and P values are based on log-likelihood statistics. For definitions of abbreviations, see Table 2.

of children infected increased 20% for every 10-fold increase in transmission intensity. This log-linear relationship should not be extrapolated beyond the transmission range defined by the highest and lowest village. However, the range covered by these six villages is considerable, covers most malaria-endemic areas in sub-Saharan Africa, and resembles transmission prevalence relationships found in meta-analysis.²³⁻²⁵ The relationship between exposure to malaria parasites and prevalence of parasitemia in young children has two important implications for malaria control. First, a reduction in transmission intensity will result in a reduction in infection where the pattern and intensity of transmission is similar to that experienced in the Usambaras. However, it should be noted that the reduction in prevalence will be proportionately smaller than the reduction in transmission. For example, it required a more than 1,000-fold reduction in transmission intensity to reduce parasite prevalence from 87% to 13% in 2-4-year-old children. Second, our findings suggest that almost all children will be infected if they receive more than 90 infective bites each year; this has also been found in meta-analysis.^{24,25} In such villages, transmission must be reduced sharply to have any impact on prevalence of infections in children.

Although there are large differences in parasite prevalence

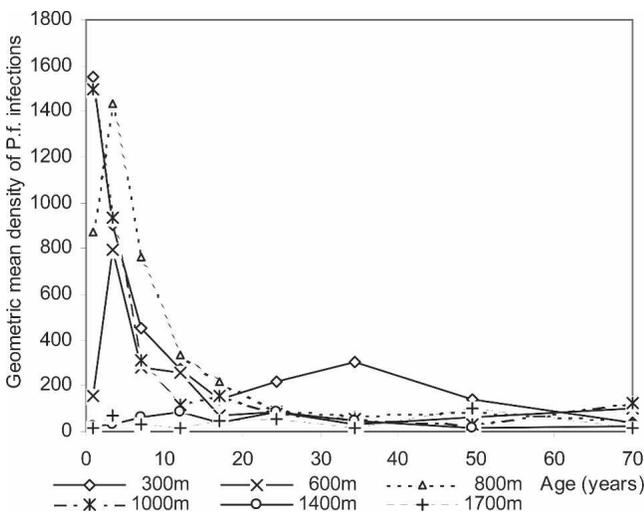


FIGURE 4. Geometric mean density of *Plasmodium falciparum* infections at different ages in six villages at different altitudes.

between children in the different villages, the prevalence in adults from the different villages is fairly similar, regardless of the large differences in transmission intensity. The age-prevalence relationships found in the present study closely resemble theoretical age-incidence relationships previously reported.²⁶

Logistic regression models identified an inverse relationship between age and prevalence of both infections and enlarged spleens, with prevalences decreasing with age. There were two different age-prevalence patterns seen in adults and children more than three years of age. In the four villages with greatest transmission, prevalence decreased with age after the initial peak in the 2-3-year-old age group, and the higher the initial prevalence, the steeper the decrease in prevalence with age. In contrast, in the two villages with lowest transmission, prevalence was similar in all age groups.

Similar relationships were found when looking at changes in parasite densities with age and exposure intensity. When transmission increased above two infective bites annually, the highest parasite densities were found in the 2-3-year-old group, followed by a dramatic decrease with age, but there was no significant change in densities with age at lower inoculation rates.

We found no evidence of a long-term negative impact of reduced transmission. At any age between 2 and 70 years, people living in low-transmission villages were either better off or the same compared with people in neighboring villages with higher transmission with regard to prevalence of infection, density of infections, and prevalence of enlarged spleen. The data therefore suggest that the benefits in infection rates

TABLE 4

Linear regression analysis of the relationship between log-density of parasites and the square root of age for each village*

Village altitude (meters)	Annual infective bites	Density of <i>Plasmodium falciparum</i> infection				
		Slope	95% CI		t	P
			Lower	Upper		
300	91	-0.16	-0.24	-0.09	-4.14	< 0.001
600	9.7	-0.21	-0.28	-0.14	-6.14	< 0.001
800	1.7	-0.26	-0.33	-0.19	-7.03	< 0.001
1,000	1.8	-0.20	-0.27	-0.14	-5.95	< 0.001
1,400	0.08	-0.04	-0.14	0.05	-0.94	0.35
1,700	0.03	-0.02	-0.10	0.10	-0.38	0.71

* The impact of age is significant and similar in the villages with transmission more than two infective bites annually. Parasite densities showed no correlation with age in the two low-transmission villages. CI = confidence interval.

reported from many transmission control studies will be sustainable throughout life. Persistent reductions in parasitemia have been reported after four to six years in prolonged bed net intervention studies in high-transmission areas in Tanzania and Kenya, with sustainable reduction in morbidity and mortality in children.^{12–14}

Density of infection is likely to be relevant to disease. Our data indicate that as transmission increases the geometric mean density of parasitemia increases to a plateau, with any further increase in transmission failing to increase density of parasitemia. This threshold occurs at approximately 0.1–2 infective bites per year. Such a plateau has been suggested previously for the relationship between transmission intensity and malaria morbidity and mortality.^{1,27,28}

More malaria was found in children in highland areas than expected from the low-transmission intensity. It is difficult to explain how 0.08 and 0.03 estimated infective bites annually could maintain prevalences in 2–4-year-old children of 27% and 14% in the two highest villages. However, similar high prevalences have been reported in other studies.^{24,25} Even if all infective bites were to result in human infections, which is unlikely,^{29–31} it would take a mean duration of infection of more than 2.5 years at 1,400 meters and 4 years at 1,700 meters, assuming prevalence to be the product of the number of infective bites and the duration of infection. However, few infections are expected to last for more than a year.^{32–36} The highland transmission rates are estimations based on entomologic data, and the confidence intervals of this kind of estimates are likely to be wide.³⁷ It is also possible that prior to the collection of transmission data there was a period of higher transmission intensity that resulted in a new, albeit decreasing, number of cases as the prevalence regressed to a new equilibrium that was not reached at the time of the survey.

It is tempting to suggest that all infections in the highest villages originated during brief trips to the highly malarious lowlands, but we believe that this is not the case. We are confident that malaria transmission does occur in the highest villages because parents of infected children often told us that the children had never left the village. Two surveys 12 months apart of a total of 138 children at the slightly higher village of Longoi (2,000 meters) failed to identify a single infection, suggesting relatively little importance of imported cases in the highland villages.²² We therefore suggest that movement of children to high-risk areas must be of minor or no importance in the highland villages. Nonetheless, some adult villagers do travel to the lowlands, where the force of transmission is formidable. The risk of inoculation during one night in the lowlands may be equivalent to more than three years accumulated risk at 1,700 meters,¹⁵ and we detected a significant overall increase in the odds of infection in people with a recent history of staying overnight outside their village. Migration has also been shown to be relatively important in Kayanza Province in the highlands of Burundi where transmission appears to be very low.³⁸

The reduced parasitologic prevalence and parasite density in adults compared with children are the results of immunity developing as the villagers get older. To what extent the developing immunity is the result of accumulated exposure or a result of age itself is an important question.^{1,2,7} If immunity is the result of accumulated exposure, the long-term effect of transmission control may hinder the development of protec-

tive immunity by reducing exposure to parasite antigens.⁹ However, if immunity is the result of a maturation of the immune system and thus largely an effect of age itself, transmission control will not prevent the development of protective immunity.^{10,11}

The lack of a simple linear relation between transmission intensity and prevalence suggest an immune mechanism. The log-linear relationship between transmission intensity and prevalence of infections may occur for two reasons. As the number of infective bites increases, fewer infective bites may result in a patent infection or the duration of infection is shortened. Both explanations are examples of density-dependent effects reducing the reproductive success of specific parasite strains. These mechanisms may be explained by acquired immunity increasing with intensity of transmission. A similar log-linear relationship between exposure and child prevalences has been predicted by mathematical models assuming exposure-dependent immunity.³⁹ The log-linear relationship between transmission intensity and prevalence of both infections and enlarged spleens thus support the existence of exposure-dependent acquired immunity. However, other studies have reported that the proportion of infective bites giving rise to infections decreases with increasing transmission.^{31,40–42} The proportion of inoculations giving rise to infections in infants decreased in the high-transmission season compared with the low-transmission season in a holoendemic village. In nearby East Usambaras, the proportion of inoculations leading to a patent infection was eight times higher in low-transmission villages compared with high-transmission villages.^{31,40} Similarly, a disproportionately small reduction in re-infection rates compared with reduction in transmission intensity was observed in the Usambara lowlands with the introduction of impregnated bed nets.^{41,42} Thus, a non-immune mechanism may be involved in this phenomenon.

The logistic regression model of parasite prevalence suggested that the prevalence was significantly related to the interaction between age and the annual inoculation rate. This interaction between age and exposure intensity causes the prevalence to decrease faster in villages with high transmission and decrease faster in the youngest age groups. We interpret this interaction as a measure of accumulated exposure. The analysis was adjusted for the effect of transmission intensity, and we therefore suggest that the developing immunity in the four lowest villages is partly caused by an independent effect of accumulated exposure separate from the effect of transmission intensity. The logistic regression model also suggested that parasite prevalence was significantly related to an effect of age alone. This effect of age can be observed in the age-prevalence curves, which in the four lowest villages peaks at the same age group and levels out at the same age group, despite the accumulated exposure being 50-fold greater in the lowest village. Thus, the accumulated exposure in the lowland at two years of age is equivalent to that accumulated after 100 years at 1,000 meters. A sub-sample from each village also showed that super infections are related to both age and transmission intensity, but that the diversity of parasite strains in the six villages was similar.¹⁷ The proportionally few high-density parasitaemias in adults in all villages strongly suggests that the acquired immunity protecting against high-density infections is related more to age itself than to accumulated exposure. The regression model would thus suggest that non-immune children suddenly exposed to

malaria transmission would develop anti-parasite immunity much more slowly than non-immune older age groups exposed to malaria transmission. Such an effect of age has been observed in Indonesia in people moving from malaria-free islands to malaria-endemic areas.^{10,11}

The data reported were collected during cross-sectional surveys in November–December. Thus, these findings apply to the low-transmission season, and the degree to which this season reflects the entire year remains to be explored. It should be appreciated that the findings presented in this study are parasitologic and not clinical. There may be antitoxic immune mechanisms that result in high-density infections without morbidity, but immunity against infection and high infection density discussed here is likely to contribute to clinical immunity.

The findings from the present study suggest that both exposure and age-dependent acquired immune mechanisms are involved in anti-parasite immunity. The relative impact of these two mechanisms has important implications for the effectiveness of different types of control strategies, for example, transmission control, mass drug administration, and vaccination.⁴³

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