

House Structure Is Associated with Malaria among Febrile Patients in a High-Transmission Region of Zambia

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Abstract. Since the late nineteenth century, the importance of house structure as a determinant of malaria risk has been recognized. Few studies to date have examined the association of housing and malaria in clinical populations. We conducted a cross-sectional study of febrile patients ($n = 282$) at two rural health clinics in a high malaria-transmission area of northern Zambia. Participants underwent testing for *Plasmodium falciparum* infection by PCR. Demographic and other risk factors including house structure, indoor residual spraying (IRS), bed net use, education level, and household income were collected. Data were fitted to logistic regression models for relational and mediation analyses. Residing in a house with a thatch roof was associated with higher odds of malaria than residing in a house with corrugated metal (odds ratio: 2.6; 95% CI: 1.0–6.3, $P = 0.04$). Lower income and educational attainment were also associated with greater odds of malaria. Living under a thatch roof accounted for 24% (95% CI: 14–82) of the effect of household income on malaria risk, and income accounted for 11% (95% CI: 8–19) of the effect of education. Neither IRS nor bed net use was associated with malaria risk despite large, local investments in these vector control interventions. The findings testify to malaria as a disease of rural poverty and contribute further evidence to the utility of housing improvements in vector control programs.

INTRODUCTION

When the transmission of malaria was first discovered over a century ago to occur mainly through indoor biting by anopheline mosquitoes, the importance of house structure to malaria risk was recognized. The earliest experiments were conducted by Angelo Celli in the Italian campagna during the 1890s, and the first review on the subject was published in 1931 by the Malaria Commission of the League of Nations and updated only 85 years later by Tusting and others.^{1–3} Today, housing-based approaches to malaria control are not routinely deployed, although growing evidence supports their effectiveness.⁴

The National Malaria Control Program of Zambia aims to eliminate malaria within its borders in this decade, yet transmission remains intractably high in the northern wetlands of Luapula Province despite 12 years of concerted efforts.⁵ To the south, by contrast, malaria remitted in the wake of drought, aggressive vector control, mass drug administration, case management, and improvements in housing over time.^{6–11}

Housing modifications can safeguard against malaria by reducing contact between mosquito vectors and human hosts. Indoor mosquito abundance, mosquito behavior and life span, and uptake of vector control measures vary with housing.¹² Mosquito abundance is affected by construction features such as eaves and other structural gaps which are the primary entry points for mosquitoes.^{13–15} Resting and feeding behaviors fluctuate with ambient temperature and humidity, which vary with the type of building materials.^{16,17} Metal roofs appear to discourage mosquito resting and reduce mosquito

longevity because of higher temperatures than natural roofs; feeding anophelines rely on evaporative cooling during blood meals and risk overheating when ambient temperatures are too high.^{16,18} Housing features can ease or restrict bed net use, different wall materials can impact the adsorption and residual efficacy of sprayed insecticide (e.g., different insecticides adhere differently to wood versus plaster), and brighter interiors or lighter walls can facilitate personal protection against mosquitoes by increasing the mosquitoes' visibility.^{19–21}

House structure and its relationship to malaria risk are interconnected with other socioeconomic indicators such as income, education, occupation, household consumption, asset indices, and other metrics.^{22,23} Studies that seek to characterize or quantify the associations between socioeconomic indicators and malaria risk are complicated by the tortuosity of the causal pathways and multiply connected variables. For example, the relationship between income and education is bidirectional and relies on their temporal relationship: higher education leads to higher earning potential, and, conversely, greater income affords greater educational opportunities.²⁴ Both education and income modify a person's likelihood or ability to access preventive resources, which in turn influence malaria risk,^{25–30} and both are correlated with a person's occupation and the type of house in which they live.^{23,31,32} Models that do not account for the mediating relationships across variables can miss or misestimate important associations.^{33,34}

Previous studies of housing and malaria in sub-Saharan Africa focused on community-based populations.³ Here, we investigated housing and other socioeconomic variables to assess their potential as risk factors for malaria within a clinical population. We hypothesized that better housing reduces the odds of malaria independent of other sociodemographic factors, and that house structure plays an important role in the pathways that relate income and education to malaria risk.

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METHODS

Study design. This was a cross-sectional study of child and adult patients presenting with acute febrile illness to rural health centers in Nchelenge District, Luapula Province. Patients were recruited during the rainy season from November to December 2017 for a validation study of a novel isothermal PCR diagnostic test for *Plasmodium* spp. infection (data not shown).³⁵ Participants provided informed consent. The study protocol was approved by the Ethics Review Committee of the Tropical Diseases Research Centre in Ndola, Zambia.

Study site. Recruitment was from two rural health centers in Nchelenge District, a high malaria-transmission area that encompasses wetlands along Lake Mweru, bordering the Democratic Republic of Congo.³⁶ The local economy is largely agrarian and fishing based. Local building materials include wooden pole-and-straw construction for walls, sunbaked mud bricks, fired bricks, mixed cement, dried straw thatch, and corrugated metal. Eaves, the ventilation gaps between roof and wall that provide a path of entry for mosquitoes, are present in most houses with thatch roofs but not in those with metal roofs (Figure 1).

Malaria is holoendemic, with an average parasite prevalence of 51% year round peaking in the rainy season (October–April).³⁶ *Plasmodium falciparum* is the vastly predominant species with rare instances of *Plasmodium malariae* coinfection or mono-infection. The main vector species is *Anopheles funestus* sensu stricto (s.s.), most abundant inland from the end of the rainy season and throughout the dry season, and *An. gambiae* s.s., which peaks lakeside during the rains.^{37,38} Since 2008, indoor residual spraying (IRS) has been conducted annually, targeted to the lakeside area and timed to the onset of the rainy season, but has had little overall impact on transmission.³⁹ Malaria continues to account for upward of 30–40% of admissions to the children’s ward and 40% of pediatric in-hospital deaths.⁴⁰

Study participants. Participants were pediatric and adult patients presenting with acute febrile illness. Inclusion criteria were willingness to participate and provision of informed consent (and assent for children younger than 18 years). Exclusion criteria were severe signs or symptoms of malaria or other illness due to the need of these patients to be transferred from the study site to the nearby hospital.

Study procedures. All participants underwent testing for *P. falciparum* infection by thick blood smear microscopy, rapid diagnostic test (RDT, Standard Diagnostics Inc., Suwon, Korea), and subsequent PCR targeting *P. falciparum* species-specific 18S rRNA using whole blood collected as dried blood spots on Whatman 903 protein saver cards

(Sigma-Aldrich, St. Louis, MO) according to published methods.^{41,42} Blood smears were reviewed independently by two expert microscopists. Parasites were counted against 200 leukocytes and densities estimated assuming 8,000 leukocytes per mm³ of blood.

House structure was classified according to composition of wall (straw-and-pole, cement, or brick) and roof (straw thatch and corrugated metal), as reported by participants. Demographic and other details including IRS within the last 6 months, whether the participant slept under an insecticide-treated bed net (ITN), educational background, occupation of the head of household, and monthly household income were also collected. Housing and demographic data were collected via questionnaires administered to the participant (or participant’s legal guardian) by a trained study team member.

Exposure and outcome. The main exposure of interest was house type defined according to roof and wall composition (thatch or metal roof, straw-and-pole, or brick walls). Other exposures were participant and household socio-demographic features. The primary outcome was PCR-confirmed diagnosis of malaria.

Statistical analysis. Data were fitted to unadjusted and adjusted logistic regression models for relational and mediation analyses. Baseline characteristics were compared between groups using Student’s *t*-test for continuous variables in pairwise comparisons or one-way analysis of variance in multiple group comparisons, or Pearson’s χ^2 test for dichotomous variables. Adjusted models incorporated posited confounders that differed across house types ($P < 0.10$). Mediation of the association between income and malaria by housing, and between education and malaria by income, were assessed using procedures developed by Imai et al. to accommodate binary outcomes.³⁴ These methods apply a counterfactual framework that formally distinguishes main effects from mediation effects. The mediation analyses were predicated on the theories that past educational attainment is positively and causally associated with income in the present, and that present income is positively and causally associated with quality of housing (Figure 2). Statistical analyses were carried out using Stata 16.0 (StataCorp, College Station, TX).

RESULTS

Participant characteristics. A total of 282 participants were enrolled in the primary study, of whom 272 provided complete housing data. Table 1 displays participant characteristics according to house type. The median age was 19 years (interquartile range [IQR]: 8–32), and a slight majority (56%) were female. Median monthly household income was Zambian kwacha 250 (IQR: 100–600), equivalent to less than US \$1/day. Individuals residing in higher quality houses (metal roof $\pm$ solid walls) had on average higher educational attainment and heads of household with higher paying occupations than those in lower quality houses. Almost half (46%) of participants living in the highest quality houses completed secondary school, compared with less than a quarter (22%) in the lowest quality houses (Pearson’s χ^2 , $P < 0.01$).

Most participants (56%) resided in houses of straw-and-pole walls and thatched roof. The next most common house type (32%) was brick wall and metal roof. There were few living in houses of mixed construction, with 9% in houses with solid walls and thatched roofing, and 3% in houses with natural

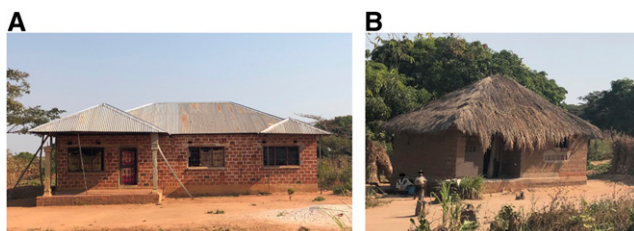


FIGURE 1. Photographs of representative house types showing (A) fired-brick walls and metal roof and (B) sunbaked mud brick walls and thatch roof. This figure appears in color at www.ajtmh.org.

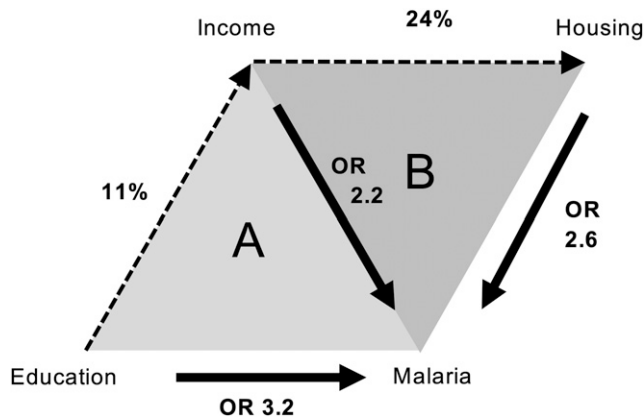


FIGURE 2. Directed acyclic graph of the hypothesized relationships among education, income, housing, and malaria in febrile patients within a highly malarious area of Zambia. Graph A depicts the partial mediation of the association of income with malaria by housing, and graph B shows the partial mediation of the association of education with malaria by income. Odds ratios (ORs) were computed from logistic regression of malaria PCR test positivity on education (primary vs. secondary or higher), daily income (< 2 USD vs. $\geq$ 2 USD), and housing (thatch vs. metal roof). Percent contributions were calculated from mediation analyses conducted according to Imai et al.³⁴

walls and solid roofing. Prior IRS was more common in lower quality houses (58–71%) than the highest quality houses (44%) (Pearson's χ^2 , $P = 0.04$).

Malaria was diagnosed by PCR in 180 of the 272 participants (66%) (Table 2). Rapid diagnostic test and microscopy detected fewer infections (48% and 38%). Among those with positive blood smears, the median parasite count was 83,200 parasites/ μ L (range 1,500–2,806,000). One participant had a

positive blood smear (17,500 parasites/ μ L) but negative PCR result, attributed to compromised integrity of the dried blood spot. Eighty participants (29%) had sub-patent malaria defined by a positive PCR result and negative blood smear.

Association of participant characteristics with malaria.

The highest proportion of cases occurred in school-aged children, and the lowest proportion in adults older than 40 years. Adjusted for sex, prior IRS, ITN usage, and house features, school-aged children had twice the odds of infection relative to other age-groups (odds ratio [OR]: 1.9; 95% CI: 0.1–3.7, $P = 0.05$). Adjusted for the same conditions, adults older than 40 years had 67% reduced odds compared with other age-groups (OR: 0.33; 95% CI: 0.17–0.67, $P = 0.002$).

Lower income and educational attainment were also associated with greater odds of malaria (OR: 2.2; 95% CI: 1.3–3.9, $P = 0.005$ for income less than USD 2/day, OR: 3.2; 95% CI: 1.9–5.6, $P < 0.001$ for less than secondary-level education). Patient sex and ITN use were not associated with malaria.

Association of house features with malaria. Residing in a house with a thatch roof was associated with 2.6 times greater odds of malaria than living in a house with a metal roof, including after adjustment for wall type, number of rooms, number of co-occupants, and recent IRS (OR: 2.6; 95% CI: 1.0–6.3, $P = 0.04$; Table 3, Figure 3). Compared with all other house types, residing in a house with the highest quality construction materials—metal roof and brick walls—was associated with 62% lower odds of malaria (OR: 0.38; 95% CI: 0.20–0.73, $P = 0.004$). Wall construction alone, number of rooms, number of occupants, or prior IRS was not associated with malaria in either unadjusted or adjusted models. Mediation analyses showed that roof type accounted for a large portion of the association between household income and

TABLE 1
Sociodemographic characteristics of participants according to house type

Characteristic	Straw-and-pole walls		Cement or brick walls		P-value
	Thatch roof n = 154	Metal roof n = 7	Thatch roof n = 24	Metal roof n = 87	
Median age (IQR) (years)	18 (6–30)	18 (5–52)	18 (6–26)	20 (15–35)	0.23
Age distribution (years), no. (%)					
< 5	29 (19)	1 (14)	3 (13)	5 (6)	0.05
5–15	42 (27)	1 (14)	8 (33)	17 (20)	0.37
16–29	43 (28)	3 (43)	8 (33)	35 (40)	0.24
30–39	18 (12)	0 (0)	1 (4)	11 (13)	0.51
≥ 40	22 (14)	2 (29)	4 (17)	19 (22)	0.41
Female sex, no. (%)	87 (61)	2 (33)	11 (48)	45 (51)	0.26
Educational attainment, no. (%)					
Primary	75 (49)	1 (14)	8 (33)	31 (36)	0.06
Secondary	33 (22)	4 (57)	8 (33)	40 (46)	< 0.01
Tertiary	0 (0)	0 (0)	0 (0)	4 (5)	0.04
Occupation, no. (%)					
Farmer	82 (54)	5 (71)	14 (58)	35 (40)	0.09
Fisher	21 (14)	1 (14)	0 (0)	2 (2)	0.01
Laborer	9 (6)	1 (14)	0 (0)	4 (5)	0.44
Merchant	13 (9)	0 (0)	1 (4)	6 (7)	0.74
Office profession	3 (2)	0 (0)	1 (4)	22 (25)	< 0.01
None	14 (9)	0 (0)	2 (8)	7 (8)	0.85
Other	9 (6)	0 (0)	6 (25)	11 (13)	0.01
Median income, Zambian kwacha/mo. (IQR)	200 (100–400)	500 (200–1,000)	400 (100–800)	500 (250–1,700)	< 0.01
Bed net use, no. (%)	126 (82)	100 (100)	23 (96)	77 (89)	0.16
Indoor residual spraying in prior 6 months, no. (%)	95 (62)	5 (71)	14 (58)	38 (44)	0.04
Mean no. of occupants (SD)	5.7 (2.2)	6.6 (1.5)	5.7 (2.3)	7.2 (3.1)	< 0.01
Mean no. of rooms (SD)	3.6 (0.8)	5.0 (1.3)	4.0 (1.4)	5.7 (2.0)	< 0.01

IQR = interquartile range. P-values were computed by one-way analysis of variance for continuous variables or Pearson's χ^2 test for dichotomous variables.

TABLE 2
Sociodemographic and clinical characteristics of participants according to *Plasmodium falciparum* infection status

Characteristic	PCR result		P-value
	Negative n = 92	Positive n = 180	
Median age (IQR) (years)	24 (10–42)	18 (8–28)	< 0.01
Age distribution (years), no. (%)			
< 5	13 (14)	25 (14)	0.96
5–15	16 (17)	52 (29)	0.04
16–29	30 (33)	59 (33)	0.98
30–39	8 (9)	22 (12)	0.38
≥ 40	25 (27)	22 (12)	< 0.01
Female sex, no. (%)	50 (56)	92 (56)	0.95
Educational attainment, no. (%)			
Primary	31 (34)	84 (47)	0.04
Secondary	44 (48)	41 (23)	< 0.01
Tertiary	2 (2)	2 (1)	0.49
Occupation, no. (%)			
Farmer	42 (46)	94 (53)	0.30
Fisher	8 (9)	16 (9)	0.96
Laborer	4 (4)	10 (6)	0.67
Merchant	9 (10)	11 (6)	0.27
Office profession	13 (14)	13 (7)	0.07
None	4 (4)	19 (11)	0.08
Other	11 (12)	15 (8)	0.34
Wall type, no. (%)			0.15
Straw-and-pole	49 (53)	112 (62)	
Cement or brick	43 (47)	69 (38)	
Roof type, no. (%)			0.03
Thatch	52 (57)	126 (70)	
Metal	40 (43)	54 (30)	
Mean monthly income, Zambian kwacha, (SD)	400 (150–1,000)	200 (100–500)	< 0.01
Bed net use, no. (%)	80 (87)	153 (86)	0.74
Indoor residual spraying in prior 6 months, no. (%)	53 (58)	99 (55)	0.68
Mean no. of occupants (SD)	6.2 (2.9)	6.2 (2.5)	0.94
Mean no. of rooms (SD)	4.4 (1.6)	4.4 (1.7)	0.99
Rapid diagnostic test positive, no. (%)	8 (9)	121 (67)	–
Blood smear positive, no. (%)	0 (0)	93 (52)	–
Gametocytemia, no. (%)	0 (0)	7 (4)	–
Median parasites per μ L (IQR)	17,500	84,960 (15,200–402,210)	–

IQR = interquartile range. P-values were computed by Student's t-test for continuous variables or Pearson's χ^2 test for dichotomous variables.

malaria (24%, 95% CI: 14–82), and household income in turn accounted for 11% (95% CI: 8–19) of the association of education with malaria (Figure 2).

DISCUSSION

This cross-sectional study of patients presenting with fever to rural health centers in a highly malarious region of Zambia identified house structure as a risk factor for *P. falciparum* infection. Residing in a house with a thatched roof nearly tripled the odds of malaria compared with living in a house with a metal roof, whereas residing in a house with brick walls and a corrugated metal roof more than halved the odds compared with other house types. Higher income and greater educational attainment were also associated with lower odds of malaria. Mediation analyses suggested that roof type explained one-fourth of the association between household income and malaria, and household income explained one-tenth of the relationship between education and malaria. Notably, IRS and ITN use were not associated with malaria risk despite local investments in these vector control measures. Together, these findings attest to the significance of house structure to malaria risk: even in this population of individuals with a remarkably high pretest probability of malaria,

differences in house structure were independently able to discern those who tested positive from those who tested negative. These findings also may explain, in part, the recalcitrance of malaria despite control efforts in this region and similar areas. The highest risk house feature, thatch roof, was also the most prevalent (65%).

Housing is a known, modifiable risk factor for malaria, but the evidence is equivocal with regard to the relative contributions of wall construction or roof construction.^{3,43–50} The present study suggests that in certain settings, roof construction and its attendant factors play a greater role in modulating malaria risk than wall construction. Concealed crannies in thatch roofs that foster higher mosquito densities,⁵¹ relatively faster parasite development and prolonged indoor dwelling due to differences in indoor temperature across different roof materials,^{16,52,53} ease of entry via eaves,^{14,54} and hindrances to bed net use (related structural features and effect on ambient environment)^{19,55,56} are possible mechanisms of the observed associations between thatch roofs and malaria risk.

The protective association between higher household income and malaria is mediated by several factors apart from housing. Higher income has been shown to be associated with greater uptake of malaria preventive measures such as ITN ownership and retreatment.^{25,27,29,30} When they fall ill,

TABLE 3
Unadjusted and adjusted ORs for *Plasmodium falciparum* infection according to house structure

Characteristic	Unadjusted			Adjusted		
	OR	95% CI	P-value	OR	95% CI	P-value
Wall type						
Straw-and-pole	1.45	0.87–2.40	0.16	0.90	0.39–2.07	0.81
Cement or brick	Ref	–	–	Ref	–	–
Roof type						
Thatch	1.79	1.07–3.02	0.03	2.56	1.03–6.31	0.04
Metal	Ref	–	–	Ref	–	–
Overall house type						
Brick wall and metal roof	0.56	0.33–0.94	0.03	0.38	0.20–0.73	< 0.01
Other	Ref	–	–	Ref	–	–

OR = odds ratio. Estimated from logistic regression models. The adjusted model included wall type, roof type, number of rooms, number of cohabitants, and prior indoor residual spraying.

wealthier individuals are more likely to seek care and less likely to use leftover drugs than their poorer counterparts.^{57,58} The role of education is similarly multifarious and its association with malaria risk previously shown.^{23,59–61} Studies found a positive correlation of education with malaria knowledge and ITN ownership,^{62,63} as well as with health facility use and whether biomedical or ethnomedical care was sought.^{62,64}

Our other results agree with previously reported findings in the literature. Higher prevalence of malaria in school-aged children than in other age groups is also seen in similar settings.⁶⁵ The protective contribution of older age is explained by acquired immunity over time with repeat infections

(premunition).⁶⁶ The imbalance toward female adult patients (66% women versus 34% men, χ^2 test, $P < 0.001$) suggests underuse of health clinics by men, a common experience in similar subsistence economic settings.⁶⁷ The absence of a protective effect of IRS is consistent with a contemporaneous report of only marginal impact of IRS on malaria in the study area, and echoes findings of the landmark Garki Project.^{40,68} Outdoor transmission, incomplete spray coverage in the community, inaccurate timing of IRS in relation to malaria vector density, poor residual efficacy, or mosquito resting behaviors that avoid sprayed surfaces are among factors that could explain its low efficacy in this setting. Similarly, ITN use

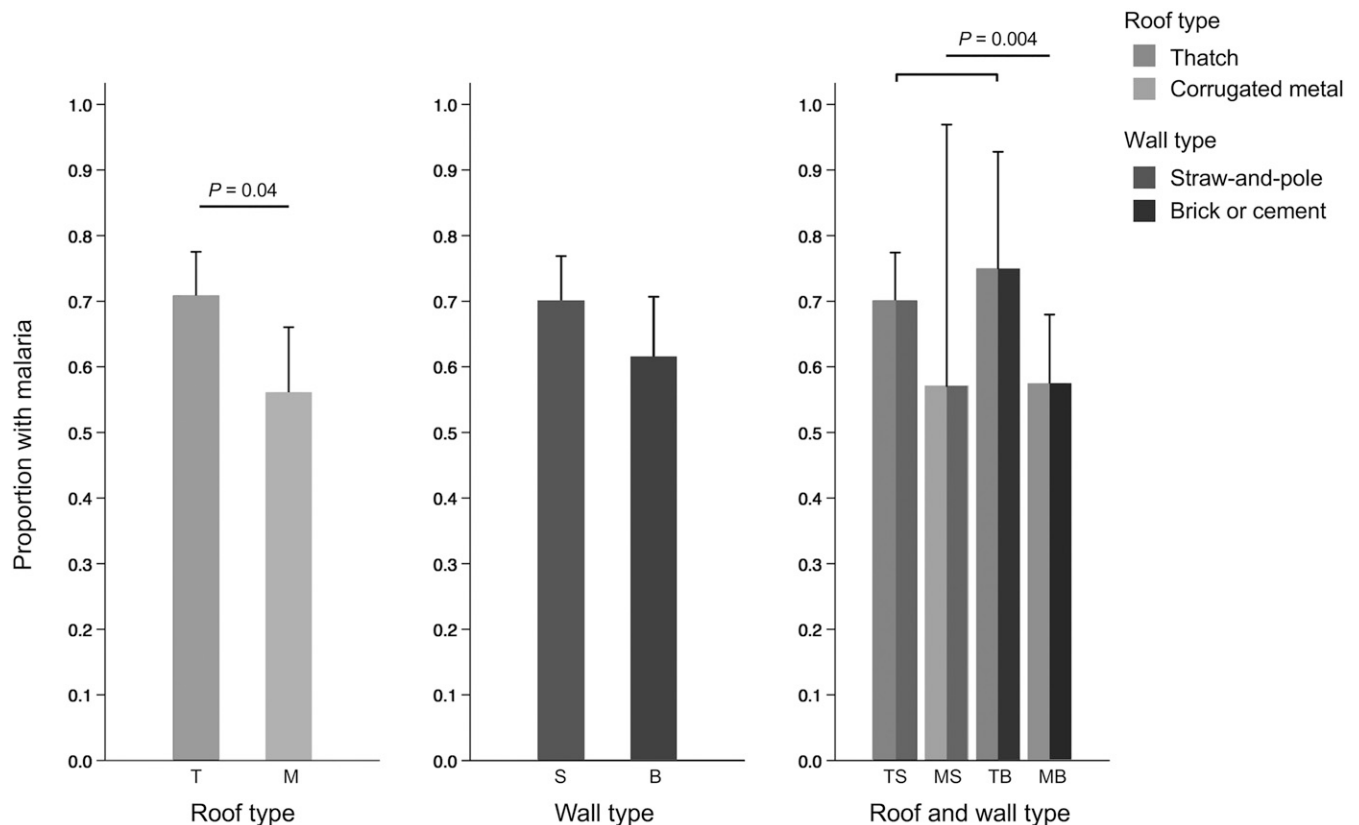


FIGURE 3. Malaria prevalence by house construction type. (A) shows comparison by roof construction (T = thatch and M = metal), (B) shows comparison by wall material (S = straw-and-pole and B = brick or cement block), and (C) shows results stratified by combinations of roof and wall types. Among patients presenting to rural health clinics with fever, living in a house with a thatch roof was associated with increased odds of malaria (adjusted OR: 2.6; 95% CI: 1.0–6.3, $P = 0.04$ denoted by asterisk). Error bars represent 95% CIs.

was not significantly associated with malaria in our sample. We suspect this is explained by the small sample size, reporting bias, and ascertainment bias due to the nature of the study population. The study population consisted of febrile clinic patients residing in a highly malarious area who therefore had a high pretest probability of malaria, and hence may represent a group of people less likely to receive a benefit from ITN use than their nonfebrile, nonclinical counterparts.

This was an observational study using cross-sectional data from rural health centers in a high malaria-transmission area Zambia and therefore bears inherent limitations in its ability to demonstrate causation and generalizability to other populations. However, the specific protective mechanisms of housing against malaria are plausible and well described in previous studies in similar settings, including recent cluster-randomized trials that examine window and eave screening and construction with alternative materials.⁴ This is a secondary analysis of data collected during the course of a validation study of a diagnostic test; data collection was not optimized for in-depth study of housing features. We lacked data on the presence or absence of eaves, ceilings, windows, and other potentially important features. Similarly, an ideal study of malaria and housing would incorporate entomological and geospatial data, which were not collected given the clinical scope of the parent study. The definition of malaria used herein subsumes clinical malaria but may have included incidental parasitemia occurring in the presence of non-malarial causes of fever. However, parasitemia without clinical malaria (sub-patent malaria and chronic malaria) is itself a relevant outcome to the study, given the interest in examining associations with *P. falciparum* infection and house structure.

Malaria is foremost a disease of rural poverty with a complex array of predisposing factors that include environmental, vector bionomic, and sociodemographic.²² The association between housing and malaria encompasses direct and indirect effects, from directly impeding mosquito entry to indirectly influencing IRS durability and bed net usage.^{13–16,19,20} House structure tracks predictably with income, occupation, and education, each of which entail downstream factors ranging from health-seeking behavior to access to health care and purchasing power.⁶⁹ House structure appeared to account for a significant fraction (24%) of the association between income and malaria, and household income in turn explained a fair portion (11%) of the association of education with malaria. Understanding the extent of these associations can help guide malaria control policies and direct resources to those at greatest risk.

CONCLUSION

For over a century, housing modifications that reduce exposure to mosquito vectors have been recognized as a potential ward against malaria. Alongside IRS and ITNs, housing improvements represent an effective yet underused tool for vector control.^{3,4} Current Zambian housing regulations set standards for ventilation, overcrowding, and other public safety elements but do not take advantage of the opportunity to promote malaria control through evidence-based housing guidelines.⁷⁰ Housing-directed initiatives, independent of other malaria control or economic development policies, are predicted to reduce malaria transmission in northern Zambia and similar high-transmission settings. Formulation of local and national housing standards with an eye toward vector control could help advance malaria control.

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