How house design affects malaria mosquito density, temperature, and relative humidity: an experimental study in rural Gambia

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Summary

Introduction Unprecedented improvements in housing are occurring across much of rural sub-Saharan Africa, but the consequences of these changes on malaria transmission remain poorly explored. We examined how different typologies of rural housing affect mosquito house entry and indoor climate.

Methods Five typologies of mud-block houses were constructed in rural Gambia: four were traditional designs with poorly fitted doors and one was a novel design with gable windows to improve ventilation. In each house, one male volunteer slept under a bednet and mosquitoes were collected indoors with a light trap. Typologies were rotated between houses weekly. Indoor conditions were monitored with data loggers and the perceived comfort of sleepers recorded with questionnaires. We used psychrometric modelling to quantify the comfort of the indoor climate using the logger data. Primary measurements were mean number of Anopheles gambiae and mean temperature for each house typology.

Findings In thatched-roofed houses, closing the eaves reduced A gambiae house entry by 94% (95% CI 89–97) but increased the temperature compared with thatched-roofed houses with open eaves. In houses with closed eaves, those with metal roofs had more A gambiae, were hotter (1.5°C hotter [95% CI 1.3–1.7]) between 2100h and 2300 h, and had 25% higher concentrations of carbon dioxide (211·1 ppm higher [117·8–304·6]) than those with thatched roofs. In metal-roofed houses with closed eaves, mosquito house entry was reduced by 96% (91–98) by well fitted screened doors. Improved ventilation of metal-roofed houses made them as cool as thatched houses with open eaves. Metal-roofed houses with closed eaves were considered more uncomfortable than thatched ones with closed eaves. In metal-roofed houses, ventilated houses were more comfortable than unventilated houses before midnight, when people retired to bed.

Interpretation Closing the eaves reduced vector entry in thatched houses but increased entry in metal-roofed houses. Metal-roofed houses with closed eaves were, however, protected against malaria vectors by well fitted screened doors and were made comfortable by increasing ventilation. House designs that exclude mosquitoes and are comfortable to live in should be a priority in sub-Saharan Africa.

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Introduction

The International Monetary Fund forecasts that Africa will have the world’s second fastest growing economy by 2020.1 Increased prosperity means families having more disposable income to spend on housing improvements. The improving economy has contributed to a quiet revolution in rural African housing, with traditional thatched-roofed houses gradually being replaced by more modern housing materials, particularly with metal roofs.2 The scale of building new housing will be huge in Africa, more than half of the anticipated growth in global population will occur between 2017 and 2050.3 Of the forecasted extra 2.2 billion people, 1.3 billion will be born in Africa.3 The implications of these unprecedented changes in rural housing on health have not been considered.

Since 80–100% of malaria transmission in sub-Saharan Africa occurs indoors,4 reduction of the entry of malaria vectors indoors should reduce the numbers of malaria cases. Indeed, evidence is growing that suggests modern housing provides greater protection against malaria vectors than traditional housing. A systematic review and meta-analysis5 found that residents of modern houses were 47% less likely to contract malaria and had a 45–65% lower incidence of malaria than those living in traditional houses. However, a meta-analysis6 of malaria surveys carried out in 21 sub-Saharan African countries between 2008 and 2015 found that modern housing was associated with a 9–14% reduction in the odds of malaria infection compared with traditional housing. If modern housing is protective against malaria, which features of modern sub-Saharan African housing are protective?

References

Research in context

Evidence before this study
Despite 80–100% of malaria transmission in sub-Saharan Africa occurring indoors, few experimental studies have investigated how house design affects mosquito house entry and even fewer have considered how the design of rural houses in sub-Saharan Africa affects indoor climate. We searched Google Scholar using the terms “Anopheles gambiae” and (“architecture” or “house” or “indoors” or “indoor climate” or “comfort index”) for articles published in any language between database inception and Dec 20, 2017. We also examined reference lists from review articles. Considerable evidence suggests that open eaves—ie, the gap between the top of the wall and the roof—are the major route by which A gambiae sensu lato, the major sub-Saharan African malaria vector, enters houses. Nowadays, however, modern houses are built with metal roofs with closed eaves and the traditional thatched-roofed houses with open eaves are less common. The consequences of these changes on house entry by malaria vector has not been quantified, and pilot studies on indoor climate in The Gambia and Tanzania suggest that modern housing, in which the eaves are closed and the roof is made of metal, is hotter and more uncomfortable than traditional housing.

Additional value of this study
This experimental study is the first to use buildings of a size and structure similar to those constructed in rural parts of sub-Saharan Africa, which is important since the heating and cooling of houses is dependent on the mass and position of the different materials used for house construction.

Ultimately, the typology of house shapes the way plumes of human odours are released from the house, which are used by mosquitoes to locate a human bloodmeal indoors, and makes a building comfortable or not for the human occupants. Rotating the typologies between houses each week allowed us to adjust for any variation in mosquito numbers that might arise from house position—eg, one house having high numbers of mosquitoes since it is positioned closer to aquatic habitats than the other houses. The replicated, Latin rectangle experimental design simultaneously quantified how four different building typologies common in rural Gambia and one novel house type, with a metal roof and increased ventilation, affected house entry by A gambiae sensu lato and indoor climate. Indoor climate is important for malaria control since although a perfectly sealed house might reduce mosquito house entry, it might be too hot for the occupants to use a bednet. We found that closing the eave gaps reduced mosquito house entry in thatched houses but increased entry in metal-roofed houses. This difference is important since most new houses in sub-Saharan Africa are constructed with metal roofs. We showed that screening the doors of metal-roofed houses reduced the number of vectors entering the house and improving ventilation, by inserting screened windows in the gable ends under the saddle roof, made the house cooler at night.

Implications of all the available evidence
Roll Back Malaria, UN Development Programme, and UN-Habitat’s Housing and Malaria consensus statement asked what architectural features are protective against malaria. The available evidence shows clearly that closing the eaves of thatched-roofed houses will reduce malaria transmission, but that this modification is insufficient for metal-roofed houses because mosquitoes enter through gaps in poor quality doors. The use of well fitted screened doors, together with improved ventilation, should be encouraged. The unknown factor is the acceptability of the interventions and how local populations will use them. Building designs that include effective screening against mosquitoes and increase airflow in the house could help reduce malaria transmission and maintain areas free from malaria after elimination.

To date, little research has been done on this subject. Observational studies have found associations between reduced numbers of malaria vectors indoors and the presence of closed eaves, the gap between the top of the wall and the overhanging roof and ceilings, which has been supported by experimental studies. The findings show that open eaves are the major route by which Anopheles gambiae sensu lato enters houses and that closing them or installing a ceiling below the eaves prevents a substantial proportion of the vectors from entering the living space. A pilot study of modern houses in rural Tanzania showed that mosquito numbers indoors were 96% less in screened double-storey buildings than outdoors, with corresponding values of 77% less in screened single-story buildings and 23% less in traditional houses. Thus, accumulating evidence suggests that mosquito house entry can be reduced appreciably by filling or screening entry points.

In rural Gambia, single-room houses have distinct typologies, which are also common in many parts of sub-Saharan Africa. Nowadays, most rural Gambian houses are constructed from sundried mud bricks, which became common during the mid-twentieth century. These traditional houses have two doors, front and back, one or two windows, or none at all, and have thatched roofs with open eaves (appendix). In the past 5–10 years, however, finding thatched-roofed houses with open eaves is increasingly more difficult in The Gambia since householders are closing them with mud, partly because of recommendations broadcast by the national malaria control programme to reduce the entry of mosquitoes and also because they think it prevents strong winds removing the roof. The most obvious change in housing stock, however, is the gradual replacement of thatched-roofed houses with metal-roofed ones, most of which also have closed eaves.

See Online for appendix
Alongside the single-room houses are some multiroom line houses, which are also increasing in number and almost always have metal roofs. One problem with metal-roofed houses is that they are often hotter than thatched ones, and this increase in temperature might reduce the number of people sleeping under a long-lasting insecticidal net (LLIN; Olyset, Sumitomo Chemical, Tokyo, Japan)—one of the most effective malaria control tools currently available. In this study, we assessed not only how local house designs affected mosquito ingress but also how mosquito screening could be used to protect occupants from mosquitoes and keep the house cooler. The costs of building alterations were also assessed. This study is the first to use an experimental design to quantify how different house typologies affect mosquito house entry and indoor climate. The conundrum to solve is one of two opposing forces, to maximise airflow in a house to keep the occupants cool and to keep mosquitoes out. Building homes that reduce malaria vector house entry might not only reduce malaria transmission but also, after elimination, when current interventions are scaled back, might help prevent malaria from returning.

Methods

Study design
This was an experimental study of five human-baited houses identical in size, shape, and walls. Each house was modified to represent different house typologies, which were rotated weekly between the different houses following a replicated Latin rectangle design (appendix). We did two experiments. The first experiment investigated the relative attractiveness of different housing typologies to mosquitoes and compared the indoor climates, and the second experiment re-examined the differences between metal-roofed and thatched-roofed houses, both with closed eaves and poorly fitted doors.

Study area
The study site was in Wellingara village (N 13° 33·365’, W 14° 55·461’) on the south bank of the River Gambia in Lower Fulladu West, Central River Region, The Gambia (appendix). This area is an open Sudanian savannah with extensive rice irrigation nearby. An intense rainy season runs from June to November, followed by a long dry season. High numbers of *A gambiae* sensu lato occur in the area during the rainy season, with *Anopheles coluzzii* predominating.

Experimental houses
Five experimental houses positioned on a north–south axis were constructed 10 m apart on the western perimeter of the village close to the large irrigated Jahally-Pacharr rice fields to the west (appendix). Houses were the average size of a single-roomed house in rural Gambia, obtained from a survey of 400 randomly selected houses in the Upper River Region of The Gambia. The base of each house was 4·20×4·20 m and the 2·20 m high walls were constructed from sunbaked mud blocks (each 16 cm high×20 cm wide×32 cm long), with a front and back door on opposite sides, perpendicular to the line of houses, each 175 cm high and 75 cm wide. The only non-traditional building components were reinforced concrete ring-beams (20 cm high) on top of the wall, which were added to prevent the mud blocks cracking when the heavy roofs were moved between houses, and the metal profiles used to construct the roof frame.

The study was explained in the local language to male villagers and five healthy male volunteers aged older than 15 years who live in the local community provided signed-witnessed consent and were recruited to the study. When the volunteers were giving consent, emphasis was placed on the fact that if they fell ill during the study they would be treated at the local health clinic and treatment costs and transport would be reimbursed by the project. Each volunteer slept under an intact LLIN in each house from 2100 h to 0600 h, and a field assistant was posted throughout the night to ensure that the volunteers did not leave the huts except to use the bathroom. Mosquitoes were collected indoors with a US Centers for Disease Control and Prevention light trap, with the light bulb positioned 1 m above the mud floor next to the foot of the bed from 2100 h to 0600 h. The same man slept in the same house for the duration of the study, so the relative attractiveness of the person to mosquitoes was aliased with house position. Sleepers subjectively graded the night-time indoor climate as comfortable or uncomfortable. Mosquito collections were carried out for five nights each week for 5 weeks.

Experiment 1: differences between house typologies
Four house typologies common in The Gambia were included in the experiment, along with one novel design of a metal-roofed house, which was screened and ventilated. Houses with open eaves had a 3 cm gap between the top of the wall and the roof and those with closed eaves were blocked with a mixture of broken mud blocks and clay mortar. Traditional doors were constructed from a single panel of corrugate galvanised steel pinned to a wooden frame (2×2 cm). To simulate poorly fitted doors, which are common in villages, we made a 2 cm gap along the top and bottom of each door. Screened doors were made of 25 mm square steel profiles treated with anticorrosion paint. Two screened panels made from polyester netting (2×2 mm mesh; appendix) were placed at the top and bottom of the door, each 75 cm wide and 60 cm high and fixed to the steel frame with flat bars and bolts. Each door was connected to the doorframe by a short bungee cord that made it self-closing, unlike the traditional doors. The ventilated metal-roofed house had screened doors and triangular screened windows (200 cm wide and 45 cm high at the apex), constructed with wooden frames (2×2 cm) and mosquito screening and were positioned in the gable ends of the building. Thatched roofs were pyramidal in
shape and 3·6 m high and metal roofs were saddle shaped and 3·1 m high. Thatched-roofed houses had a volume of 47·0 m³ and metal-roofed houses had a 46·8 m³ volume. Floors were beaten mud.

At the start of the experiment, we randomly allocated each typology using computer software to one of five identical partially-built houses, each consisting of a mud-walled building with no doors, windows, or roof. Each house was then completed according to the typology selected by randomisation for week one (appendix). The typologies rotated weekly between houses replicating a Latin rectangle design—ie, the houses were partially deconstructed and reconstructed at the end of each week. At the end of the 5-week study, each of the five typologies had been tested in each of the five experimental houses, which allowed us to measure the effect of the different typologies adjusting for geographical position of the house.

**Experiment 2: differences between metal-roofed and thatched-roofed houses with closed eaves**

In experiment 1 we were surprised to find more mosquitoes in closed-eave houses with metal roofs than thatched ones. Therefore, we repeated the experiment and examined whether the hotter temperatures in metal-roofed houses increased carbon dioxide production, a major mosquito attractant. In experiment 2, we made three changes to experiment 1. First, we enrolled two human participants to sleep in each house, since most Gambian houses have more than one occupant. Second, we fitted two metal windows on the same sides as the doors, 1·6 m above the ground, measuring 30×30 cm, with 1 cm gaps at the top and bottom of each one. Third, we measured carbon dioxide concentrations indoors. The primary purpose of experiment 2 was to compare the concentration of carbon dioxide in both house typologies. To avoid repetition, we only describe the comparison between closed-eave houses with metal-roofed and thatched-roofed houses here.

**Outcomes**

The primary outcomes measured were mean number of *A gambiae* sensu lato in the light trap at night and mean temperature for each house typology. In both experiments, indoor temperature and relative humidity were measured every 30 min with data loggers (Tiny tag, TGU 4500) positioned 1 m from the floor in the centre of the room. Outdoor temperature, relative humidity, wind speed, and wind direction were recorded with an automatic weather station (MiniMet, Skye Instruments, Llandrindod Wells, UK) positioned next to the houses. Thermal images were captured with a thermal imaging camera (FLIR ONE). Carbon dioxide concentrations were measured indoors in experiment 2 with data loggers (Onset Hobo MX1102) at 15 min intervals throughout the night from 2100 h to 0600 h for 25 nights, with the two loggers being moved between houses on alternate nights to reduce recording bias because of one logger recording consistently higher or lower than the other. All environmental measurements were made when the men were resident in the houses at night. Each morning during experiment 1, the volunteers were asked to score whether they had been comfortable or uncomfortable during the night.
Statistical analysis

For analyses, apart from psychrometric analysis, we used IBM SPSS Statistics 20 and Stata version 14. We estimated the sample size via simulation based on data from an experimental hut trial done in the same area, where the mean number of *Anopheles gambiae* sensu lato collected indoors over a 25-night study was 10·8 mosquitoes per house per night (SD 8·7). From the simulation, a 5×5 Latin square was powered to detect an intervention that reduced the number of mosquitoes collected in light traps by at least 50% at the 5% level of significance and 80% power.

We based the cost of materials and construction of each house type on actual payments made to local suppliers and builders in 2016, converted from Gambian Dalasi to US dollars (42·61 GMD=US$1; Sept 1, 2016). The costs included materials and labour and excluded transportation costs. We calculated the permeability of each typology from the area of entry points in the building—ie, including gaps in the eaves, around the doors, and screening. We assumed that screening doors and windows would reduce airflow by 64%.16

In experiment 1, we assessed the effect of house typology on mosquito house entry and indoor climate using generalised linear modelling, using a negative binomial model with a log link function for count data and a normal distribution with identity link for continuous variables. In addition to house typology, we included house position and day in the model as fixed effects. For experiment 2, we used generalised linear modelling to compare mosquito numbers between typologies. We used polar plots to depict the direction and strength of the wind during the day and night. We used linear regression to explore the relationship between carbon dioxide concentration and covariates.

We analysed human comfort in two ways. First, we summed the number of nights people were comfortable and uncomfortable for each type of housing type from their questionnaire answers. Second, we assessed human comfort using the software package LadyBug (LadyBug Products, Athol, ID, USA), which was used to estimate the proportion of time occupants of various house typologies spent in the so-called comfort zone.17

### Anopheles gambiae females per night

<table>
<thead>
<tr>
<th>House Type</th>
<th>Mean (95% CI)</th>
<th>Mean ratio (95% CI)</th>
<th>Effect estimate</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thatched roof, open eaves, traditional, poorly fitted doors</td>
<td>10·4 (3·8 to 17·0)</td>
<td>Reference</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Thatched roof, closed eaves, traditional, poorly fitted doors</td>
<td>0·7 (0·0 to 1·4)</td>
<td>0·06 (0·03 to 0·11)</td>
<td>–94% (89 to 97)</td>
<td>&lt;0·001</td>
</tr>
<tr>
<td>Thatched roof, closed eaves, screened, well fitted doors</td>
<td>0·4 (0·1 to 0·7)</td>
<td>0·04 (0·02 to 0·09)</td>
<td>–96% (91 to 98)</td>
<td>&lt;0·001</td>
</tr>
<tr>
<td>Metal roof, closed eaves, traditional, poorly fitted doors</td>
<td>17·2 (11·0 to 23·3)</td>
<td>2·99 (1·96 to 4·57)</td>
<td>199% (96 to 357)</td>
<td>&lt;0·001</td>
</tr>
<tr>
<td>Metal roof with ventilation in gables, closed eaves, screened, well fitted doors</td>
<td>0·8 (0·0 to 1·6)</td>
<td>0·06 (0·02 to 0·10)</td>
<td>–</td>
<td>&lt;0·001</td>
</tr>
</tbody>
</table>

### Other female mosquitoes per night

<table>
<thead>
<tr>
<th>House Type</th>
<th>Mean (95% CI)</th>
<th>Mean ratio (95% CI)</th>
<th>Effect estimate</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thatched roof, open eaves, traditional, poorly fitted doors</td>
<td>47·2 (36·0 to 58·4)</td>
<td>Reference</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Thatched roof, closed eaves, traditional, poorly fitted doors</td>
<td>36·8 (22·8 to 50·9)</td>
<td>0·57 (0·42 to 0·77)</td>
<td>–43% (23 to 58)</td>
<td>&lt;0·001</td>
</tr>
<tr>
<td>Thatched roof, closed eaves, screened, well fitted doors</td>
<td>6·2 (3·6 to 8·9)</td>
<td>0·11 (0·07 to 0·16)</td>
<td>–89% (4·8 to 93)</td>
<td>&lt;0·001</td>
</tr>
<tr>
<td>Metal roof, closed eaves, traditional, poorly fitted doors</td>
<td>66·2 (50·4 to 82·1)</td>
<td>1·21 (0·90 to 1·64)</td>
<td>+21% (10 to 64)</td>
<td>0·204</td>
</tr>
<tr>
<td>Metal roof with ventilation in gables, closed eaves, screened, well fitted doors</td>
<td>4·6 (2·1 to 7·1)</td>
<td>0·07 (0·04 to 0·10)</td>
<td>–</td>
<td>&lt;0·001</td>
</tr>
</tbody>
</table>

Data calculated with 95% CIs. General linearised modelling results, adjusted for house position and night.

<table>
<thead>
<tr>
<th>Maximum temperature</th>
<th>Average temperature 2100-2330 h</th>
<th>Average temperature 0000-0600 h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average (95% CI)</td>
<td>Difference from traditional house (95% CI)</td>
</tr>
<tr>
<td>Outdoor</td>
<td>33·5°C (32·8 to 34·2)</td>
<td>–</td>
</tr>
<tr>
<td>Thatched roof, open eaves, traditional, poorly fitted doors</td>
<td>33·0°C (32·9 to 33·2)</td>
<td>–</td>
</tr>
<tr>
<td>Thatched roof, closed eaves, traditional, poorly fitted doors</td>
<td>33·3°C (32·3 to 33·5)</td>
<td>0·3 (0·1 to 0·5)</td>
</tr>
<tr>
<td>Thatched roof, closed eaves, screened, well fitted doors</td>
<td>33·0°C (32·8 to 33·1)</td>
<td>0·0 (–0·3 to 0·2)</td>
</tr>
<tr>
<td>Metal roof, closed eaves, traditional, poorly fitted doors</td>
<td>34·7°C (34·6 to 34·8)</td>
<td>1·7 (1·5 to 1·9)</td>
</tr>
<tr>
<td>Metal roof with ventilation in gables, closed eaves, screened, well fitted doors</td>
<td>37·7°C (33·6 to 33·9)</td>
<td>0·7 (0·5 to 0·9)</td>
</tr>
</tbody>
</table>

Data calculated with 95% CIs. General linearised modelling results, adjusted for house position and night.
The comfort zone is defined by the comfort polygon for temperature and relative humidity and provides an estimated proportion of people satisfied with the indoor climatic comfort. The human energy balance model used by the psychrometric chart is the predicted mean vote model developed by P O Fanger. The predicted mean vote model is a seven-point scale from cold (–3) to hot (+3) that is used in comfort surveys. Each integer value of the scale indicates cold, –3; cool, –2; slightly cool, –1; neutral, 0; slightly warm, +1; warm, +2; and hot, +3. The accepted range of comfort is a predicted mean vote between –1 and +1 and defines the area of the comfort polygon on the psychrometric chart. We assumed that from 2100 h to 0000 h men were seated and quiet and wore thin straight trousers, briefs, and T shirts. From 0000 h to 0600 h the men were reclining or sleeping. χ² tests were used for making comparisons between the proportions of time spent comfortable or uncomfortable, as predicted from the psychometric modelling. For each typology, we calculated the proportion of time the indoor climate was in the comfort zone for two periods: 2100–0000 h, when people retire to bed, and 0000–0600 h, when people are usually sleeping. In experiment 2, we fitted a mixed effects regression model to each response to allow for random effects (experiment) and fixed effects (position and data logger).

The study was approved by the Gambia Government and Medical Research Council’s joint ethics committee (May 16, 2016, and March 16, 2017) and the Department of Biosciences ethics committee, Durham University, UK (May 13, 2016, and June 29, 2017).

Results
In experiment 1, from Sept 18, 2016, to Oct 21, 2016 (rainy season), a total of 4762 female mosquitoes were collected in the five house typologies (figure 1; table 1; appendix) over 25 nights (n=125 nights): 2857 (60·0%) were Culex spp, 1088 (22·8%) were Mansonia spp, 734 (15·4%) were A gambiae sensu lato, and 83 (1·7%) were other anophelines. Of the 728 A gambiae sensu lato that were identifiable by PCR, 460 (63·2%) were Anopheles arabiensis and 268 (36·8%) were A coluzzii. A breakdown of mosquito species by typology is shown in the appendix.

Closing the eaves of a thatched house with poorly fitting doors resulted in 94% (95% CI 89–97) fewer A gambiae sensu lato collected indoors, with a 43% (23–58) reduction in other mosquito species compared with a thatched house with open eaves (table 2). A similar reduction in A gambiae sensu lato that were identifiable by PCR, 460 (63·2%) were Anopheles arabiensis and 268 (36·8%) were A coluzzii. A breakdown of mosquito species by typology is shown in the appendix.

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Permeability strongly influences air flow in a building and varied markedly between housing typologies (table 1). The greatest permeability was in the ventilated metal-roof house, which was 85% greater than the permeability in the thatched-house with open eaves. Closing the eaves in houses with poorly fitting doors reduced the permeability by 89% compared with the traditional thatched-roofed house with open eaves, whereas fitting screened doors in houses with closed
eaves only increased permeability by 150% relative to the thatched house with open eaves.

Closing the eaves of a thatched-roofed house increased indoor temperature by 0.5°C (95% CI 0.3–0.6; p<0.0001) from 2100 h to 2330 h and 0.4°C (0.2–0.6; p<0.0001) from 0000 h to 0600 h compared with the traditional thatched-roofed house and open eaves (table 3). Temperatures could be made cooler than a house with open eaves by adding the screened doors to a thatched-house with closed eaves. Metal-roofed houses with closed eaves and doors with gaps were 1.5°C (95% CI 1.3–1.7; p<0.0001) hotter than traditional thatched-roofed houses from 2100 h to 2330 h but could be made cooler than the traditional houses by screening the doors and windows of metal-roofed houses. All indoor temperatures were at their lowest shortly after sunrise but increased as the sun began to heat the house and peaked at 1900 h, around sunset (figure 2A). During the night, indoor temperatures declined progressively in all house typologies. The daily pattern of indoor temperatures differed to those outdoors. First, from a minimum at dawn, indoor temperatures rose far more slowly than outdoor temperatures. Second, they peaked in the late evening, several hours later than outdoor temperatures. A thermal image of a metal-roofed house (appendix) taken in the evening shows the hot walls and cool roof, illustrating the different heat capacities of the two materials.

The mean relative humidity of thatched-roofed houses with open eaves was lower than that in the other typologies of housing (table 4). In all typologies, the daily pattern of indoor relative humidity was the opposite of that seen with temperature, with the relative humidity declining during the heat of the day and rising slowly after sunset through the night and until the first few hours after sunrise. During the day, outdoor relative humidity was considerably lower than that indoors, but at night relative humidity outdoors was higher than that indoors (figure 2B).

The predominant wind direction in the study site came from the west, with wind strength dropping substantially at night (appendix). Thus, since the major aquatic habitats in the vicinity are to the west of the houses, most mosquitoes will travel with the wind and enter through the side of the house facing away from the village.

Metal-roofed houses with closed eaves were considered uncomfortable by volunteers on 14 (56%) occasions of 25 and were significantly more uncomfortable than thatched-roofed houses with closed eaves, which were deemed uncomfortable on two (8%) occasions (χ²=13.2; p=0.001). All other house typologies were considered comfortable by volunteers on every night of the study. Volunteers were uncomfortable 14 times at higher temperatures (34-3°C [95% CI 33-4-35-1] at entering the house at 2100 h) and were comfortable 96 times at lower temperatures (32-8°C [32-5-33-0] at entering the house at 2100 h; t test −3.769; temperature difference 1.5°C [0.7–2.3]; p<0.001).

Analysis of psychrometric data (figure 3) showed that all houses cooled during the night; therefore, after midnight sleepers might need a covering sheet to stay comfortable. Between 2100 h and 0000 h, when people are preparing to sleep, the metal-roofed houses with closed eaves were more uncomfortable, because of the higher temperatures, than the thatched-roofed houses with open eaves (χ²=22.86; p<0.001). Conversely, from 0000 h to 0600 h, when most people sleep, the metal-roofed houses were more comfortable since they were warmer than the thatched-houses with open eaves (χ²=19.03; p<0.001). In the early morning both screened houses tended to be cooler than the thatched-roofed house with open eaves. The ventilated metal-roofed house was more comfortable than the unventilated metal-roofed house before midnight (χ²=12.64; p<0.001), but it was less comfortable later from 0000 h to 0600 h (χ²=39.15; p<0.001) because it was cooler during both periods.

### Table 4: Relative humidity in the five different house typologies and outdoors during the rainy season

<table>
<thead>
<tr>
<th></th>
<th>Outdoor relative humidity</th>
<th>Thatched roof; open eaves, traditional, poorly fitted doors</th>
<th>Thatched roof; closed eaves; traditional, poorly fitted doors</th>
<th>Thatched roof; closed eaves; screened, well fitted doors</th>
<th>Metal roof; closed eaves, traditional, poorly fitted doors</th>
<th>Metal roof with ventilation in gables, closed eaves, screened, well fitted doors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average relative humidity</td>
<td>Average</td>
<td>Difference from traditional house</td>
<td>p value</td>
<td>Average</td>
<td>Difference from traditional house</td>
<td>p value</td>
</tr>
<tr>
<td>Average relative humidity 1900–2330 h</td>
<td>(71.7 to 77.4)</td>
<td>(66.0 to 74.5)</td>
<td>0.027</td>
<td>(72.8 to 79.1)</td>
<td>(75.0 to 80.6)</td>
<td>0.025</td>
</tr>
<tr>
<td>Average relative humidity 0000–0600 h</td>
<td>(76.0 to 78.8)</td>
<td>(76.0 to 78.8)</td>
<td>0.052</td>
<td>(77.3% to 78.0%)</td>
<td>(76.0% to 77.5%)</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Data calculated with 95% Cl. General linearised modelling results, adjusted for house position and night.
The cost of constructing a metal-roofed house was over US$100 more than a traditional thatched-roofed house (table 1). A thatched-roofed house with open eaves cost $210 in materials and $224 for labour. Filling the eaves with mud cement and broken bricks cost an additional $26 and the two metal-screened doors cost $129. A metal roof costs $80 more than a thatched roof. The cost of a ventilated metal-roofed house is $132 more expensive than an unventilated house due to the cost of the two screened doors and two screened windows. The cost of labour varied between 39% and 53% of building costs, thus the price of building could be reduced if the owners built the house themselves or used cheaper labour.

In experiment 2, from Sept 4, 2017, to Oct 8, 2017 (rainy season), a total of 3685 female mosquitoes were collected in two house typologies over 25 nights (n=50 nights): 2360 (64·0%) were Mansonia spp, 819 (22·2%) were Culex spp, 436 (11·8%) were A gambiae sensu lato, and 70 (1·9%) were other anophelines. Greater numbers of female A gambiae sensu lato were collected in metal-roofed houses each night (mean number of mosquitoes per house per night was 11·0 [95% CI 7·9–14·1]) than thatched-roofed houses (6·4 [3·7–9·1]; odds ratio [OR] 2·51 [95% CI 1·54–4·10]; p<0·001). The same was also true for other species of mosquito, with...
more caught in metal-roofed houses (75·3 [53·3–97·3])
than thatched ones (54·6 [35·8–73·4]; OR 1·42 [1·07–1·90];
p=0·016).

The shapes of the carbon dioxide concentration profiles
over time were highly variable (figure 4). Despite the
shape variability—ie, the gradient of concentration
increase between 2100 h and 2300 h—the magnitude and
time to peak concentration were consistent features and
were selected as summary statistics for each profile
(table 5). Evidence suggests that carbon dioxide accumu­
lated more rapidly (1·9 ppm/min [95% CI 1·3–2·5])
and to higher concentrations in metal-roofed houses
(211·1 ppm greater [117·8–304·6]) than in thatched-roofed
houses (p<0·0001). The time taken to reach peak carbon
dioxide concentration was 73·7 min (95% CI –1·9 to 149·3)
slower in metal-roofed houses than thatched ones, although
this difference was of borderline significance
(p=0·056).

Discussion
The number of A gambiae sensu lato mosquitoes entering
houses of different typologies varied greatly and thus the
difference in the risk of malaria transmission could also
be large. Importantly, this study highlights two ways of
reducing the number of malaria mosquitoes entering
houses with thatched or metal roofs. First, the simplest
and cheapest method is to close the eaves with mud
mortar; if large gaps are present, close with broken mud
blocks and mortar. Thatched-roofed houses with closed
eaves and poorly fitted doors had 94% fewer A gambiae
sensu lato than those with open eaves and fewer than
metal-roofed houses with closed eaves and poorly fitted
doors. This difference is important since most modern
houses in rural areas have metal roofs, closed eaves, and
poorly fitted doors. Nonetheless, the consequence of
closing the eaves of thatched houses is that indoor
temperature will increase 0·4–0·5°C during the night,
closing the eaves of thatched houses is that indoor
Poorly fitted doors. Nonetheless, the consequence of

Table 5: Differences in CO2 concentrations between thatched-roofed and metal-roofed houses

<table>
<thead>
<tr>
<th>House typology</th>
<th>Adjusted difference between typologies, ppm (95% CI)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thatched-roofed house</td>
<td>1·9 (1·3 to 2·5)</td>
<td>0·0001</td>
</tr>
<tr>
<td>Metal-roofed house</td>
<td>3·41 (2·26 to 4·25)</td>
<td>0·056</td>
</tr>
</tbody>
</table>

Data are median (IQR), unless otherwise specified. Adjusted differences are from a formal regression analysis, fitting a linear mixed model, separately for each of the summary statistics with experiment night as a random effect, which removed any influence of night to variation, such as temperature or humidity. The effect of roof type was adjusted for house position, data logger, and within-day differences. CO2—carbon dioxide. *Min rather than ppm.
In The Gambia,29 and for many other parts of Saharan Africa,30 more profound host location by A gambiae is considered to fly upwind.28 In this study, the experimental houses were located along a north–south axis with major gable ends and screened doors will result in hot houses during the day, which might increase house entry of malaria mosquitoes and potentially reduce malaria. Our findings are likely to be relevant to similar typologies of housing in hot humid regions of sub-Saharan Africa, but further research is needed where house designs differ from those described in this study and where the climate is cooler. Our findings are likely to be of relevance to the transmission of malaria and also other vector-borne diseases in which transmission occurs indoors at night, such as lymphatic filariasis. A Roll Back Malaria, UN Development Programme and UN Habitat’s Housing and Malaria consensus statement11 asked, “What architectural features are protective against malaria?” Our study illustrates that sealing the eaves and adding screened doors will reduce house entry of mosquitoes substantially both in thatched-roofed and metal-roofed houses. Moreover, a metal-roofed house can be made as cool as a thatched-roofed house by encouraging airflow through the house by screening the doors and adding a screened window directly under the roof. The ventilated metal-roofed house is hotter than a traditional thatched-roofed house during the day, which might increase the mortality
of malaria mosquitoes; however, at night a ventilated metal-roofed house becomes as cool as a thatched-roofed house, making it more probable that people will sleep under an LLIN. Further changes in house structure are also required to prevent overcrowding, increase airflow, reduce indoor air pollution, and keep the occupants cooler.\textsuperscript{9} The transition of housing stock in sub-Saharan Africa from traditional thatched-roofed houses to metal-roofed houses is likely to have profound effects on the transmission of malaria and represents an enormous opportunity to reduce transmission further and keep malaria out in areas where malaria is eliminated but vectors remain.

**Contributors**

SWL, MP, JBK, and DJ conceived and designed the study. JBK designed the ventilated metal-roofed house. Ej and MJ carried out the fieldwork, supported by MP, BK, ALW, UD'A, and SWL. Ej, SWL, JB, DJ, and JBK analysed the data. All authors reviewed the final manuscript.

**Declaration of interests**

We declare no competing interests.

**Acknowledgments**

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**References**


