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Changes in house design reduce exposure to malaria mosquitoes

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Summary House design may affect an individual's exposure to malaria parasites, and hence to disease. We conducted a randomized-controlled study using experimental huts in rural Gambia, to determine whether installing a ceiling or closing the eaves could protect people from malaria mosquitoes. Five treatments were tested against a control hut: plywood ceiling; synthetic-netting ceiling; insecticide-treated synthetic-netting ceiling (deltamethrin 12.5 mg/m^2); plastic insect-screen ceiling; or the eaves closed with mud. The acceptability of such interventions was investigated by discussions with local communities. House entry by *Anopheles gambiae*, the principal African malaria vector, was reduced by the presence of a ceiling: plywood (59% reduction), synthetic-netting (79%), insecticide-treated synthetic-netting (78%), plastic insect-screen (80%, $P < 0.001$ in all cases) and closed eaves (37%, ns). Similar reductions were also seen with *Mansonia* spp., vectors of lymphatic filariasis and numerous arboviruses. Netting and insect-screen ceilings probably work as decoy traps attracting mosquitoes into the roof space, but not the room. Ceilings are likely to be well accepted and may be of greatest benefit in areas of low to moderate transmission and when used in combination with other malaria control strategies.

keywords malaria, house design, screening, mosquitoes, The Gambia

Introduction

Malaria control in the tropics is currently based largely on case treatment, and personal protection against malarial mosquitoes using insecticide-treated bednets or indoor spraying (www.rbm.who.int). The development of a multistage vaccine, new drugs and insecticides are seen as the strategic goals in the fight against malaria, but scant consideration has been given to environmental strategies to control the disease. It was not always so. In the early 20th century improved housing and screening were regarded as some of the main methods to control malaria (Lindsay *et al.* 2002). Screening was used by Manson (1900) to demonstrate the role of mosquitoes in malaria transmission and modifying house structure was used to protect people from malaria in Italy (Celli 1901), Greece (Ross 1913), Panama (Le Prince & Orenstein 1916) and the USA (Boyd 1926). There is ample evidence that house screening contributed to the elimination of malaria from many parts of the world (Lindsay *et al.* 2002).

Anopheles gambiae, the main malaria vector in Africa, is well adapted for entering houses because they fly upwards when encountering a vertical surface (Snow *et al.* 1987). Attracted to human odours pouring out of a house, many reach an outside wall and fly up, funnelled indoors by the over-hanging roof, through the open eaves. This mode of house entry implies that closing the eaves or installing ceilings can give protection. This hypothesis is supported by many studies showing that houses with open eaves, or which lack ceilings, are associated with increased numbers of mosquitoes and higher levels of malaria compared with neighbouring houses with closed eaves or ceilings (Lindsay *et al.* 2002). We tested a range of locally available materials as barriers against house-entry by mosquitoes in The Gambia.

Methods

Experimental huts

Different structural modifications against mosquitoes were compared using six identical experimental huts at Wali Kunda (13°34′N, 14°55′W), in rural Gambia. The square huts were made with mud walls, thatched roof, open eaves, a verandah and window on each side and a door to the south (Figure 1) and arranged in a straight line, 3.5 m apart. To prevent ant infestation, the huts were raised off the ground on concrete legs surrounded by water-filled

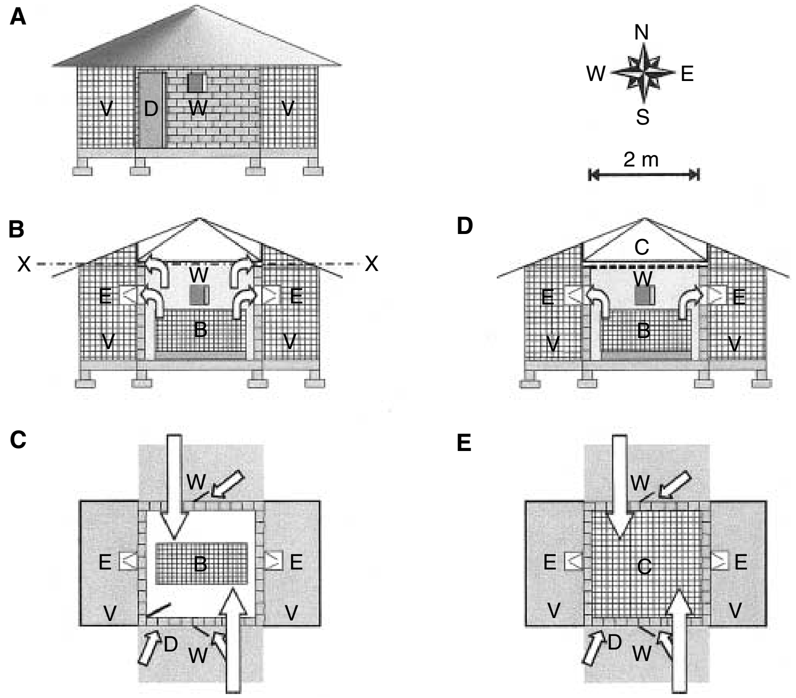

Figure 1 Movement of mosquitoes in experimental huts. A is an external view of a hut, B is a section of a hut, without a netting ceiling or closed eaves, showing how mosquitoes leaving the room (arrows) are collected in window traps or verandahs, C is a plan view of a hut (sectioned at X–X in Figure B), without a netting ceiling or closed eaves, showing how mosquitoes enter the room (arrows), D is a section of a hut with a netting ceiling (dashed line), showing how most exiting mosquitoes can only be collected in window traps, E is a plan view of a hut (sectioned at X–X in Figure B), with a netting ceiling, illustrating that mosquitoes can only enter the room through the windows and door. Where B is an untreated bednet under which a man sleeps, D is an open door, E is an Exit Trap, V is an enclosed verandah and W is an open window.

moats. The east and west sides of the huts were fitted with screened verandahs and had window traps to capture mosquitoes leaving from these sides.

A man slept in each hut to attract mosquitoes, which entered through the eaves (except when blocked), and windows on the north and south sides or the door. The door and windows were held ajar to simulate village conditions (20 mm gap between door and frame; 30 mm for windows). Mosquitoes could leave via the unblocked eaves, windows and door. Mosquitoes leaving via the north and south sides were lost, but those leaving on the east and west sides were captured in the window traps or enclosed verandahs. The door and windows were shut at 05.00 hours, and the window traps plugged at 06.45 hours. The huts and enclosed verandahs were then searched for mosquitoes for 30 man-minutes per hut.

Treatments

Huts were randomly allocated to a control or one of five treatments: (1) plywood ceiling; (2) synthetic-netting ceiling; (3) insecticide-treated synthetic-netting ceiling (deltamethrin 12.5 mg/m^2, Moustiqare, AgrEvo Environmental Health, Berkhamsted, UK); (4) plastic insect-screen ceiling (The Flyscreen Company); or (5) eaves closed with mud blocks. Ceilings were installed below the open eaves. A man slept in each hut under an untreated bednet between 21.00 and 06.00 hours, for four nights each week for the duration of the trial. To control for differing attractiveness to mosquitoes of men and huts, the men always slept in the same hut. Treatments were rotated weekly so that after 6 weeks each hut had had each treatment and been the control.

Meteorological measurements

Room temperatures were recorded at 22.00 hours with a mercury-bulb thermometer and evaporation was measured between 22.00 and 06.15 hours with a Piche evaporimeter (Casella CEL, Kempston, Bedfordshire, UK).

Social science

Key informant discussions about the use and acceptability of ceilings and closed eaves were held with village leaders, masons, carpenters and home-owners. Separate group discussions were also conducted with men and women. Discussions were held in six local villages which represented the three dominant ethnicities in The Gambia: Mandinka, Wollof and Fula.

Analysis

Nightly exposure to mosquitoes in the treatment huts was estimated to be the sum of the mosquitoes caught in the room and window traps only (mosquitoes caught in the enclosed verandahs of huts with ceilings had been prevented from entering the room by the ceiling, and mosquitoes were unable to enter the verandahs of huts with closed eaves). In the control hut, exposure was the sum of mosquitoes from the room and window traps plus double the number from the enclosed verandahs. We doubled the catch from the verandahs as we assumed that half the mosquitoes leaving the room during the night would be caught in the verandahs, the other half would have left through the open eaves. Open windows were shut before dawn when increased light intensity would have stimulated unfed mosquitoes to leave the room. Counts were expressed as geometric mean values and log transformed to normalize the data. ANOVA was conducted using GLIM with SPSS software.

Ethics

The study was approved by the joint Gambian Government and Medical Research Council Ethics Committee.

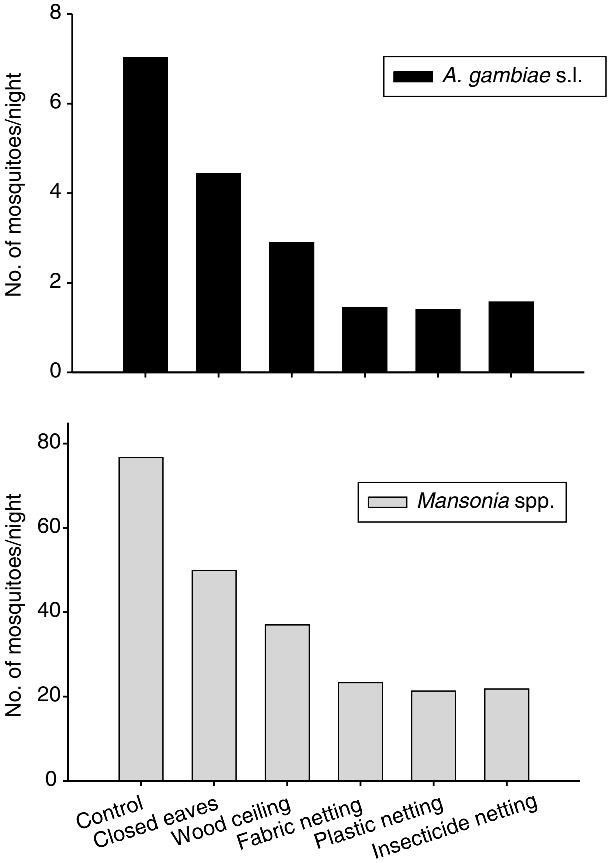

Figure 2 Mean number of mosquitoes entering huts.

Results

There was a significant difference between the number of *A. gambiae* and *Mansonia* spp. caught in the control and treatment huts (GLIM, allowing for variations in night and hut attractiveness, $P < 0.001$, Figure 2). There were significantly fewer *A. gambiae* and *Mansonia* spp. (Table 1) in huts with ceilings compared with the controls (Dunnett test for multiple comparisons, $P < 0.001$). The 37% reduction in *A. gambiae* associated with closed eaves narrowly missed statistical significance ($P = 0.057$). Netting and insect-screen ceilings reduced the number of *A. gambiae* entering huts by 78–80% and for *Mansonia* spp. by 70–72% ($P < 0.001$) compared with controls. In order to determine whether this was an artefact caused by the doubling of mosquitoes in the verandahs of the control huts, we repeated the analysis summing the number of

Table 1 Protective efficacy of structural modifications against house-entering mosquitoes

	Anopheles gambiae		*Mansonia* spp.	
Structural modification	GM number of mosquitoes/night (95% CIs)	Percentage reduction compared with control	GM number of mosquitoes/night (95% CIs)	Percentage reduction compared with control
Control (no modification)	7.0 (4.3–11.1)	–	76.7 (11.3–278.7)	–
Closed eaves	4.4 (2.6–7.2)	36.9	49.9 (9.0–287.1)	34.9
Plywood ceiling	2.9 (1.5–5.1)	58.7*	37.0 (3.7–231.8)	51.8*
Synthetic-netting ceiling	1.5 (0.7–2.6)	79.4*	23.3 (6.0–87.4)	69.6*
Plastic insect-screen	1.4 (0.7–2.4)	80.1*	21.3 (3.6–65.4)	72.2*
Insecticide-impregnated synthetic-netting ceiling	1.6 (0.7–2.8)	77.7*	21.8 (3.2–120.3)	71.6*

GM, geometric mean; CI, confidence interval.
* $P < 0.001$.

Table 2 Number of mosquitoes collected in verandahs of experimental huts with different ceilings

	Anopheles gambiae		*Mansonia* spp.	
Treatment	GM number of mosquitoes/night (95% CIs)	Percentage increase compared with solid (plywood) ceiling	GM number of mosquitoes/night (95% CIs)	Percentage increase compared with solid (plywood) ceiling
Plywood ceiling	0.5 (0.2–0.9)	–	6.6 (3.5–8.8)	–
Synthetic-netting ceiling	1.5 (0.8–2.4)	300*	18.7 (13.8–25.1)	283*
Plastic insect-screen ceiling	2.1 (1.2–3.3)	420*	15.9 (11.5–21.8)	241*
Insecticide-impregnated synthetic-netting ceiling	1.5 (0.7–2.6)	300*	25.7 (14.6–44.3)	389*

GM, geometric mean; CI, confidence interval.
* $P < 0.001$.

mosquitoes collected in the verandah, room and exit traps for each collection. Again, there were significant differences in the numbers of mosquitoes collected between the treatments or control ($P < 0.01$), and, apart from the mud-blocked eaves ($P = 0.29$ and 0.43 respectively), all treatments reduced significantly the number of mosquitoes entering the huts compared with the control ($P < 0.05$).

There were significantly more mosquitoes caught in the verandahs of huts with netting or screen ceilings compared with solid (plywood) ceilings (GLIM, adjusting for night and hut, $P < 0.001$ in each case, Table 2).

The average temperature at 22.00 hours in the control hut was 26.4 °C (95% CI: 25.9–26.9 °C). Netting or insect-screen ceilings did not make the huts hotter than controls, unlike those with closed eaves (0.9 °C warmer, $P < 0.001$) or a wooden ceiling (0.8 °C warmer, $P < 0.001$). Netting and insect-screen ceilings had significantly lower rates of evaporation than control huts (range of mean evaporation for huts with netting and insect-screen ceilings = 4.8–4.9 mm water/night *vs.* 5.4 mm water/night in controls, $P = 0.006–0.021$).

Individual and group interviews were conducted with 128 Gambian adults (54 mens and 74 womens). Responses were remarkably consistent, demonstrating a general perception that ceilings improved the functionality and beauty of houses. The presence of both ceilings and closed eaves was generally associated with a reduced disturbance by mosquitoes. Less than 20% of houses had ceilings or closed eaves; the cost of materials and extra effort required in house construction were cited as the main reasons for not including them.

Discussion

We demonstrated that the addition of simple ceilings to houses of traditional design substantially reduced exposure to the mosquito vectors of malaria and other diseases. All netting and insect-screen ceilings reduced house entry by *A. gambiae* mosquitoes by about 80% and *Mansonia* spp. by approximately 70%. This degree of protection compares well with the 86–91% reduction in biting seen with insecticide-treated bednets in earlier studies using the same huts and similar methodology (Lindsay *et al.* 1991; Miller *et al.* 1991). The greatest protection was given by netting and insect-screen ceilings.

The two- to fourfold greater number of mosquitoes caught in the verandahs of huts with netting ceilings compared with solid ceilings (Table 2) suggests that huts with netting ceilings acted as decoy traps. Presumably, host odours from the room pass up through the netting and out the eaves, attracting mosquitoes into the roof space, where they were prevented from entering the room by the ceiling (Figure 3). In contrast, in huts with solid ceilings, host odours would not leave the eaves and attract mosquitoes into the roof space.

The protection afforded by a netting ceiling was not enhanced by insecticide treatment, suggesting that

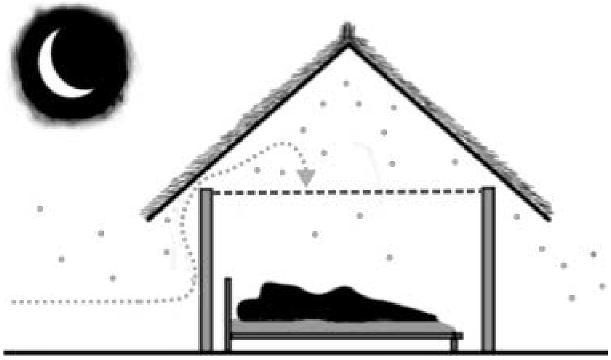

Figure 3 Path taken by mosquitoes when entering a house (dotted line), attracted by warm human odours (dots), but prevented from biting by the netting ceiling (dashed line).

treatment did not repel mosquitoes from entering via the door and window. However, if insecticide was applied to curtains around the door and windows it is likely that protection would be improved because treating curtains with permethrin in experimental huts in Burkina Faso was associated with a reduction in malaria transmission by about 63% (Majori *et al.* 1987).

A 1988 village survey close to the study site found that most houses with closed eaves were built to prevent metal roofs from being blown off in strong winds (Lindsay & Snow 1988). Although blocking eaves in this trial restricted entry of mosquitoes, the huts were noticeably warmer (+1 °C) than those with open eaves. Thus, although closing the eaves is a simple and cheap intervention it is unlikely to be enthusiastically received in hot and humid environments like The Gambia.

Netting or insect-screen ceilings did not make huts hotter, but they did reduce evaporation by about 10%. This is consistent with a reduction in air flow – which made the rooms feel stuffy. Whether this is likely to reduce acceptability of installing ceilings is unknown. Group interviews showed that ceilings were considered to improve houses, and were widely associated with reduced disturbance by mosquitoes, suggesting that installing ceilings to reduce entry by mosquitoes would receive community support.

All the structural changes made to the experimental huts were cheap; almost free for closing eaves with mud or £0.36–0.59/person/year for locally made ceilings (assuming a life of 3–5 years, four people per room; cost of screening only). In places where people are reluctant to use bednets because there are few nuisance mosquitoes (Aikins *et al.* 1993; Clarke *et al.* 2002), ceilings or closed eaves could be an effective method of protection. This is important as there is an evidence from The Gambia that communities with the lowest vector densities are at greatest risk of disease (Clarke *et al.* 2002).

Our study shows that netting and insect-screen ceilings can substantially reduce the biting rate of malaria vectors. It is likely that the greatest effect on clinical malaria would be seen in areas of low to moderate transmission where a reduction in exposure to malaria parasites would lead to a proportional reduction in morbidity, although it is not known what effect this would have on clinical malaria in holoendemic areas where the entomological inoculation rate is high. On the present evidence we recommend that randomized-intervention trials should now be conducted in areas of low transmission to determine the protective efficacy of ceilings against clinical malaria. Ceilings may also be suitable for inclusion as part of an integrated approach to malaria control.

Simple improvements in building design could reduce the intensity of malaria transmission for the occupants, and provide long-term protection (3–5 years) against this, and other vector-borne diseases. Those keen to control malaria in the tropics should not forget the lessons of the past, that improvements in living conditions can reduce malaria. Changes in house design can contribute to a reduction in malaria in many parts of the world.

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