Durham University

Durham E-Theses

The impact of different housing designs on mosquito house entry in The Gambia

EBRIMA JATTA

How to cite:

JATTA, EBRIMA (2018) The impact of different housing designs on mosquito house entry in The Gambia. Masters thesis, Durham University.

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a https://etheses.durham.ac.uk/id/eprint/12865/ is made to the metadata record in Durham E-Theses
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the full Durham E-Theses policy for further details.

Academic Support Office, The Palatine Centre, Durham University, Stockton Road, Durham, DH1 3LE
e-mail: e-theses.admin@durham.ac.uk Tel: +44 0191 334 6107
https://etheses.durham.ac.uk

THE IMPACT OF DIFFERENT HOUSE DESIGNS ON MOSQUITO HOUSE ENTRY IN RURAL GAMBIA

Ebrima Jatta

Department of Biosciences

Durham University

A thesis submitted for the award of Degree of Masters of Science by Research

April, 2018

Table of Contents

	Page
List of Acronyms	4
List of Tables	5
List of Figures	5
Statement of copyright	6
Acknowledgements	7
Dedication	8
Executive Summary	9
Study Rationale	28
Study Objectives	29
Chapter 1 - Review of housing and malaria in sub-Saharan Africa	12
1.1 Summary	12
1.2 The global malaria burden	12
1.3 Malaria in sub-Saharan Africa	13
1.4 Economic impact of malaria in sub-Saharan Africa	14
1.5 Malaria transmission	16
1.6 Malaria control in sub-Saharan Africa	17
1.6.1 Historical efforts to control malaria	17
1.6.2 Challenges faced in controlling malaria in sub-Saharan Africa	18
1.6.3 The need for additional interventions	20
1.7 Housing and malaria	20
1.7.1 Historical use of housing as a malaria intervention	20
1.7.2 Mosquito house entry	22
1.7.3 Open eaves	23
1.7.4 Ceilings	24
1.7.5 Screening	24
1.8 The changing face of sub-Saharan Africa	25
1.9 Conclusion	27
1.10 Study rationale	28

1.11 Overall goal 29
1.12 Study objectives 29

Chapter 2 – Impact of different building components on mosquito house entry and human comfort in The Gambia 30
2.1 Summary 30
2.2 Background 31
2.3 Methods 33
2.4 Findings 40
2.5 Discussion 45
2.6 Conclusion 47

Chapter 3 – How gaps around the door and addition of screened and unscreened windows affect mosquito house entry in The Gambia 48
3.1 Summary 48
3.2 Background 49
3.3 Methods 50
3.4 Findings 56
3.5 Discussion 61
3.6 Conclusion 64

Chapter 4- General Discussion 65
4.1 General conclusion 65
4.2 Further considerations 67
4.3 Study limitations 68
4.4 Major conclusions 69

References 71
Appendix 78

List of acronyms

ACTs	Artemisinin -based Combination Therapy
CDC	Center for Disease Control
CI	Confidence Intervals
DDT	Dichloro-Diphenyl-Trichloroethane
DHS	Demographic Heath Survey
GBoS	Gambia Bureau of Statistics
GDP	Gross Domestic Product
GTS	Global Technical Strategy
IRS	Indoor Residual Spraying
ITNs	Insecticide-treated nets
IVM	Integrated Vector Management
LLINs	Long-Lasting Insecticidal nets
MIS	Malaria Indicator Survey
MRC	Medical Research Council Unit The Gambia at the London School of Hygiene & Tropical Medicine
NMCP	National Malaria Control Programme
OR	Odds Ratio
PCR	Polymerase Chain Reaction
RBM	Roll Back Malaria
RDTs	Rapid diagnostic Tests
SMC	Seasonal Malaria Chemoprevention
SREA	Special Report Emerging Africa
UNCHS	United Nations Center for Human Settlement
UNH	United Nations Habitat
UNHSP	United Nations Human Settlement Programme
USA	United State of America
WHO	World Health Organization

List of Tables

Table 1.1 Literature review on entomological findings from studies on house improvements in sub-Saharan Africa 26
Table 2.1 Latin rectangle design for rotating house typologies between different positions 36
Table 2.2 Gonotrophic stages of total *An. gambiae s.l.* found in each house type 40
Table 2.3 Mosquito density found in each house type 42
Table 2.4 Shows outdoor and indoor night time mean temperature of each house 43
Table 2.5 Sleepers responses on comfort for each house type 44
Table 3.1 Impact of door gaps and screened windows on mosquito house entry 57
Table 3.2 Effect of small screened windows on mosquito house entry 59
Table 3.3 Effect of large screened windows on mosquito house entry 60

List of Figures

Fig. 1.1 Global distribution of malaria 15
Fig. 1.2 Malaria transmission cycle 17
Fig. 1.3 Mosquito house entry 23
Fig. 1.4 The changing face of housing in sub-Saharan Africa 27
Fig. 2.1 The five single-roomed experimental houses 35
Fig. 2.2 Shows the Roo*Pfs* house and the screened gable window 35
Fig. 2.3 Experimental houses under construction 37
Fig. 2.4 Shows the outdoor weather station 39
Fig. 2.5 Changes in CO_2 concentration in thatch roofed and metal roofed house with closed eaves 44
Fig. 3.1 Experimental houses showing large windows 54
Fig. 3.2 Shows characteristics of houses used in each experiment 55
Fig. 3.3 Relationship between area of screened window and reduction in house entry by *An. gambiae s.l.* 61

Statement of copyright

A thesis submitted for partial fulfillment for the award of MSc degree by research from Durham University, I agree that the University Library shall make it available for use in accordance with its regulations governing materials of this type. I agree that permission to quote from, to copy from, or to publish this thesis may be granted by the author or by the professor under whose direction it was written and information derived from it should be acknowledged. Such quoting, copying or publishing must be solely for scholarly purposes and will not involve potential financial gain. It is understood that any copying from or publication of this dissertation which involves potential financial gain will not be allowed without written permission of the author.

Acknowledgements

I am very grateful to numerous people who contributed towards the success of this work. First my supervisor, Prof. Steve W. Lindsay who supported, guided and reviewed all the sections and provide substantial comments for their improvement. Mr. Musa Jawara, my field supervisor, was very helpful and provided me with field technical guidance and training. These two people are the champions of my success and I will always remember them in my life.

I wish to thank Sir Halley Stewart Trust for providing the funds for us to conduct the experiments presented in this thesis. I would like to thank my family for the support and encouragement and the field workers; Amfaal Fofana, Bakary Manneh and Lamin Ceesay for their hard work and cooperation. I would also thank all other staff of the Medical Research Council Unit The Gambia at the London School of Hygiene & Tropical Medicine, Wali Kunda Field Station for their support during this period and the driver Ousman Barry for being so cooperative during field work. My appreciation is also extended to the people who offered their land for experimental houses to be built, the volunteers who slept in the houses, masons, carpenters and the villagers for their support.

Lastly, I would like to thank all the staff of National Malaria Control Programme and the entire Ministry of Health for their support and encouragement. This work could not have been completed without the support of all those mentioned above.

Dedication

This work is dedicated to my parents, Yahya Jatta and Fatou Jatta who worked hard to see me educated. They suspended spending money on their needs and spent it on my education. God bless my parent and I will always be proud of them.

Executive Summary

The impact of different housing designs on mosquito house entry in The Gambia

Background

Although 80-100% of malaria transmission occurs indoors in sub-Saharan Africa, little is known about how changes to the design of houses affects this risk. Simple house modifications can affect house occupant's exposure to malaria mosquitoes in rural houses in sub-Saharan Africa. This is important since Africa's housing stock is changing rapidly from the traditional thatched roofed houses with open eaves to metal-roofed houses with closed eaves. In order to study the effect of different housing features on mosquito house entry I carried out a series of experiments using five single-roomed experimental houses with different housing typologies in Wellingara village, The Gambia. It was also important to consider how the different typologies affected indoor climate since a hot house is likely to reduce the use of long-lasting insecticidal nets (LLINs) indoors. These experiments were conducted to address the following questions;

1. What is the impact of different housing typologies on mosquito house entry and indoor climate?
2. What effect do different gaps around the doors have on mosquito house entry in houses with closed eaves?
3. Are small and large screened windows effective in reducing mosquito house entry in houses with closed eaves and badly-fitting doors?

Methods

The five single-roomed experimental houses were the average size of a single-roomed house in The Gambia built from mud block walls. Four experiments were carried out during the malaria transmission season from July to November. The first experiment was run in 2016 and tested five different housing typologies: 1) thatched roof, open eaves, badly-fitting unscreened doors; 2) thatched roof, closed eaves, badly-fitting unscreened doors; 3) thatched roof, closed eaves, screened louvered metal doors; 4) metal roof, closed eaves, badly-fitting unscreened doors and 5) a novel ventilated metal roof house (Roo*Pf*s house), with closed eaves, screened gable windows and screened louvered metal doors. The Roo*Pf*s house had two screened windows at the top of each gable ends and the eaves (gaps between the roof and walls) closed with mud blocks and a

mixture of mortar. In addition, it had well-fitting screened doors (no gaps exist between the doors and the frame) and self-closing doors . The second experiment investigated the role of gaps around doors in mosquito house entry in houses with closed eaves and was carried out in 2017. The third and fourth experiments examined the effect of different sizes and numbers of screened windows in houses with closed eaves and badly-fitting doors in 2017. Each experiment ran for five weeks and at the end of each five nights, each individual house was rebuilt according to typology, based on a replicated Latin rectangle design. In the first experiment, one healthy adult man slept in each house under a treated bed net (Olyset) for five weeks, whilst in the other experiments two healthy adult men slept in each house each night. In each experiment mosquitoes were collected nightly from each house using Center for Disease Control (CDC) light trap. In the first experiment data loggers were used to measure temperature and relative humidity through the day.

Findings

In the first experiment, closing the eaves in thatch-roofed houses with badly-fitting doors reduced the number of *Anopheles gambiae s.l.* by 94% (Odds ratio (OR)=0.058, 95% confidence intervals (CI)=0.03-0.11) compared with traditional thatched-roofed houses with open eaves. A similar reduction in mosquito house entry was found in thatched-roofed houses with well-fitting screened doors. However, closing the eaves of metal-roofed houses did not reduce the number of mosquitoes entering the house compared to the thatched-roofed house with open eaves (metal roofed house closed eaves (OR=2.99, 95% CI=1.96-4.57). The metal-roofed house was hotter than the thatched-roofed house and sleepers in these houses produced more carbon dioxide than thatched-roofed houses. Nonetheless, the number of mosquitoes collected in ventilated metal-roofed houses (Roo*Pf*s) with closed eaves was reduced by 94% (OR=0.057, 95% CI=0.03-0.10) when well-fitting screened doors were added to the building. Similar reductions were observed in other *Anopheles* spp., *Culex* spp. and *Mansonia* spp. There was no significant different in night time mean temperature between thatch roofed, open eaves and the ventilated metal-roofed house with closed eaves, screened doors and windows (thatch roofed, open eaves mean temperature=33.08^{o}C, 95% CI=32.58-33.58^{o}C; ventilated metal-roofed house with closed eaves, screened doors and windows mean temperature=33.81^{o}C, 95% CI=33.25-34.37^{o}C). However, it was hotter in metal-roofed houses with closed eaves (mean temperature=34.72^{o}C, 95% CI=34.06-35.39^{o}C) than thatched-roofed houses with open eaves (mean temperature=33.08^{o}C, 95% CI=32.58-33.58^{o}C). In the second experiment, the number of *An. gambiae s.l.* entering houses was not affected by having a

single gap above or below the door compared with houses with gaps at the top and bottom of the door. However, the number of *Culex* spp. and *Mansonia* spp. were reduced if the gap was above the door. In the third and fourth experiment, the number of *An. gambiae s.l.* entering metal-roofed houses with badly fitting doors was reduced as the area of screened window increased. Similar reductions were observed in other *Anopheles* species, *Culex* spp. and *Mansonia* spp..

Interpretation

These findings demonstrate that design of a house affects mosquito-house entry. Reductions in *An. gambiae s.l.* was achieved by closing the eaves of thatched-roofed houses or adding screened doors to metal-roofed houses with closed eaves. Screened doors and windows increase ventilation and help keep the house cool at night, which may lead to increased bed net use, especially during the hot periods of the year. In houses where eaves were closed, presumably most of the odours escape from the house through screened windows and this may attract mosquitoes to the windows keeping them away from entry points around the door. Increasing the number of screened windows in a house will reduce house entry of malaria vectors entering badly-fitting doors. Thus housing features such as closed eaves, screened doors and windows should be included in new buildings to reduce mosquito house entry.

Chapter 1-Housing and malaria in sub-Saharan Africa

1.1 Summary

Historically, improved housing and house screening had contributed to malaria control and elimination in many parts of the world. Since then improved housing has been neglected as a public health intervention for malaria control. Today, malaria control in sub-Saharan Africa has stalled and additional approaches to malaria control are needed. Improved housing is being considered as a key intervention to be incorporated in a multi-sectoral approach in the fight against malaria. This review explored the evidence that good housing was protective against malaria in sub-Saharan Africa. Since most malaria transmission in sub-Saharan Africa occurs indoors housing quality is an important determinant of malaria risk, through its effect on modulating house entry by mosquitoes. There is evidence that housing features such as closed eaves, installing ceilings, screened doors and windows reduce contact between humans and malaria vectors. These features should be included in new housing and integrated in malaria control programmes.

1.2 The global malaria burden

At the beginning of the millennium malaria received worldwide recognition as a priority global health issue (WHO, 2015). Since then malaria mortality globally has reduced by 50%, with a 25% reduction in cases (WHO, 2014). This progress has led to continued optimism and commitment by global and regional partners to commit to global malaria elimination. The World Health Organization (WHO) together with Roll Back Malaria (RBM) have embraced the goal of a "world free of malaria" and set ambitious targets for reducing malaria case incidence and mortality rates globally by at least 90% by 2030. In 2016, 44 countries reported fewer than 10,000 malaria cases, an increase from 37 countries in 2010 (WHO, 2017). During the same year, WHO certified Kyrgyzstan and Sri Lanka free of malaria and identified 21 countries with the potential to eliminate malaria by the year 2020. Although some of the elimination countries remain on track to achieve their elimination goals, 11 have experienced an increase in indigenous malaria cases since 2015, and five countries reported an increase of more than 100 cases in 2016 compared with 2015.

Despite the enormous achievements made in malaria control over the past 15 years, malaria remains a substantial public health problem with approximately 3.3 billion people at risk in 109 countries and territories around the world (WHO, 2017), mainly in the tropics and sub-tropics (Fig.

1.1). In 2016, there were an estimated 216 million cases globally leading to 445,000 deaths, of which 91% occurred in sub-Saharan Africa.

The cost of malaria prevention and treatment is huge and there are great economic losses caused by malaria. In 2016, an estimated US$ 2.7 billion was invested in malaria control and elimination efforts globally by governments of malaria endemic countries and interested partners. Of this, 74% were spent in the WHO African Region, 7% in South-East Asia, 6% in the Eastern Mediterranean, 6% in the Americas and 4% in the Western Pacific. Governments of endemic countries contributed 31% of the total funding (US$ 800 million) (WHO, 2017). Although funding for malaria has remained relatively stable since 2010, the level of investment in 2016 is far from that needed to reach the first milestone of the Global Technical Strategy (GTS), to reduce the global malaria burden by 90% by 2030 and strengthen the health system to address emerging resistance. It also highlights the urgent need to increase investments across all interventions and further emphasized the importance of scaling up malaria responses and moving towards elimination.

1.3 Malaria in sub-Saharan Africa

Since 2000, a substantial expansion of malaria interventions has led to unprecedented levels of intervention coverage across sub-Saharan Africa, which in turn led to 40% decline in malaria incidence (Bhatts et al., 2015). During the same period, the malaria mortality rate in children under five years of age was reduced by 58% (WHO, 2016). Case incidence declined by 321/1,000 persons per annum in 2000 to 192/1,000 persons per annum in 2015 (Bhatts et al., 2015). These achievements were a result of the massive deployment of the malaria interventions. Insecticide-treated nets (ITNs), were responsible for 68% of the reduction in cases, artemisinin-based combination therapy 19% reduction and indoor residual spraying 13% (Bhatts et al., 2015).

Despite this progress, malaria remains a major threat in sub-Saharan Africa. The World Health Organization's (WHO) current World Malaria Report shows that the region continues to carry a disproportionately high share of the global malaria burden, with 407,000 malaria cases and 91% of global malaria deaths in 2016 (WHO, 2017). Furthermore, in 2016 of all the countries that reported indigenous malaria, 15 countries in Africa, except India, carried 80% of global malaria burden. Similarly, 15 million children in 12 countries were protected with seasonal malaria

chemoprevention (SMC). However, about 13 million children age 3-59 months who could have benefited from this intervention were not covered, mainly due to lack of funding (WHO, 2017).

For now, malaria control has stalled in sub-Saharan Africa (WHO, 2017). Although some countries remain on track to achieve their elimination goals, 11 have reported increases in indigenous malaria cases since 2015, and five countries reported an increase of more than 100 cases in 2016 compared with 2015. There are worrying signs that investment in malaria control is on the decline. Government contributions for malaria patient care services has declined by 11% (WHO, 2017), and the proportion of people protected by insecticide treated nets (ITNs) is 54%, far from the target coverage of 80%. Indoor residual spray (IRS) protection has dropped from 80 million individuals to 45 million.

1.4 Economic impact of malaria in sub-Saharan Africa

Malaria causes immense human suffering across sub-Saharan Africa and has a huge economic impact (Gallup et al., 1998). The cost of malaria prevention and treatment is huge, and there are great economic losses caused by malaria as a result of infections. For households, this relates to expenditure on personal protective measures, treatment and reduced productivity or time off work due to illness or caregiving to sick household members (Sachs et al., 2002). Economists believe that malaria is responsible for a growth penalty of up to 1.3% per year in some African counties (RBM, 2010). Malaria is both a disease of poverty and a cause of poverty. In countries with a heavy malaria burden, the disease may account for 40% of public health expenditure, 30-50% of inpatient admissions and up to 50% of outpatient visits. Individually, the disease causes loss of workdays or absenteeism from formal employment and the value of unpaid work done in the home by both men and women (RBM, 2010). In Cote d'Ivoire, farmers diagnosed as sick

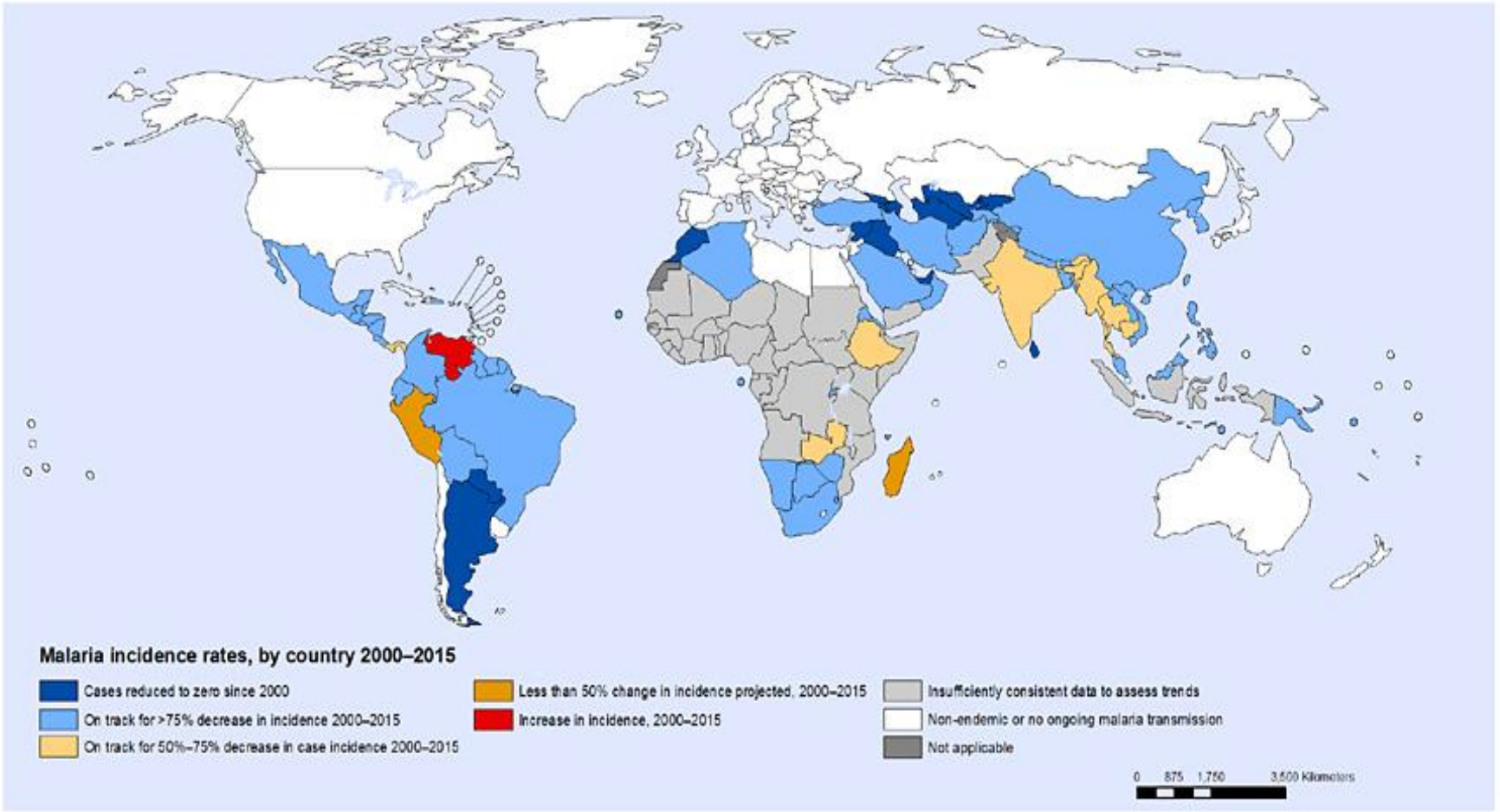


Fig. 1. 1: Global distribution of malaria ***Source***: *www.who world malaria map*

from malaria for more than two days out of growing season had 47% lower yields and 53% lower revenues than farmers who missed no more than two days of work (Hoek, 2004). The disease also hampers children's schooling and social development through both absenteeism and permanent neurological and other damage associated with severe episodes of the disease (RBM, 2010).

1.5 Malaria transmission

Malaria is caused by infection with *Plasmodium* parasites. There are five parasite species that cause malaria in human and two of these species, *Plasmodium falciparum* and *vivax* posing the greatest threat (WHO, 2016). Parasites are transmitted to people through the bites of an infective female *Anopheles* mosquito. There are 430 different species of *Anopheles* mosquito, of which 30-40 are major malaria vectors of public health importance (CDC, 2014). The *Anopheles gambiae* complex and *An. funestus* complex are the major and most efficient malaria vectors in sub-Saharan Africa (Sinka et al., 2012) and partly explain why malaria is so entrenched in this region. Mosquitoes become infected after biting an infected human. The parasite then develops infective sporozoites within the salivary glands of the mosquito, which are injected into human when the mosquito feeds (Anderson et al., 2014). Inside the human, sporozoites first infect liver cells and produce merozoites in vast numbers. These merozoites infect erythrocytes and further develop into gametes which are taken up by mosquitoes feeding on blood (Fig. 1.2). Eventually, these gametes develop into infective sporozoites that are transmitted to humans if the mosquito feeds again (Anderson et al., 2014). Malaria symptoms appear after people are bitten by an infective *Anopheles* mosquito and include fever, headache, chills and vomiting which may be mild and difficult to recognize as malaria (WHO, 2016).

Transmission is more intense in places where the mosquito lifespan is longer (so that the parasite has time to complete its development inside the mosquito) and where it prefers to bite humans rather than other animals. The long lifespan, preference for feeding on people and the propensity to feed indoors make these species such efficient vectors.

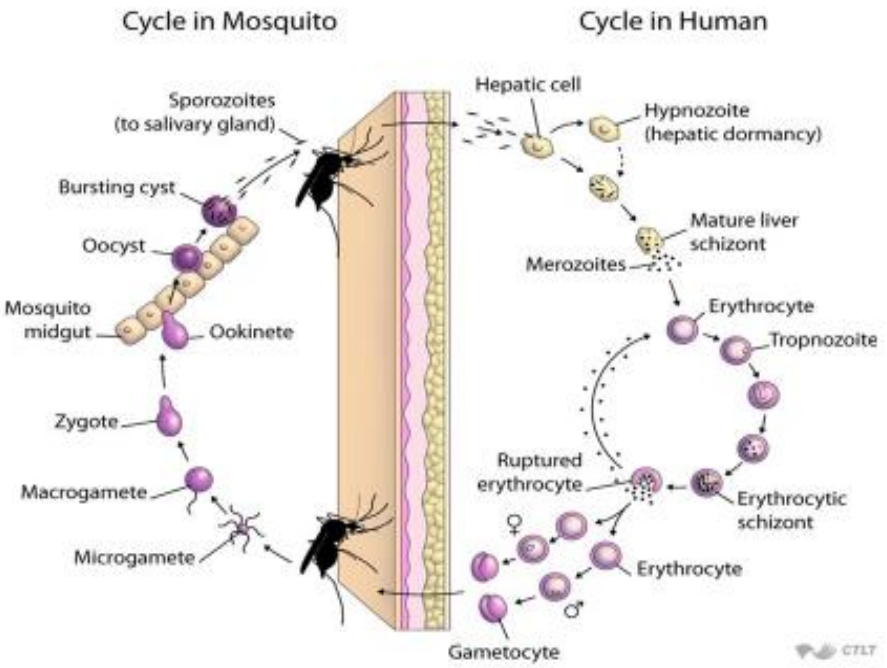


Fig. 1.2: Malaria transmission cycle. ***Source***: *https://www.malariasite.com/life-cycle*

1.6 Malaria control in sub-Saharan Africa

1.6.1 Historical efforts to control malaria

The modern history of malaria control in sub-Saharan Africa began in 1900 when Ronald Ross recommended environmental control methods. The reduction of aquatic habitats became a public health priority after the First World War for many of the rapidly expanding urban centers in Africa (Snow, 2012). Re-routing of streams, draining of swamps and the construction of canals was highly labour-intensive in urban centers, where most Europeans were based (Webb, 2011). The discovery by Alphonse Laveran of the blood stages of the malaria parasite in French troops stationed in Algeria (Bruce-Chwatt, 1981) led to the use of quinine as a therapy for malaria (Shah, 2010; Snow et al., 2012). Quinine was used for personal prophylaxis for malaria and was administered through mass drug administration, for example in Dar es Salaam (Orenstein, 1914; Snow et al., 2012). At this time, Africans were using herbal remedies for malaria treatment and pioneered their own

techniques for mosquito control using smoke and, in some countries, untreated bed nets to prevent mosquito bites or moved away from mosquito infested areas. (Webb, 2011).

At the end of the Second World War, the development of dichloro-diphenyl-trichloroethane (DDT) promised a new era in malaria control (Webb, 2011). This new insecticide, relatively inexpensive and long lasting, might replicate in Africa the successful malaria control programmes seen in the Mediterranean basin. In the early 1950s, pilot projects were conducted in rural tropical Africa with the aim of determining the feasibility of malaria eradication. These projects were primarily based on the use of residual insecticides like DDT for indoor spraying. By the mid-1950s, these trials indicated that IRS reduced malaria transmission and might in some areas interrupt transmission. This led to the mass use of DDT for IRS in most malaria endemic countries. After several years, however, it was realized that IRS using DDT in sub-Saharan Africa was insufficient to eliminate malaria in many parts of the region.

In the mid-1980s, a new approach to vector control was developed. Trials of ITNs tested personal protection (Ranque et al., 1984; Snow et al., 2009) and large-scale trials in The Gambia (Alonso et al., 1993) demonstrated that bed nets substantially reduced malaria mortality in children. This study was replicated in different sites across Africa in the 1990s to confirm that ITNs provide significant, cost-effective protection against child mortality (Lengeler, 2004; Snow, 2012). Based on these findings, millions of ITNs were produced and distributed through routine and mass campaign to the general population, resulting in substantial reductions in malaria (Bhatt et al. 2015). Since 2000, 7 million lives have been saved and 663 million clinical cases averted as a result of successful vector control strategies and treatment with antimalarial medication (WHO, 2017).

1.6.2 Challenges faced in controlling malaria in sub-Saharan Africa

Although malaria control has been extraordinarily successful at reducing the burden of malaria in sub-Saharan Africa, future success is threatened by a drop in malaria funding, poor vector control coverage, insecticide resistance and antimalarial resistance. Perhaps the greatest threat to malaria control in sub-Saharan Africa is a lack of robust, predictable and sustained international and

domestic financing (WHO, 2015). Although global funding for malaria has remained relatively stable since 2010, the level of investment in 2016 is far from what is required to reach the milestone of the Global Technical Strategy (GTS) (WHO, 2017). To reach the GTS milestone, an increase in annual funding from the present level of US$ 2.7 billion to US$ 6.5 billion per year is required. Since there are 41 high malaria burden countries that rely mainly on external funding for malaria programmes this is a serious concern. This problem is compounded by the difficulty in maintaining political commitment and collaboration at the highest level. If future disease control and elimination strategies are to succeed, they will need to take these challenges into account.

More effective malaria control can only be achieved by increasing the coverage of interventions. Whilst WHO's target for coverage of LLINs and IRS is 80%, current coverage for LLINs is 54% and IRS coverage has declined from 80 million people in 2010 to 45 million in 2016 (WHO, 2017). These interventions required effective implementation and consistent use. They must reach a critical mass to achieve community wide protection. Furthermore, replacement of old nets and regular IRS application is needed to maintain effectiveness. For most insecticide, effectiveness is reduced after six months, with no protection after a year.

Resistance to pyrethroids, the only insecticide class currently used in LLINs is widespread (Ranson et al., 2016). The proportion of malaria endemic countries that monitored and subsequently reported pyrethroid resistance increased from 71% in 2010 to 81% in 2016 (WHO, 2017). Metabolic and target site resistance are the two major mechanisms responsible for physiological resistance to insecticides (Ranson et al., 2011). Behavioural changes can also be important if vectors bite outdoors, earlier in the evening the effectiveness of using insecticides indoors will be reduced (Gatton et al., 2013). Another threat to the fight against malaria is the emergence of parasite resistance to artemisinin (WHO, 2017). A study in southern Cambodia reported unsatisfactory cure rate where 47% of the patients remained parasite positive by blood smear two days after the start of treatment compared to 10% in the previous study (Woodrow et al., 2016). Although few studies reported parasite resistance to artemisinin the rate at which it is being used may cause resistance in the future.

1.6.3 The need for additional interventions

It is clear that in many places LLINs and IRS will be insufficient to eliminate malaria, particularly in areas with high malaria transmission and where insecticide-resistant vectors occur. Over the past two decades a substantial investment has been made in the development and testing of new vector control tools (VCAG, 2016). Here I explore the potential of using interventions directed at mosquito-proofing housing.

1.7 Housing and malaria

1.7.1 Historical use of housing as a malaria intervention

The knowledge that mosquitoes transmit malaria, discovered by Ronald Ross in 1897, gave our fight against this disease a focus. In 1899, Angelo Celli carried out the first study on improved housing on families' resident near five malarious railway lines near Rome (Celli, 1900). He provided protection to some families by screening their homes and others were unprotected. Results of the study showed that nearly all families in the unprotected home had malaria, compared with only four malaria cases in 24 people that had malaria in the protected home. In 1900, he extended his work to other parts of the railway where some intervention homes were screened. In this study there were 96% fewer malaria cases in the protected group than in the control group (Celli, 1900).

From these early studies, the practice of improved housing against malaria began to spread to different parts of the world and contributed to malaria elimination in Europe and the United States of America (USA) (Hackett et al., 1937). In 1910 it was used in a larger scale to protect Europeans living in the tropics and those building the Panama Canal (Orenstein, 1912; LePrince and Orenstein, 1916). In 1921, a malaria survey in Missouri, USA found that people living in well-made homes with good screens had less malaria than those who lived in well-made home without screens (5% versus 12% respectively) (Kiker, 1941). In poorly-built homes, malaria reductions were achieved through screening even though other entry points remained. In 1925, the British barracks in Amritsar in India were screened and malaria incidence reduced from 613 per 1,000 to 48 per 1,000 by 1927 (Richard et al., 2002). In the 1930s a study in Alabama, USA showed a substantial reduction in incidence of disease after 700 homes were screened compared to control homes without screening (Kiker, 1941). In this study screened houses had a mean of 5.7 *Anopheles*

quadrimaculatus compared with 8.0 in unprotected houses, (Hewitt and Kotcher, 1941). Improving homes continued to be recognized as a highly effective technique through the middle of the century, even with the emergence of indoor residual spraying to fight malaria. In 1941, C. C. Kiker wrote that 'improvement of homes by the application of mosquito-proofing is probably the most practical, economical, and effective malaria control measure available'.

Today, there is compelling evidence that improved housing helps protect against malaria in sub-Saharan Africa (Table 1.1). Although there have been a number of narrative reviews on the subject (Lindsay et al., 2002; Carter et al., 2014), stronger evidence for efficacy comes from two recent analytic reviews (Tusting et al., 2015; 2017). A systematic review and meta-analysis assessed whether modern housing was associated with a lower risk of malaria than traditional housing in malaria-endemic settings. The review included 90 studies that measured the association between housing and malaria. Overall, residents of modern houses had 47% lower odds of malaria infection compared to traditional houses and 45-65% lower odds of clinical malaria (Tusting et al., 2015). There were though a number of limitations to the study. Firstly, it had limited power to detect publication bias, secondly, since the study included observational studies, there was low comparability between groups, and lastly, there was potential residual confounding by wealth. Due to these problems, the overall strength of the study was judged to be low. Nonetheless, a recent multi-country analysis of 15 Demographic and Health Surveys (DHS) and 14 Malaria Indicator Surveys (MIS) in 21 countries in sub-Saharan Africa between 2008 and 2015 showed that modern housing was associated with 9-14% reduction in the odds of malaria infection (Tusting et al., 2017), similar to the level of protection seen with LLINs. Both major studies provide support for improved housing being protective against malaria in sub-Saharan Africa.

There has been only one randomized control trial (RCT) of a housing intervention (Kirby et al., 2009), although another trial is currently in progress (Pinder et al., 2016). The RCT carried out by Kirby and colleagues was done to assess whether houses with either full screening of windows and doors, and closed eaves, or installation of screened ceilings could reduce the frequency of anaemia in children in The Gambia. Children living in full screened houses had a 47% reduction in anaemia compared to children living in the control. Houses with full screened had 54% reduction in *Anopheles gambiae s.l.* indoor compared to the control houses (Kirby et al., 2009).

Recently, a study in Uganda in an area where IRS greatly suppressed malaria infections found that those in modern houses had 46% lower odds of malaria infection compared to those in traditional houses (Ssempiira et al., 2017). This result suggests that housing has an additional impact after IRS. Although housing improvements alone are unlikely to lead to eradication, when used as a supplementary intervention it is likely to lead to a reduction in malaria transmission. Housing is likely to be a long-term solution to malaria transmission.

1.7.2 Mosquito house entry

Around 80-100% of malaria transmission in sub-Saharan Africa occurs indoors (Huho et al., 2013) at night (Gillies et al., 1968). As a result, entry rates and hence malaria transmission are affected by house construction. The house is the focal point where humans and the malaria vector most commonly come in contact. Whilst the home is often viewed as a place of relative safety, in many settings it is the place where the risk of malaria and other vector-borne disease is highest (Boyd, 1926).

Host-seeking mosquitoes find little or no obstacle to entering a house when openings are available. *Anopheles gambiae*, *s.l.*, the main malaria vector in Africa, is well adapted for entering houses (Snow et al. 1987 & Lindsay et a. 2003). Attracted to intermittent odours plumes such as carbon dioxide (Breugel et al., 2015) pouring out of a house (Lindsay et al., 2003) *An. gambiae* approaches the house at the level of the open eaves (Fig.1.3) (Spitzen et al., 2016). A number of risk factors have been associated with increased vector-density indoors including open eaves, unscreened doors and windows.

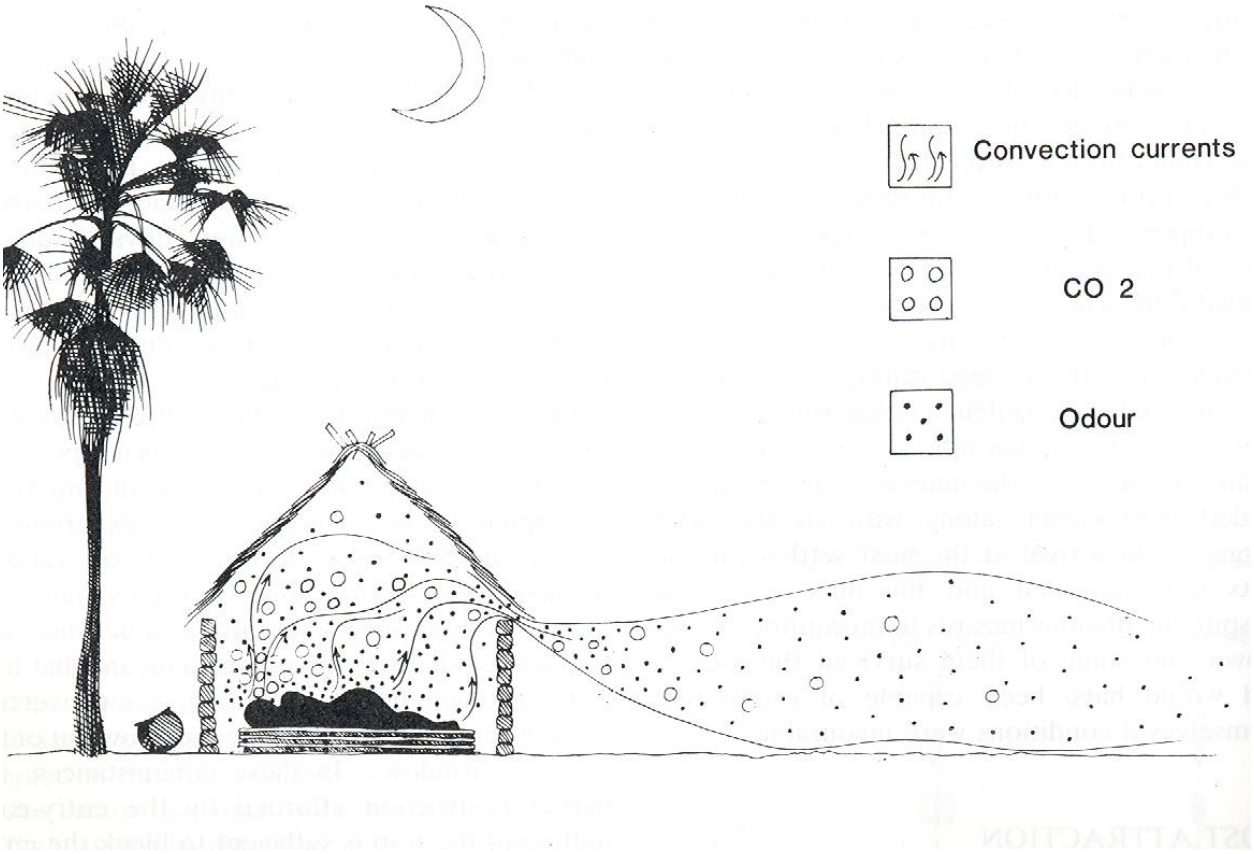


Fig. 1.3*:* Mosquito house entry. (Gillies, 1988)

1.7.3. Open eaves

There is strong evidence that open eaves, the gap between the top of the wall and the over-hanging roof, is the main route by which *An. gambiae* mosquitoes enter houses in sub-Saharan Africa. An observation study in The Gambia showed that children who lived in houses with closed eaves had 20% less malaria than those in houses with open eaves (Lindsay and Snow, 1988). Similarly, it was shown that houses with closed eaves had 43.2% fewer mosquitoes than houses with open eaves. In a study on risk factors for house-entry by malaria vectors in houses in a rural town and satellite villages in The Gambia (Kirby et al., 2008), houses that had closed eaves had 29% fewer *An. gambiae s.l.* compared to houses with open eaves. Further evidence for the protective effect of closing eaves comes from an experimental hut study in rural Gambia, which found 37% fewer *An. gambiae* in huts with closed eaves compared with huts with open eaves, although the p value narrowly missed statistical significance (Lindsay et al., 2003). The strongest evidence to date comes from a cross-over study in The Gambia that showed 65% reduction in *An. gambiae s.l*

caught indoors when houses had their eaves closed compared with when they were open (Njie et al, 2009). Support for the generalizability of this finding comes from a study in southern Tanzania (Lwetoijera et al., 2013) where in an Idete village, houses with closed eaves had 34% reduction in *An. gambiae s.l.* caught indoor compared with houses with open eaves.

1.7.4 Ceilings

In houses with open eaves, ceilings fitted below the line of the eaves can reduce house entry by malaria vectors. An experimental hut trial in rural Gambia showed that screened ceilings reduced the number of *An. gambiae* entering huts by 78-80% compared with huts without ceilings (Lindsay et al., 2003). Similar results were reported from Kenya, where ceilings made from papyrus mats reduced house entry of *Anopheles gambiae s.l.* by 78-80% and *An. funestus* densities by 86% compared to unmodified houses (Atieli et al., 2009). Unmodified houses were associated with relatively higher densities of malaria vectors. In the RCT conducted by Kirby and colleagues (Kirby et al., 2009) screened ceilings reduced the number of mosquitoes entering the house by 40% compared to control houses lacking a ceiling. Presumably the house becomes an odour-baited trap, with mosquitoes that enter the house through the open eaves being unable to pass through the screened ceiling to bite people sleeping in the room.

1.7.5 Screening

House screening has long been used to protect people against malaria. Experimental hut trials in Tanzania showed screening reduced *Anopheles* mosquito house entry by 57-63% compared to unscreened houses (Ogoma et al., 2010). The only randomized control trial carried out to date showed that screened doors and windows reduced house entry of *An. gambiae s.l* by 54% (Kirby et al., 2009). Another randomized control trial of screen doors and windows in south-west Ethiopia found that closing the eaves of a house and screening doors and windows reduced the indoor density of *An. arabiensis* by 40% (Massebo et al., 2013). The limited evidence to date suggests that screening homes in sub-Saharan Africa could be an effective long-term strategy for malaria control.

A summary of how alterations to a house can affect mosquito house entry is shown in Table 1.1., providing evidence that simple changes to a house can reduce malaria vector transmission.

1.8 The changing face of sub-Saharan Africa

Today, the unprecedented population expansion and socioeconomic development in sub-Saharan Africa presents an unrivalled opportunity to build healthy homes. The continent's population is projected to double between 2010 and 2040 to nearly 2 billion and may surpass 3 billion by 2070, with 144 million new houses needed by 2030 in rural and urban areas (UN-Habitat, 2010). Influencing improvements to housing designs to create healthier homes and domestic environments that reduce the threat of malaria and other vector-borne diseases is a prime opportunity that should not be missed. Housing quality is also transforming across much of the continent with traditional thatched houses being replaced by metal-roofed houses (Fig. 1.4), as personal income has increased by 30% from 2006 to 2012 (ESREA, 2013). This trend is likely to increase in the future as Gross domestic product (GDP) is expected to rise by 6% a year for the next few years (ESREA, 2013). Concurrent with the increases in personal wealth are improvements in living standards, including improvements in the availability and quality of housing (RBM VCWG, 2015).

This economic and cultural revolution represents an exceptional opportunity for malaria control (UNHSP, 2014). To make best use of this, WHO in their Global Vector Control Response 2017-2030 stress the need for countries to implement malaria vector control that goes beyond the health sector and strengthen multi-sectoral approaches, with housing being a key intervention (WHO, 2017). Attention to the impact of housing and the built environment on vectors in urban and per-urban settings provides opportunities to engage a wider range of government agencies and development partners in the housing sectors (RBM VCWG, 2015). Today, in The Gambia, many agencies such as Darboe Estate, Green Vision, Paradise Estate, Kombo Real Estate and Sahel Real Estate are involved in constructing new homes with metal roofs, cement bricks or concrete walls and closed eaves replacing the traditional thatched roofs, mud walls and open eaves. While in urban areas, homes are often built with well-fitting doors and windows to improve security and prevent mosquitoes entering the house.

Table 1.1: Literature review on entomological findings from studies on house improvements in sub-Saharan Africa

Study site	Mosquito species	Subjects	Sampling methods	Intervention	Reduction in mosquito numbers (%)	*P*	Ref.
Magoda, Tanzania	All mosquitoes	All houses	furvela tent traps	Full screening	96	Not indicated	Von Seidlein et al., 2017
Magoda, Tanzania	*An. gambiae s.l.*	All houses	furvela tent traps	Full screening	97	Not indicated	Von Seidlein et al., 2017
Magoda, Tanzania	*An. gambiae s.l.*	All houses	furvela tent traps	Full screening	75	Not indicated	Von Seidlein et al., 2017
Wali Kunda, Gambia	*An. gambiae s.l.*	All houses	exit traps	Closed eaves	37	-0.057	Lindsay et al., 2003
Farafenni, The Gambia	*An. gambiae s.l.*	All houses	light traps	Closed eaves	89	<0.001	Kirby et al., 2008
Dibba Kunda Wollof, The Gambia	*An. gambiae s.l.*	All houses	light traps	Closed eaves	65	<0.004	Njie et al., 2009
Farafenni, The Gambia	*An. gambiae s.l.*	All houses	light traps	Full screening	54	<0.0001	Kirby et al., 2009
Farafenni, The Gambia	*An. gambiae s.l.*	All houses	light traps	Screened ceiling	40	<0.0001	Kirby et al., 2009
Kore and Ahero, Kenya	*An. gambiae s.l.*	All houses	pyrethrum spray collection	Full screening	84	<0.001	Atieli et al., 2009
Kore and Ahero, Kenya	*An. funestus*	All houses	pyrethrum spray collection	Full screening	87	<0.001	Atieli et al., 2009
Chano, Ethiopia	*An. arabiensis*	All houses	light traps	Full screening	42	<0.004	Massebo et al., 2013

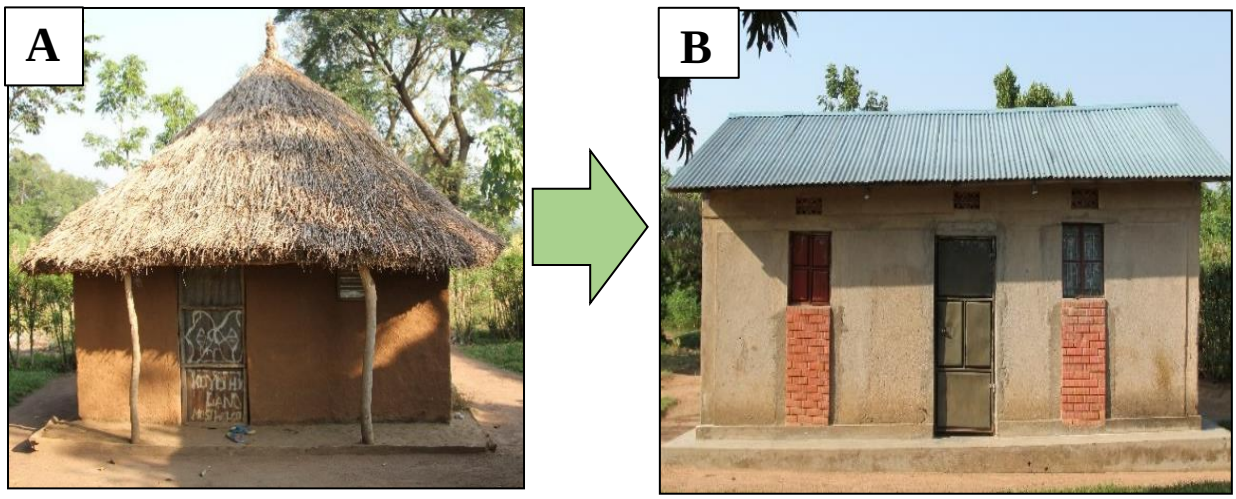


Fig. 1.4: The changing face of housing in sub-Saharan Africa. A) a traditional thatched-roofed house and B) a metal-roofed house near Tororo, Uganda (Pictures by Prof S. Lindsay).

1.9 Conclusion

Improved housing has potential for reducing malaria infection and, perhaps, for keeping areas malaria free after elimination. This intervention should be seen as a supplementary strategy for malaria control augmenting other vector control interventions. Given recent alarming reports of poor coverage of current malaria control interventions and increased insecticide resistance, adopting integrated vector management (IVM) including improved housing may go a long way in reducing the disease. This is important in sub-Saharan Africa since most people are bitten by mosquitoes inside their houses. Compared with the current interventions, housing may have additional protective effect, with limited risks related to insecticide resistance management. In a house where all the eaves are closed and screened doors and windows, everyone indoors should be protected as long as they are inside, not only when sleeping under a net. However, more studies are needed to assess the impact of various improved housing methods in different settings and identify the most effective and acceptable improved housing method for large-scale implementation. It is particularly important to assess the efficacy of different housing designs in reducing house entry by malaria vectors.

1.10 Study rationale

The rationale for this study was to find out how *An. gambiae s.l.* enter typical Gambian houses and to develop better methods for protecting people against these malaria vectors. In The Gambia, there are two common housing types: 1) traditional thatch roofed, made from mud blocks with closed or open eaves; or 2) the modern metal roofed house, made from mud or cement blocks with closed or open eaves. The choice of house type is based on household income, with those on low incomes more likely to build traditional thatch-roof houses which are relatively short-lived, requiring re-thatching every two to four years. Whereas households with higher incomes will build metal-roofed houses, ideally with cement blocks, that will last substantially longer. Due to recent increases in household income and the involvement of new agencies in building and selling new houses, the type of house built in the country is changing rapidly. Many families are demolishing their traditional houses and replacing them with modern houses in both rural and urban parts of the country. Even in the poorest parts of the country where thatched houses are common, it is difficult to find houses with open eaves. Part of the reason for this comes after sensitization by the National Malaria Control Programme on the importance of closed eaves, as a consequence of the findings of the study reported by Njie and colleagues (Njie et al., 2009).

Whilst we know that closing the eaves are important for reducing house entry by *An. gambiae s.l.*, we do not understand the importance of entry points around the doors and windows, and how indoor climate is changed when entry points are opened or closed. This study set out to examine how changes to entry points of a house affect mosquito house entry and indoor climate. The study is novel since this is the first time anyone has examined this. In this study the experimental houses are the same size as village houses, unlike experimental huts which are typically smaller than village houses. Size matters since the heating and cooling of a house depends on the relative size of the materials used. I also test a novel house design, the Roo*Pfs* house, which has two screened doors and two screened gable windows, designed to maximize air flow in the house and keep the occupants cool (Pinder et al., 2016). We hope this design will be suitable for keeping people cooler at night in hot environments in sub-Saharan Africa. Keeping the occupants cool at night may encourage people to sleep indoors under a LLIN and prevent them from being bitten by malaria mosquitoes. If successful, the studies will provide valuable information on how mosquitoes enter houses and that could be used for improved house designs in sub-Saharan Africa.

1.11 Overall goal:

To reduce the entry of *An. gambiae s.l.* mosquitoes into houses and keep the indoors cool at night.

The specific objectives of this thesis are detailed below.

1.12 Study Objectives

1. To find out how the different typologies of rural Gambian housing affects the entry of malaria mosquitoes and indoor climate (Chapter 2);
2. To determine how gaps around the doors of houses affects the entrance of malaria mosquitoes into a house with closed eaves (Chapter 3);
3. To determine how different types of windows affects the entrance of malaria mosquitoes into a house with closed eaves and badly-fitting doors (Chapter 3).

Chapter 2 – Impact of different building designs on mosquito house entry and indoor temperature in The Gambia

2.1 Summary

Background: There is growing evidence that simple house modifications reduce the occupant's risk of malaria exposure in rural houses in sub-Saharan Africa. Here I explored how different rural house designs common in The Gambia affect the risk of mosquito house entry and human comfort.

Methods: Five experimental houses were built along a straight line on the outskirts of Wellingara village adjacent to large irrigated rice fields in The Gambia. The houses were the average size of single-roomed houses and were constructed from mud blocks with a front and back door. There were five types of house designs: 1) the traditional house with thatched-roof, open eaves and badly-fitting doors, 2) traditional house with thatched-roof, closed eaves and badly-fitting doors, 3) traditional house with thatched-roof, closed eaves and well-fitting screened doors, 4) Metal-roof house, closed eaves and badly-fitting doors and 5) a ventilated house with metal roof, closed eaves, two screened gable windows and two screened doors (Roo*Pfs* house). Each typology of house was rotated weekly using a replicated Latin rectangle design so that at the end of the five weeks study each typology had been in each house position. Each week houses were rebuilt according to the typology of house allocated to each position. One man slept under a treated bed net in each house from 21:00 h to 06:00 h for five nights each week for five weeks from 18th September to 21st October, 2016. Mosquitoes were collected using Center for Disease Control (CDC) light trap each night. Indoor climate was recorded in each house using data loggers. A questionnaire was administered each morning to assess the comfort of the sleepers during the night.

Findings: A total of 4,767 mosquitoes were caught during the study. Of these 734 were *Anopheles gambiae s.l.*, 83 other *Anopheles* spp, 2,862 *Culex* spp and 1,088 *Mansonia* spp. In thatch roofed houses closing the eaves reduced house entry of *An. gambiae s.l.* by 94% (Odds ratio, OR=0.06, 95% confidence intervals, CI=0.03-0.11, p<0.001), whilst the addition of screened doors reduced house entry by 96% (OR=0.04, 95% CI=0.02-0.09, p<0.001). The ventilated metal-roofed house resulted in 94% fewer *An. gambiae s.l.* (OR = 0.06, 95% CI = 0.03-0.10, p<0.001), whilst there were similar numbers in metal-roofed houses with closed eaves compared with the thatched-house with open eaves (OR = 2.99, 95% CI = 1.96-4.57, p<0.001).

There was no significant difference in night time mean temperature between thatch roofed, open eaves and Roo*Pfs* house, closed eaves, screened doors and windows (thatch roofed, open eaves mean temp=33.08^{o}C, 95% CI=32.58-33.58^{o}C; Roo*Pfs* house closed eaves, screened doors and windows mean temp=33.81^{o}C, 95% CI=33.25-34.37^{o}C). However, an increase in night time mean temperature was observed between thatch roofed open eaves and metal roofed closed eaves (thatch roofed open eaves mean temp=33.08^{o}C, 95% CI=32.58-33.58^{o}C, metal roofed closed eaves mean temp=34.72^{o}C, 95% CI=34.06-35.39^{o}C). The Roo*Pfs* house and thatch roofed, closed eaves and screened doors were found to be the most comfortable houses. Whereas metal roofed house with closed eaves was found to be the most uncomfortable house.

Conclusion: Closing the eaves in the thatch roofed houses reduce mosquito house entry but not in the metal roofed house. Mosquito house entry in the metal roofed houses were reduced by screening the doors and windows. Improving ventilation in metal-roofed houses makes it cool at night and comfortable for living. Changes in house design should be encouraged to reduce malaria transmission and keep people cool at night. Thus housing features that create comfort indoor and prevent mosquito house entry should be included in future buildings.

2.2 Background

Historically major reductions in malaria disease were achieved by building 'good–quality' houses (Boyd, 1926). More recently, housing improvement has been largely neglected as an intervention for malaria control. Today we have growing evidence that in sub-Saharan Africa sound housing protects against malaria and is potentially an important additional tool in the path toward malaria elimination (Tusting et al., 2017). A recent systematic and meta-analysis showed that residents of modern houses had 47% lower odds of malaria infections compared to traditional houses and a 45-65% lower odds of clinical malaria (Tusting et al., 2015). In a major multi-country analysis of survey data of 29 Demographic Health Surveys (DHS) and Malaria Indicator Surveys (MIS) shows that living in a modern house is associated with 9-14% lower odds of malaria infection in children age 0-5 years, compared to living in a traditional house. These findings indicate that improved housing could be a promising intervention for malaria control and for the prevention of malaria reintroduction after elimination.

The principal Africa malaria vectors *Anopheles gambiae s.s* and *An. funestus* have evolved to feed on humans late at night indoors when people are asleep and less able to protect themselves from blood-feeding mosquitoes (Gillies and DeMeillon, 1968). Importantly 80-100% of malaria transmission by malaria mosquitoes occurs indoors at night in sub-Saharan Africa (Huho et al., 2013). Attracted to human odours pouring out of the eaves (Snow, 1987) and are funneled indoors by the over-hanging roof, through the open eaves, the major route of entry for *An. gambiae s.l.* (Njie et al., 2009). Closing the eaves or screening the doors and windows can be effective at reducing house entry by *An. gambiae s.l.* (Njie et al., 2009, Kirby et al. 2009). Thus preventing house entry from this major vector should protect people against malaria.

In The Gambia a transition in housing typologies is in progress, where traditional thatched-roofed houses with open eaves and mud walls are having their eaves closed. Or, more commonly, are being replaced by metal-roofed houses with closed eaves and walls of mud or cement blocks. It is not known, how these changes in design will affect mosquito house entry, nor how effective house screening will be with different designs. One concern is that metal-roofed houses may be too hot for the occupants, which may reduce the number of people sleeping under a long-lasting insecticidal net (von Seidlein et al., 2017). In a RCT of housing currently in progress in The Gambia the intervention arm consisted of ventilated metal roof houses (Pinder et al., 2016). This house is expected to be cooler since the design incorporate both screened doors and screened gable windows which should increase airflow through the building and keep the occupants cooler.

Despite the accumulating evidence on the protective efficacy of improved housing in sub-Saharan Africa, there is no study, to my knowledge, that has looked at the relationship between different typologies of rural African housing, house entry by malaria vectors and human comfort. This study is also novel since we used houses of an average size in The Gambia, rather than the diminutive huts traditionally used for experimental hut trials. The findings from this study will be of relevance to those interested in future building designs in sub-Saharan Africa. The study is particularly timely since the continent's population is projected to double between 2010 and 2040 to nearly 2 billion and may surpass 3 billion by 2070, with 144 million new houses needed by 2050 (UN-Habitat, 2010). Identifying housing features that could be added to the new houses may contribute to reducing the disease burden from malaria, and perhaps other mosquito-borne diseases.

2.3 Methods

2.3.1 Study area

The study took place on the edge of Wellingara village (N 13^0 33.365', W 14^0 55.461'), Lower Fulladu West, south bank of the river Gambia, Central River Region in October 2016. It has a population of 629 people (GBoS, projected population 2017). Most villagers are Mandinkas (90%), with small numbers of Bambaras (9%) and Fulas (1%). Bed net coverage is high in the area and more than 90% of the population slept under a bed nets throughout the year (MIS, 2014). The climate is characterized by a rainy season from June to October and a dry season from November to May. Malaria is endemic and transmission is mainly at the end of the rainy season. Members of the *An. gambiae s.l.* are the principal malaria vectors in the area (Lindsay et al., 1991) with *An. arabiensis* predominant (Caputo et al., 2008). Their breeding is favour by the large irrigated rice fields nearby (Lindsay et al., 1991). In June, 2016 the National Malaria Control Programme (NMCP) conducted indoor residual spraying with bendiocarb covering the entire village, but not the experimental houses. The main economic activity of the people in the village is the cultivation of rice and maize. Due to its close proximity to the local market in Brikama Ba, there are also a few people who also engage in keeping small animals like chickens, goats and sheep for income generating

2.3.2 Study enrollment

Following ethical approval a village meeting was conducted with the compound heads to seek their consent to build experimental houses on their land. The meeting was centered on the importance of the study, duration and compensation for using their land. Those that agreed to offer their land signed or thumb printed a written consent form. Both parties kept a copy of the signed document (Appendix).

Another separate meeting was conducted with the volunteers involving the village head (Akalo), Imam, Youth leader, Women leader, Village Health Worker and other community members from the village to explain to them the purpose of the study. The meeting discussed the importance of the project, sleeper's identification, the proposed house designs for the experiment and their involvement in the fight against malaria. Those that agreed to join the study had the consent form

explained to them in the language they understand fully. Again, a written consent form was signed in writing or thumb printing. For those who could not read, a witness independent of the study was present during the explanation of the study and their names recorded on the form.

2.3.3 Experimental houses

Five single-roomed experimental houses were constructed along the edge of Wellingara village closest to the large irrigated Jahally-Pacharr rice field 500 m away. Houses were constructed from mud blocks and built 10 m apart, along a straight line facing the rice field (Fig. 2.1). The houses were the average size of single-roomed rural houses in the Upper River Region of The Gambia. Each house measured 4.2 m^2 in area with a front and back door on opposite sides. There were two doors, one at the front and one at the back of the house, each measuring 1.80 m in height and 0.80 m wide. The house typologies were based on four typical rural house designs, as well as the ventilated house design used in the Roo*Pfs* study (Pinder et al., 2016). The five typologies of houses were: 1) traditional thatched roofed, open eaves with badly-fitting doors, 2) traditional thatched roofed, closed eaves with badly-fitting doors, 3) traditional thatched roofed, closed eaves with screened doors, 4) metal roofed, closed eaves with badly-fitting doors and 5) Roo*Pfs* house with metal roof, closed eaves, screened doors and screened gable windows. This house has closed eaves, screened front and back doors and two screened gable windows directly opposite to allow maximum airflow indoor (Fig. 2.2). Three houses were provided with a typical village door made from one sheet of corrugate attached to a wooden frame with 2 cm gaps at the top and bottom of the doors, to simulate badly-fitting doors common in the villages. The other two houses were provided with metal screened louvered doors front and back. Every week, the roofs, windows and doors were rotated between different houses and the eaves opened or closed using a repeated Latin rectangle design (Table 2.1). This was done to enable us measure the effect of the different typologies adjusting for geographical position of the house. This experiment was carried out at the end of the rainy season from 18th September to 21st October 2016.

Fig. 2.1: The five single-roomed experimental houses

Fig. 2.2: Roo*Pfs* house and the gable window: A) Roo*Pfs* house B) close-up of screened gable window

Table 2.1: Latin rectangle design for rotating house typologies between different positions in 2016/

Week	House position				
	1	2	3	4	5
1	Metal roofed, closed eaves	Thatch roofed, closed eaves, screened doors	Thatch roofed, open eaves	Thatch roofed, closed eaves	Roo*Pfs* house
2	Thatch roofed, closed eaves, screened doors	Thatch roofed, closed eaves	Metal roofed, closed eaves	Roo*Pfs* house	Thatch roofed, open eaves
3	Thatch roofed, closed eaves	Roo*Pfs* house	Thatch roofed, closed eaves, screened doors	Thatch roofed, open eaves	Metal roofed, closed eaves
4	Roo*Pfs* house	Thatch roofed, open eaves	Thatch roofed, closed eaves	Metal roofed, closed eaves	Thatch roofed, closed eaves, screened doors
5	Thatch roofed, open eaves	Metal roofed, closed eaves	Roo*Pfs* house	Thatch roofed, closed eaves, screened doors	Thatch roofed, closed eaves

2.3.4 Experimental houses construction

The single room experimental houses were constructed with mud-blocks (Fig. 2.3). The mud was wetted with water and mixed with dried grass to prevent the blocks from cracking when dry, formed in a wooden mold, and left to dry in the sun for five days. The mud blocks were transported to the construction site using donkey carts. The five houses were built on the ground measuring 4.2 m^2 area and 10 m apart. The blocks were laid in layers and bonded using wetted mud up to the height of the door (1.80 m). On top of the door, a 2 cm x 12 cm wooden lintel 1 m long was placed to support the mud blocks resting on it. Two layers of blocks were laid on top of the door and then re-enforced with a concrete lining around the house to prevent the mud blocks from breaking when the roofs were moved between houses. The concrete lining was re-enforced with eight 6 mm metal rods, and the concrete mixed using sand (one wheelbarrow), gravel (two wheelbarrows), cement (one bag of 50 kgs) and water (25 L), then poured into a wooden box frame and allowed to cure for five days. The roof frames were made from square metal pipes 30mm thick and 2 cm x 2 cm wood pieces were screwed to the frame and corrugate sheeting fixed to the wood with nails. The roof frames were assembled on the ground, lifted up and placed on top of each house. The three thatch roofs were made from metal with a conical shape and the metal roofs a rectangular-prism

shape. The roofs were connected to the walls with flat metal strips to prevent them being moved by the wind. There were six unscreened doors, each made from one corrugated iron sheet attached to a 2 cm x 2 cm wooden frame while the screened doors were made of metal and netting material. The doors were then fixed to their respective houses.

Fig. 2.3: Experimental houses under construction: A) mud blocks being sun dried, B) block transportation, C) wall construction, D) wetting concrete lining, E) attaching wood to metal frame, F) assembling metal roof frame, G) putting thatch on roof frame, H) complete thatch roofed house, I) complete metal roofed house

2.3.5 Entomology

Each house was sampled nightly for five nights each week for five weeks starting 18th September to 21st October, 2016. House entering mosquitoes were sampled using CDC light traps (Model 512, John W. Hock Co.) placed with the light 1 m above the ground close to the foot of the bed with an occupant sleeping under a treated net (Olyset) and left to run overnight from 21:00 h to 06:00 h. Each morning the collection nets were taken from each house, stored individually in a

cool box and transported to the Medical Research Council Unit The Gambia's field station at Wali Kunda. Mosquitoes were then killed by transferring them to a freezer set at -20 ^{o}C for two hours and identified morphologically. Female *An. gambiae s.l.* were classified as blood fed, unfed and semi/gravid (Appendix). All female *An. gambiae s.l.* were stored individually in an Eppendorf tube containing a cotton wad with silica gel beneath.

2.3.6 Polymerase chain reaction (PCR) analysis

A total of 734 female *An. gambiae s.l.* were collected during the study. Of these, 458 were transported to Medical Research Council Unit The Gambia's main laboratory in Fajara for polymerase chain reaction (PCR) analysis. This was done to determine the members of the *An. gambiae* complex entering each house typology. Mosquitoes were dissected to separate the head and thorax from the abdomen and stored separately in labeled Eppendorf tubes (Malaria PCR protocol, 2017). Taq polymerase reagent was added to the tubes containing the head and thorax and broken into smaller pieces. The pieces were transferred into a holding tube and buffer reagent added to wash off all the particles while DNA remain attached. Master mixed was added to the DNA and stored in the fridge for 8h and later transferred into the QIAXCEL advanced machine to run the samples. Test results were then copied and transferred to an excel spread sheet for data storage.

2.3.7 Meteorology

Temperature and relative humidity were measured indoors in each experimental house using tiny-tag data loggers (model, TGU 4500) throughout the study period. These devices were hung from the roof frame in the middle of each house, 1 m above the ground. The data were downloaded weekly for five weeks. In addition, an automatic weather station (MiniMet, Skye Instruments, UK) (Fig. 2.4) was positioned outdoors 10 m from one of the experimental house to record temperature, relative humidity, rainfall, wind speed and wind direction. The data were downloaded from the weather station weekly and stored on a server kept in the office for data backup.

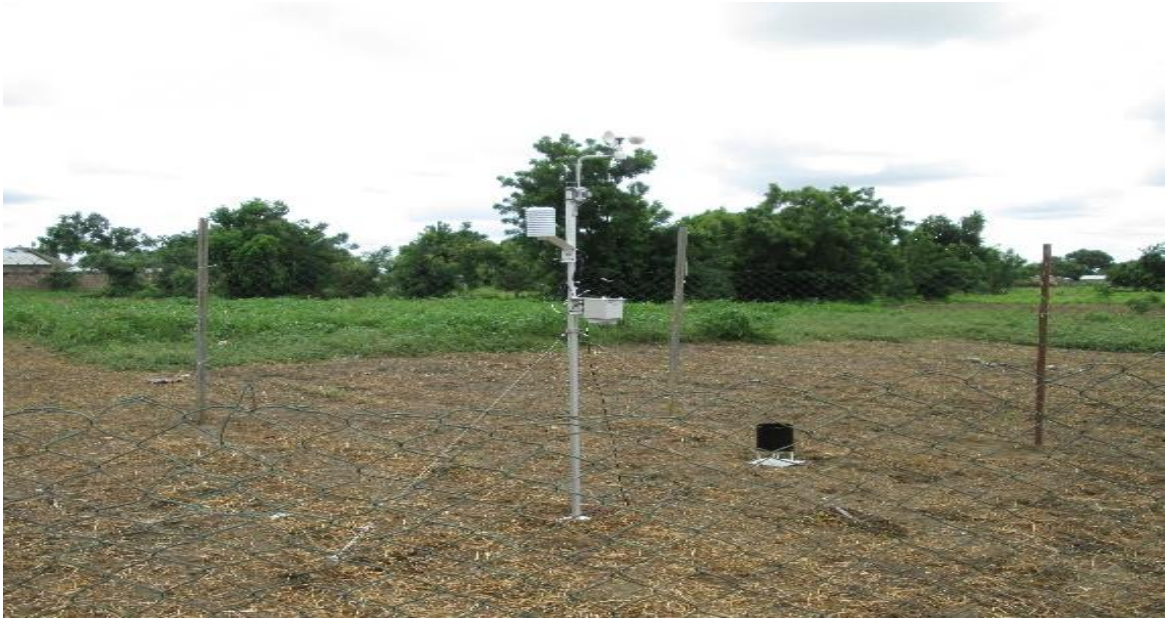


Fig. 2.4: Automatic weather station

2.3.8 Data Analysis

The mean mosquito catches and 95% confidence intervals were calculated for *An. gambiae s.l.*, other *Anopheles* spp., *Culex* spp. and *Mansonia* spp. for each house type. Mosquito numbers and indoor climate per house/intervention were described by an arithmetic mean. The effect of house typology on mosquito house entry and indoor climate was assessed using generalized linear modelling, using a negative binomial model with a logit link function for count data and a normal distribution for continuous variables. In addition to house typology, house position and week were included in the model. Sleepers comfort was scored as 1=comfortable, 2=slightly uncomfortable, and 3=highly uncomfortable. Comparisons of comfort between typologies was done by combining 2 and 3, and making comparisons with the traditional house type using the chi-square test. Data analysis was performed using SPSS vision 20.

2.3.9 Ethical Clearance

The study protocol was approved by the joint Gambia Government and Medical Research Council Ethics Committee (Reference: SCC 1478 V 2, approved 29th April, 2016).

2.4 Findings

2.4.1 Entomology

A total of 4,767 mosquitoes were caught from 125 light trap collections. Of these, 734 (15%) were *An. gambiae s.l.*, 83 (2%) other *Anopheles* spp., 2,862 (60%) *Culex* spp. and 1,088 (23%) *Mansonia* spp. Of the 734 *Anopheles gambiae s.l.* caught from 125 light trap collections, 591 were unfed, 83 gravid/semi gravid and 60 blood fed (Table 2.2).

Table 2.2: Gonotrophic stages of total *An. gambiae s.l.* found in each house type.

House type	Gonotrophic stages			
	unfed	Blood fed	semi-gravid	Total *An.gambiae s.l.* collected
Thatched roof, open eaves, unscreened doors	156	32	71	259
Thatched roof, closed eaves, unscreened doors	17	0	0	17
Thatched roof, closed eaves, screened doors	9	0	1	10
Metal roof, closed eaves, unscreened doors	395	27	7	429
Roo*Pfs* house, closed eaves, screened doors and gable windows	14	1	4	19

2.4.2 Polymerase chain reaction (PCR) results

A total of 458 *Anopheles gambiae s.l.* were taken for PCR analysis. Of these 302 (66%) were *An. arabiensis* and 156 (34%) *An. gambiae* M form.

2.4.3 Treatment Effects

The variation in mosquito mean numbers and odds ratio between different types of houses are summarized in table 2.3.

When the eaves were closed in the thatch roofed house, a 94% reduction in *An. gambiae s.l.* density indoor was realized (OR=0.06, 95% CI=0.03-0.11, p<0.001). A similar reduction was observed in *Culex* spp. (OR=0.52, 95% CI=0.37-0.74, p<0.001). When screening was added to the

thatch roofed house with closed eaves, 96% reduction was observed in *An. gambiae s.l.* density indoor (OR=0.04, 95% CI=0.02-0.09, p<0.001). However, closing the eaves in the metal roofed house resulted in an increase in *An. gambiae s.l.* density indoors compared to the thatch roofed house with open eaves (OR=2.99, 95% CI=1.96-4.57, p<0.001). When screening was added to the metal roofed house with closed eaves, a 94% reduction was observed in *An. gambiae s.l.* indoor density (OR=0.06, 95% CI=0.03-0.10, p<0.001). Similar reductions were observed in other *Anopheles*, *Culex* spp. and *Mansonia* spp.

2.4.4 Environmental measurements

Closing the eaves of a thatched-roofed house increased the indoor temperature by 0.5 ^{o}C before midnight and 0.4 ^{o}C after midnight compared to the traditional thatched-house with open eaves (Table 2.4). Thatched-roofed houses with closed eaves can be made cooler by adding screened doors to a thatched-house with closed eaves. Metal-roofed houses with closed eaves were 1.5 ^{o}C hotter than traditional thatch roofed houses, but adding screened doors and windows to metal roofed house lowered the temperature compared to traditional houses.

2.4.5 Carbon dioxide measurements

In houses with closed eaves, carbon dioxide concentrations indoors were higher in metal-roofed houses than thatched-roofed houses (Fig. 2.5). Carbon dioxide concentrations rose slowly after the volunteers entered the houses at 21.00 h, reaching a peak approximately two hours later and then levelling off for the rest of the night. The maximum nightly carbon dioxide concentration was greater in metal-roofed houses (mean maximum = 1073 ppm, 95% CIs = 955-1191) than thatched-roofed houses (826 ppm, 95% CIs = 768-884; paired t test = 3.60, df = 22, mean difference = 247 ppm, 105-390, p = 0.002). Carbon dioxide concentration was associated with house type (linear regression, t = 36.40, P<0.001), data logger (t= -23.88, P<0.001), time of night (t = -14.79, p<0.001), temperature (t = 13.84, p<0.001), house position (t= -9.08, P<0.001), and night (t=8.52, P<0.001), with the overall model being weakly predictive (adjusted R^2 = 0.303, F=371.37, df 5111, 6, p<0.001).

Table 2.3: Mosquito density found in each house type. Where CI = confidence intervals and OR = odds ratio

House type	Mosquito species											
	An. gambiae s.l.			Other *Anopheles*			*Culex* spp.			*Mansonia* spp.		
	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p
Thatch roofed, open eaves, badly-fitting doors	10.4 (3.8-17.0)	1.0		1.1 (0.3 - 1.9)	1.0		35.2 (25.5-45.0)	1.0		10.9 (7.6 – 14.2)	1.0	
Thatch roofed, closed eaves, badly-fitting doors	0.7 (0.0-1.4)	0.06 (0.03-0.11)	<0.001	1.6 (0.5 – 2.7)	1.96 (0.87-4.44)	0.104	25.4 (14.2-36.6)	0.52 (0.37-0.74)	<0.001	9.8 (6.4 – 13.2)	0.80 (0.58-1.09)	0.159
Thatch roofed, closed eaves, well-fitting screened doors	0.0 (0.1-0.4)	0.04 (0.02-0.09)	<0.001	0.0 (0.0 – 0.1)	0.04 (0.01-0.21)	<0.001	3.1 (1.6 – 4.6)	0.08 (0.05-0.12)	<0.001	3.3 (1.5 – 5.0)	0.26 (0.16-0.41)	<0.001
Metal roofed, closed eaves	17.2 (11.0-23.3)	2.99 (1.96-4.57)	<0.001	0.5 (0.1 – 0.9)	0.43 (0.17-1.06)	0.066	48.0 (36.2 – 59.7)	1.17 (0.86-1.60)	0.315	17.8 (10.2-25.4)	1.43 (1.04-1.98)	<0.029
Metal roofed, closed eaves, well-fitting screened doors and gable windows	0.8 (0.1- 1.6)	0.06 (0.03-0.10)	<0.001	0.1 (0.0 – 0.3)	0.09 (0.03-0.24)	<0.001	2.7 (1.1 – 4.4)	0.05 (0.03-0.08)	<0.001	1.8 (0.8 – 2.8)	0.13 (0.08-0.21)	<0.001

Table 2.4. Outdoor and indoor temperature experienced in five different house typologies during the rainy season. General linearized modelling results, adjusting for house position and night. (CI = confidence intervals).

Description	Maximum temperature			Average temperature 21.00-23.30h			Average temperature 00.00-06.00h		
	Average (°C) (95% CIs)	Difference from traditional house (95% CIs)	p	Average (°C) (95% CIs)	Difference from traditional house (95% CIs)	p	Average (°C) (95% CIs)	Difference from traditional house (95% CIs)	p
Outdoor temperature	33.5 (32.8-34.2)	-		27.2 (26.6-27.7)	-		25.2 (24.7-25.8)	-	
Thatch roofed, open eaves, badly-fitting doors	33.0 (32.9-33.2)	-		32.0 (31.8-32.1)		-	29.3 (29.2-29.4)		<0.0001
Thatch roofed, closed eaves, badly-fitting doors	33.3 (33.2-33.5)	0.3 (0.1-0.5)	0.009	32.5 (32.3-32.5)	0.5 (0.3-0.6)	<0.0001	29.7 (29.6-29.9)	0.4 (0.2-0.6)	<0.0001
Thatch roofed, closed eaves, well-fitting screened doors	33.0 (32.8-33.1)	0.0 (-0.3-0.2)	0.649	31.5 (31.4-31.7)	-0.4 (-0.6- -0.24)	<0.0001	28.9 (28.8-29.0)	-0.4 (-0.6 - -0.2)	<0.0001
Metal roofed, closed eaves	34.7 (34.6-34.8)	1.7 (1.5-1.9)	<0.0001	33.4 (33.3-33.6)	1.5 (1.3-1.7)	<0.0001	30.2 (30.1-30.4)	0.9 (0.7-1.1)	<0.0001
Metal roofed, closed eaves, well-fitting screened doors and gable windows	33.7 (33.6-33.9)	0.7 (0.5-0.9)	<0.0001	32.0 (31.9-32.2)	0.1 (-0.1-0.30)	0.383	29.0 (28.8-29.1)	-0.4 (-0.5 - -0.2)	0.0005

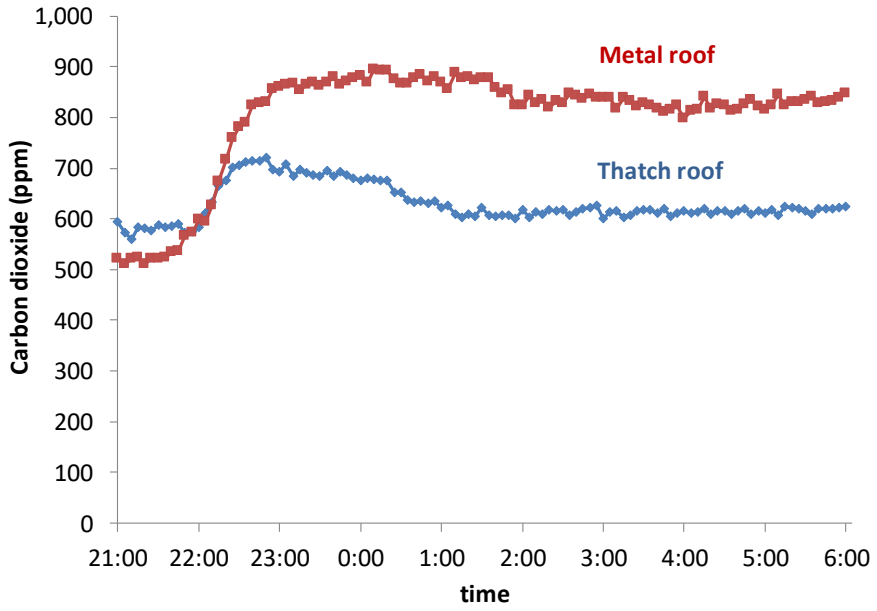


Fig. 2.5: Changes in carbon dioxide concentration from 21:00 pm to 6:00 am in a mud-walled house with closed eaves and a thatched- or metal roof.

2.4.6 Comfort surveys

Each morning sleepers were asked how comfortable they were during the night in a language they were familiar with. Responses were recorded using a questionnaire. The findings from the comfort survey are shown in table 2.5. Compared to the traditional thatched roof the only house typology that was considered uncomfortable was the metal-roofed house with closed eaves (Fisher's exact test = 0.0002, df = 1, $p < 0.05$).

Table 2.5: Sleepers responses on comfort for each house typology.

House type	Comfort index			
	comfortable	slightly uncomfortable	highly uncomfortable	total
Thatch roofed, open eaves, badly-fitting doors	25	0	0	25
Thatch roofed, closed eaves, badly-fitting doors	23	2	0	25
Thatch roofed, closed eaves, well-fitting screened doors	25	0	0	25
Metal roofed, closed eaves	11	7	7	25
Metal roofed, closed eaves, well-fitting screened doors and gable windows	25	0	0	25

2.5 Discussion

This study shows that simple modifications to rural African houses affects exposure to malaria vectors and, potentially, mosquito vectors of other diseases. Closing the eaves of thatch-roofed houses with mud resulted in a 94% reduction in *An. gambiae* s.*l.* entering the house. Similar reductions were observed with *Culex* spp and *Mansonia* spp, but not with other *Anopheles* mosquitoes. This finding concurs with a previous study conducted in The Gambia where closing the eaves results in a 65% reduction in *An. gambiae s.l.* entering the house (Njie et al. 2009). Closing eaves may be protective in other parts of sub-Saharan Africa since a study by Lwetoijera and colleagues has shown that *An. gambiae s.l.* also enter houses through open eaves in Tanzania (Lwetoijera et al., 2013). Interestingly, in the metal-roofed houses, closing the eaves increased *An. gambiae s.l.*, *Culex* spp and *Mansonia* spp but reduced other *Anopheles* mosquito by 57% indoor. One explanation for this finding could be since the metal roofed house is hotter than the thatched roofed house, sleeper's sweat more and produce more carbon dioxide and other body odours in the metal-roofed house. The increased carbon dioxide is likely to be particularly important since it is a major mosquito attractant (Gillies, 1980).

House screening proved to be an effective barrier against mosquitoes, provided the eaves were closed. Thatched-roofed houses with closed eaves and screened doors had 96% fewer *An. gambiae s.l.* indoors. Similar reductions were observed with other *Anopheles* species, *Culex* spp and *Mansonia* spp. A similar result was seen in the Roo*Pf*s house, which had closed eaves and screened doors and windows. This suggests that house screening is an effective intervention against endophagic mosquitoes and should be encouraged, particularly in houses with metal roofs. Since mosquitoes locate host by following odour plumes, screening is likely to be effective in reducing both malaria vectors and nuisance mosquito house entry in sub-Saharan Africa.

House screening works by providing protection against mosquito bites for the entire household, compared to a bed net which only protects those sleeping under the net. A study conducted in Ahero, Kenya found that closing all entry points in a house can provide an effective barrier against mosquitoes (Atieli, 2007). In Ethiopia, when closed eaves, screened doors and windows were combined there was a 40% reduction in *An. arabiensis* indoors compared to control houses (Massebo et al., 2013). Improved house designs and modifications to existing houses could substantially reduce the risk of mosquito human contact. A recent study in Tanzania assessed the

impact of improved housing on mosquito house entry and showed a 97% reduction in *An. gambiae s.l.* caught in double-storey buildings (von Seidlein et al., 2017). This demonstrates the effectiveness of improved housing against mosquito house entry. Although house improvement has been advocated as an effective intervention for malaria control, many houses in rural Africa are temporary and built with minimal material resources. This will render improvements expensive or impractical in many rural communities. Permanent houses could be easily and cheaply modified by closing eaves and screening doors and windows accompanied by community sensitization towards intervention sustainability. Temporary houses are less amenable to modification unless they are rebuilt as more permanent structures.

Designing a house that has a comfortable indoor climate is very important for wide-scale implementation. All typologies of houses were several degrees warmer at night than outdoors due to the thick mud blocks used for building the walls. Mud walls heated by sunlight during the day radiate heat at night, with the roof and walls trapping the hot air in the house. Outdoors temperature drop at night because of the lack of solar radiation and occasional heavy rains experienced during the study. With regards to indoor comfort, the metal-roofed house was deemed the most uncomfortable typology by the sleepers during the study. The ventilated metal-roofed and thatch roofed houses were though considered to be comfortable, presumably because both house typologies houses have large surface areas where airflows easily into the house making it cooler and comfortable for sleeping. A study in Tanzania where the indoor temperature was assessed revealed that most people feel comfortable when the indoor temperature is between 22-30ºC (Knudsen et al., 2013). However, the mean temperature of our study houses is slightly higher compared to the Tanzanian study, yet sleepers responded feeling comfortable sleeping in them. This shows that people respond differently to temperature, what may be a suitable temperature in one geographical location may not be suitable in other geographical location. Although the metal-roofed house was the hottest house, it can be make cooler during the night by improving the ventilation. Since improving the ventilation make it cooler during the night, the use of bed nets may be enhanced. In addition, occupants can spend their waking time indoors, while protected by the house from mosquitoes.

2.6 Conclusion

Results from this study demonstrated that the design of a house can be altered to reduce mosquito house entry. Although closed eaves are effective against reducing mosquito house entry in thatched houses, no reduction was observed in metal roofed houses with badly fitting doors. Improving the ventilation in a metal-roofed house, by installing screened doors and windows, makes it as cool as a thatch-roofed house with open eaves during the night. This is important since in The Gambia traditional thatch-roofed houses are being replaced with metal-roofed houses with closed eaves, installing screened doors and windows will make them cool and enhance bed net usage. Housing features such as closed eaves, screened doors and windows should be incorporated into the new buildings.

Chapter 3 – How gaps around the door and addition of screened and unscreened windows affect mosquito house entry in The Gambia

3.1: Summary

Background: Housing quality affects the risk of malaria transmission in sub-Saharan Africa. This study assessed how changes to entry points around the door and the addition of screened and unscreened windows affects mosquito house entry in rural Gambia.

Methods: Three experiments were carried out in 2017 using five single-roomed experimental houses to assess how mosquito house entry was affected by 1) gaps at the top and bottom of a door, 2) increasing numbers of small screened and unscreened windows and 3) increasing number of large screened and unscreened windows. In each experiment five different types of house designs were assessed, four with metal roofs and closed eaves and one with a thatched roof. Two healthy adult men slept under a treated bed net in each house from 21:00 h to 06:00 h for 25 nights in each experiment. Mosquitoes were collected using CDC light trap in each house. The different house designs were rotated weekly using a replicated Latin rectangle design.

Findings

In the first experiment, the number of *Anopheles gambiae s.l.* entering a metal-roofed house with closed eaves and badly fitting doors, was unaffected by whether there was a gap only at the top or only at the bottom of the door, or if two screened windows were added to the house. In the second experiment, the entry of *An. gambiae s.l.* indoors was reduced by 40% after adding two small screened windows (odds ratio, OR=0.60, 95% confidence intervals, CI=0.40-0.91) or by 63% after adding one large and small screened window (OR=0.37, 95% CI=0.22-0.64) compared to a house with a badly-fitting window. In the third experiment, *An. gambiae s.l.* numbers were reduced by 57% with one large screened window (OR=0.43, 95% CI= 0.28-0.64), by 79% with two large screened windows (OR=0.21, 95% CI=0.14-0.32) and by 95% with three large screened windows (OR=0.05, 95% CI=0.02-0.10) compared with the house with badly fitting windows.

Conclusion:

A similar number of *An. gambiae s.l.* enter houses if there is a gap at the top or bottom of the door or there are gaps at the top and bottom of the door. However, the number of mosquitoes entering

through gaps around the door can be reduced by installing screened windows in the building, the larger the area of screened window the greater the reduction in house entry by *An. gambiae s.l.* One explanation for these findings is that human odours emanating from the windows act as decoys for mosquitoes, reducing house entry through the doors. Screened windows should be investigated further as a malaria control intervention for reducing mosquito house entry.

3.2 Background

Considerable progress has been made in reducing malaria incidence and mortality in sub-Saharan Africa since the turn of the century (WHO, 2017). Nonetheless, today malaria continues to place a critical burden on the region's poor, with 216 million cases and 445,000 deaths reported from this disease in 2016. Millions of people continue to lack access to preventive interventions and health services providing quality-assured diagnostic testing and life-saving treatment. Currently, 46% of people at risk from malaria do not sleep under a long-lasting insecticidal net, well below the target of 80% required for universal coverage. There is also the growing threat of malaria vectors resistant to the insecticides used for treating nets and spraying on walls. This shows the need for identifying additional strategies to compliment the current gains and fill the remaining gaps (Snetselaar et al., 2017).

Making homes mosquito-proof is a key aspect of environmental management that has been associated with protection against malaria in sub-Saharan Africa. A systematic review and meta-analysis assessed whether modern housing was associated with a lower risk of malaria than traditional housing in malaria endemic settings. The review included 90 studies that measured the association between housing and malaria. The findings show residents of modern houses had 47% lower odds of malaria infection compared to traditional houses and a 45-65% lower odds of clinical malaria (Tusting et al., 2015). Although the reviewing team lacked the power to detect bias in publications, there was evidence that housing is protective. More recently, a multi-country analysis of 15 Demographic and Health Surveys and 14 Malaria Indicator Survey in 21 countries in sub-Saharan Africa between 2008 and 2015 showed that modern housing was associated with 9-14% reduction in the odds of malaria infection (Tusting et al., 2017). Both major studies provide support for improved housing being protective against malaria in sub-Saharan Africa. This is not surprising when 80% or more of malaria transmission occurs indoors at night (Huho et al., 2013).

Improving housing in sub-Saharan Africa could contribute to the reduction of malaria transmission indoors.

Screened housing works by reducing exposure to malaria-transmitting mosquitoes and has the added benefit of protecting everyone in the house avoiding the issues of inequity within the household. The attractiveness and ease of entry into a house is affected by a number of structural features such as open eaves and gaps around doors and windows. *Anopheles gambiae s.l.*, the principal malaria vector in sub-Saharan Africa enter houses through open eaves. They are attracted to the intermittent carbon dioxide and other host odours plumes (Breugel et al., 2015) that emanate from a house (Lindsay et al., 2003) and approach the house at the level of the eaves and enter. These series of studies were carried out to determine how mosquitoes get into houses with closed eaves, a type of house that is now common throughout The Gambia. In these houses the only entry points are around the doors and windows. We also tested the hypothesis that screened windows could act as decoys causing mosquitoes to accumulate around the windows and not find access to the house through gaps around the door. Although houses with windows are common in The Gambia, those with screened windows are very limited especially in the rural part of the country. Even though five single-roomed experimental houses were used to conduct these experiments, the house designs used were common in most sub-Saharan Africa.

In a randomized controlled trial in The Gambia house screening was associated with a 54% reduction in indoor vector density (Kirby et al., 2009). However, the relative importance of door gaps and screened windows in houses where the eaves were closed has not been fully explored. This study was designed to determine the importance of gaps around the doors and windows, and screening windows, for mosquito house entry. Preventing mosquitoes gaining access to houses either by closing the eaves or by screening should reduce malaria transmission.

3.3 Methods

3.3.1 Study area

The study was located in Wellingara village (N 13^{o} 33.365', W 14^{o} 55.461') Lower Fulladu West, south bank of the River Gambia, Central River Region. It is located 2 km from the Medical

Research Council field station at Wali Kunda and 1 km from Brikama Ba. It has a population of about 629 people (GBoS, projected population 2017), most of whom are Mandinkas (90%), with small numbers of Bambaras (9%) and Fulas (1%). Bed net coverage is high in the area and more than 90% of the population slept under bed nets throughout the year (MIS, 2014). The climate is characterized by a rainy season from June to October and a dry season from November to May. Malaria is endemic in the area and transmission is mainly at the end of the rainy season. *Anopheles coluzzii* and *An. arabiensis* are the principal malaria vectors in the area and their breeding is favoured by the presence of the large irrigated rice fields nearby (Lindsay et al., 1991). In June 2017, the National Malaria Control Programme (NMCP) conducted indoor residual spraying with Actellic covering the entire village, but excluding the study houses. The main economic activity of the people in the village is rice cultivation. Due to its proximity to a local market in Brikama Ba, a few people also engage in keeping small animals like chicken, goat and sheep for income generating.

3.3.2 Volunteer selection

A meeting was conducted with the volunteers who slept in the experimental houses in 2016. During the meeting, the requirements and procedures for the 2017 experiments were explained to them in a language they understood fully. They all gave their consent by signing the consent form.

3.3.3 Experimental houses

Five single-roomed experimental mud-block houses located at the edge of Wellingara village were modified to examine the impact of different door features and windows on mosquito house entry. The construction of these houses and the experimental procedures was described in detail in chapter 2. Three experiments were carried out (Fig. 3.2). The first experiment examined how gaps around the door affected mosquito house entry. The second experiment explored how small screened and unscreened windows affect mosquito house entry. The size of the windows were the traditionally windows used in experimental huts in The Gambia (Miller et al., 1991). The third experiment repeated the second experiment, but used larger windows, more typical of houses in

The Gambia. Five different typologies were tested in each experiment, four metal-roofed houses with closed eaves and one traditional thatched-roofed house with open or closed eaves (Fig. 3.1). All houses had two doors, one at the front and one at the back. The top of the windows were 1.75 m above the ground. At the start of each experiment, each typology was randomly allocated to one of the house positions. Each typology was rotated weekly between houses using a replicated Latin rectangle design, so that at the end of the study, each typology had been tested in each of the house positions.

3.3.4 Experiment 1: Impact of door gaps and screened windows on mosquito house entry

The main rationale for this experiment was to find out how *An. gambiae s.l.* entered gaps around the doors and whether host odours emanating from screened windows could act as a decoy and reduce the number of mosquitoes entering through the gaps around the doors. It also allowed us to repeat the experiment described in chapter 2 where we found higher numbers of *An. gambiae s.l.* in the metal-roofed house with closed eaves than the thatched house with open eaves. The five house typologies were: 1) metal-roofed house with closed eaves, 2 cm gaps at the top and bottom of the doors, described as a badly-fitting door, 2) metal-roofed house with closed eaves, 2 cm gaps at the top of the doors, 3) metal-roofed house with closed eaves, 2 cm gaps at the bottom of the doors and 4) metal-roofed house with closed eaves, 2 cm gaps at the top and bottom of the door, plus two screened windows, each one measured 30 cm x 30 cm and 5) a thatched-roofed house with open eaves, 2 cm gaps at the top and bottom of the doors. This experiment was carried out early in the rainy season from 2nd July to 3rd August 2017.

3.3.5 Experiment 2: Impact of small windows on mosquito house entry

The rationale for this experiment was to find out whether adding small-screened windows to the house would reduce the number of mosquitoes entering the house though the gaps around the doors. A thatch-roofed house with closed eaves and badly fitting doors and windows served as the reference typology. The five house typologies were: 1) metal-roofed house with closed eaves, badly-fitting doors, two 30 cm x 30 cm metal windows with 1 cm gap at the top and bottom, one at the front and one at the back of the house; 2) metal-roofed house with closed eaves, badly-fitting

doors and one 30 cm x 30 cm screened window at the front of the house, next to a door facing west to the large irrigated rice fields; 3) metal-roofed house with closed eaves, badly-fitting doors, two 30 cm x 30 cm screened windows at the front and back of the house, 4) metal-roofed house with closed eaves, badly-fitting doors, one 60 cm x 30 cm screened window at the front of the house and a 30 cm x 30 cm screened window at the back and 5) a thatched-roofed house with closed eaves, badly fitting doors, two 30 cm x30 cm metal windows with 1 cm gap top and bottom, installed front and back of the house. This experiment was conducted during the rainy season from 6th August to 23rd October 2017.

3.3.6 Experiment 3: Impact of large windows on mosquito house entry

The rationale for this experiment was to find out whether adding larger-screened windows to the house would reduce further the number of mosquitoes entering the house though the gaps around the doors. A thatch-roofed house with closed eaves and badly fitting doors and larger windows served as the reference typology. The five house typologies were: 1) metal-roofed house with closed eaves, badly-fitting doors, two 77 cm x 65 cm metal windows with 1 cm gap at the top and bottom, at the front and back of the house; 2) metal-roofed house with closed eaves, badly-fitting doors, one 77 cm x 65 cm screened windows front of the house, 3) metal-roofed house with closed eaves, badly-fitting doors, two 77 cm x 65 cm screened windows front and back of the house, 4) metal-roofed house with closed eaves, badly-fitting doors two 77 cm x 65 cm screened windows at the front and one 77 cm x 65 cm screened window at the back of the house and 5) thatch roofed house with closed eaves, badly fitting doors, two 77 cm x 65 cm metal windows front and back with 1 cm gap top and bottom. This experiment was carried out during the rainy season from 4th September to 8th October 2017.

Fig. 3.1: Experimental houses showing large windows.

3.3.7. Entomology

For each experiment, sampling was done in each house for five nights each week for five weeks. Mosquitoes were collected using a CDC light trap (Model 512, John W. Hock Co.) hung 1 m above the ground close to the foot of the bed with two occupants sleeping under a long-lasting insecticidal net (Olyset, Sumitomo Chemical, Japan) and operated from 21:00 h to 06:00 h the following morning. Mosquitoes were collected from each house at 06:00 h and transported to Wali Kunda field station. Mosquitoes were then transferred into a freezer set at -25°C for two hours for killing and then identified morphologically. Female *An. gambiae s.l.* were classified as blood fed, unfed and semi/gravid. These female *An. gambiae s.l.* were stored individually in Eppendorf tubes containing cotton wad and silica gel. Specimens were identified to species by PCR (Caputo et al., 2008), but the results were not available at the time of thesis submission.

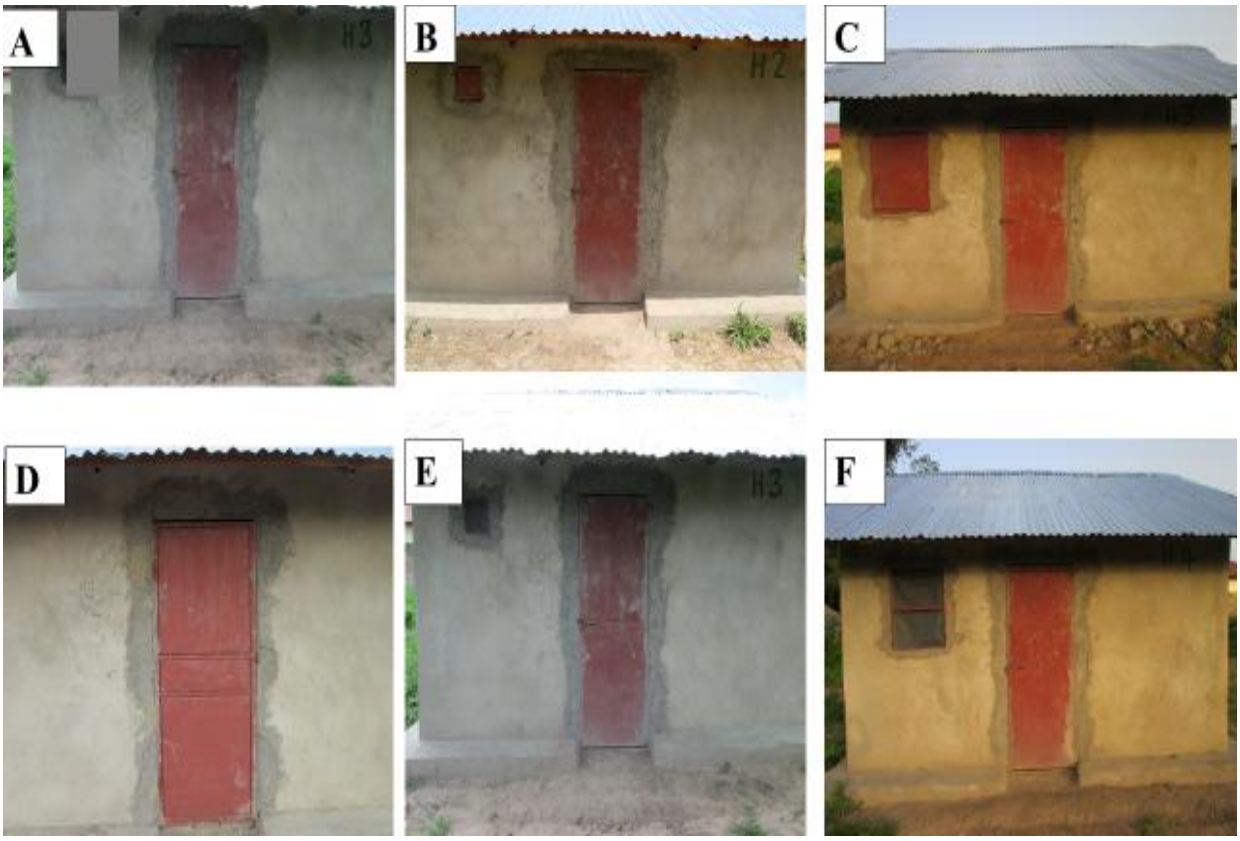


Fig. 3.2: Characteristics of houses used in each experiment. A) house showing door gaps top and bottom, B) house showing badly-fitting door and small window, C) house showing badly-fitting door and large window, D) house showing door with a gap at the top of the door, E) house with badly-fitting door and small-screened window and F) house with badly-fitting door and large-screened window.

3.3.8 Data Analysis

The effect of house typology on mosquito house entry was assessed using generalized linear modelling, using a negative binomial model with a logit link function for count data. In addition to house typology, house position and day were included in the model. Data analysis was performed using SPSS version 20.

3.3.9 Ethics

The study protocol was approved by the joint Gambia Government and Medical Research Council Ethics Committee (Reference: SCC 1478 V 3.1, approved 16th March, 2017).

3.4 Findings

3.4.1 Entomology

3.4.1.1 Experiment 1: Impact of door gaps and screened windows on mosquito house entry

A total of 2,393 mosquitoes were caught of which 424 (18%) were *An. gambiae s.l.*, 1,364 (57%) *Mansonia* spp, 552 (23%) *Culex* spp and 53 (2%) other *Anopheles* spp. In metal-roofed houses with closed eaves, reducing the number of gaps around the door or installing two small screened windows did not reduce the entry of *An. gambiae s.l.* into a house, compared with a similar house with gaps at the top and bottom of the door and no screened window (Table 3.1). However, a gap at the bottom of the door increased the number of other *Anopheles* entering houses by fourfold. Whilst a gap at the top of the door reduced the entry of *Culex* spp by 60% and *Mansonia* spp by 31% compared to a similar house with gaps above and below the door. With gaps at the bottom of the doors in the metal roofed house with closed eaves, no reduction in *An. gambiae s.l.* was observed (OR=1.30; 95% CI=0.81-2.09; p<0.285). Installing a small screened window increased the number of other *Anopheles* spp. threefold, but reduced the number of *Mansonia* entering by 34 %. The thatched-roofed house with open eaves and badly fitting doors had a similar number of *An. gambiae* s.*l.*, *Culex* spp and *Mansonia* spp., but three times more other *Anopheles* than the metal-roofed house with closed eaves and badly fitting doors.

3.4.1.2. Experiment 2: Impact of small windows on mosquito house entry

A total of 5,286 mosquitoes were collected in this experiment. Of these, 627 (12%) were *An. gambiae s.l.*, 3,154 (60%) *Mansonia* spp, 1,388 (26%) *Culex* spp and 117 (2%) other *Anopheles* spp. In metal-roofed houses, installing two small screened windows reduced the number of *An. gambiae s.l.* entering houses by 40%, whilst having one large and one small screened window

Table 3.1 Impact of door gaps and screened windows on mosquito house entry. Where OR = odds ratio, CI = confidence intervals.

House type	Mosquito species											
	An. gambiae s.l.			Other *Anopheles*			*Culex* spp.			*Mansonia* spp.		
	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p
Metal roofed, closed eaves, door gaps top and bottom	2.40 (1.45-3.35)	1.0		0.24 (0.01-0.49)	1.0		4.92 (1.85-7.99)	1.0		12.92 (9.14-16.70)	1.0	
Metal roofed, closed eaves, door gaps top only	3.96 (2.43-5.49)	1.28 (0.83-1.97)	0.259	0.36 (0.10-0.62)	1.44 (0.59-3.50)	0.423	1.60 (0.83-2.37)	0.40 (0.24-0.66)	<0.001	12.80 (6.80-18.80)	0.69 (0.54-0.90)	0.005
Metal roofed, closed eaves, door gaps bottom only	3.28 (2.13-4.43)	1.30 (0.81-2.09)	0.285	0.88 (0.50-1.26)	4.23 (1.77-10.11)	<0.001	5.44 (1.91-8.97)	1.08 (0.72-1.62)	0.723	11.36 (7.81-14.91)	0.91 (0.70-1.19)	0.495
Metal roofed, closed eaves, door gaps top and bottom, with two small screened windows	2.92 (1.52-4.32)	1.05 (0.63-1.76)	0.844	0.16 (0.07-0.39)	0.47 (0.15-1.51)	0.207	4.92 (1.67-8.17)	0.81 (0.53-1.23)	0.315	11.72 (6.71-16.73)	0.66 (0.50-0.87)	<0.003
Thatched roof, open eaves, door gaps top and bottom	4.40 (1.86-6.94)	1.34 (0.83-2.16)	0.231	0.48 (0.16-0.80)	2.96 (1.12-7.78)	<0.028	5.20 (2.98-7.42)	1.40 (0.92-2.12)	0.116	5.76 (3.06-8.46)	0.37 (0.26-0.52)	<0.001

reduced entry by 63% compare to a similar house with two small badly fitting windows (Table 3.2). Similar reductions in house entry were seen with the other taxa of mosquitoes with a general tendency for a reduction in house entry as screened windows size increases. The thatched-roofed house with closed eaves and badly fitting doors and windows had a similar number of *An. gambiae s.l.*, other *Anopheles* and *Culex* spp, but fewer *Mansonia* spp., than the metal-roofed house with closed eaves and badly fitting doors and windows.

3.4.1.3 Experiment 3: Impact of large windows on mosquito house entry

A total of 5,874 mosquitoes were collected in this experiment. Of these, 634 (11%) were *An. gambiae s.l.*, 3,576 (61%) *Mansonia* spp, 1,538 (26%) *Culex* spp and 126 (2%) other *Anopheles*. In metal-roofed houses, the number of *An. gambiae s.l.* house entry declined progressively with increased numbers of large screened windows, declining from 57% with one window, 79% with two windows and 95% with three windows (Table 3.3). A similar trend was observed with other mosquito taxa house entry decline as the number of screened windows increases. The thatched-roofed house with closed eaves, badly-fitting doors and large windows had 45 % fewer *An. gambiae s.l.* and 70% fewer other *Anopheles* than the metal-roofed house with closed eaves, badly fitting doors and large windows.

The relationship between increasing area of screened window and declining percentages of *An. gambiae s.l.* is shown in (Fig. 3.3)

Table 3.2 Effect of small screened windows on mosquito house entry. Where OR = odds ratio, CI = confidence intervals.

House type	Mosquito species											
	An. gambiae s.l.			Other *Anopheles*			*Culex* spp.			*Mansonia* spp.		
	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p
Metal roofed, closed eaves, two badly-fitting doors and small windows	6.16 (4.07-8.25)	1.0		1.44 (0.59-2.29)	1.0		14.76 (8.73-20.79)	1.0		47.16 (28.93-65.39)	1.0	
Metal roofed, closed eaves, badly-fitting doors and one small screened window	6.44 (4.04-8.84)	0.91 (0.65-1.28)	0.586	1.20 (0.59-1.81)	0.83 (0.46-1.50)	0.545	9.12 (6.13-12.11)	0.74 (0.56-0.97)	<0.027	22.00 (13.78-30.22)	0.52 (0.36-0.77)	<0.001
Metal roofed, closed eaves, badly-fitting doors and two small screened window	3.80 (1.15-6.45)	0.60 (0.40-0.91)	<0.015	0.80 (0.29-1.31)	0.49 (0.25-0.94)	<0.032	9.24 (6.33-12.15)	0.72 (0.55-0.94)	<0.015	16.64 (10.38-22.90)	0.40 (0.30-0.55)	<0.001
Metal roofed, closed eaves, badly-fitting doors and one large and one small screened window	2.60 (1.22-3.98)	0.37 (0.22-0.64)	<0.001	0.44 (0.08-0.80)	0.28 (0.11-0.69)	0.006	8.56 (5.72-11.40)	0.69 (0.53-0.91)	0.007	12.60 (8.95-16.25)	0.34 (0.24-0.48)	<0.001
Thatched roofed, closed eaves, badly-fitting doors and small windows	6.08 (2.86-9.30)	0.87 (0.53-1.40)	0.557	0.80 (0.32-1.28)	0.61 (0.30-1.22)	0.160	13.84 (8.85-18.83)	1.08 (0.81-1.45)	0.596	27.72 (19.45-35.99)	0.65 (0.43-0.10)	<0.047

Table 3.3 Effect of large screened windows on mosquito house entry. Where OR = odds ratio, CI = confidence intervals.

House type	Mosquito species											
	An. gambiae s.l.			Other *Anopheles*			*Culex* spp.			*Mansonia* spp.		
	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p	Mean (95% CI)	OR (95% CI)	p
Metal roofed, closed eaves, two badly-fitting doors and large windows	11.04 (7.72-14.36)	1.0		2.08 (0.97-3.19)	1.0		16.00 (10.41-21.59)	1.0		57.24 (37.43-77.05)	1.0	
Metal roofed, closed eaves, badly-fitting doors and one large screened window	4.72 (3.16-6.28)	0.43 (0.28-0.64)	<0.001	1.24 (0.53-1.95)	0.67 (0.38-1.19)	0.175	9.76 (6.41-13.11)	0.64 (0.45-0.90)	<0.010	25.48 (18.10-32.86)	0.50 (0.34-0.73)	<0.001
Metal roofed, closed eaves, badly-fitting doors and two large screened window	2.64 (1.55-3.73)	0.21 (0.14-0.32)	<0.001	0.56 (0.13-0.99)	0.26 (0.13-0.52)	<0.001	11.28 (7.62-14.94)	0.75 (0.53-1.06)	0.107	16.60 (9.57-23.63)	0.29 (0.19-0.46)	<0.001
Metal roofed, closed eaves, badly-fitting doors and three large windows	0.56 (0.15-0.97)	0.05 (0.02-0.10)	<0.001	0.44 (0.01-0.89)	0.18 (0.09-0.38)	<0.001	7.72 (4.14-11.30)	0.48 (0.32-0.70)	<0.001	6.56 (3.30-9.82)	0.12 (0.07-0.22)	<0.001
Thatched roofed, closed eaves, badly-fitting doors and large windows	6.40 (3.46-9.34)	0.55 (0.35-0.87)	<0.010	0.72 (0.17-1.27)	0.30 (0.14-0.64)	<0.002	16.76 (9.82-23.70)	0.96 (0.65-1.42)	0.831	37.16 (21.78-52.54)	0.70 (0.45-1.09)	0.115

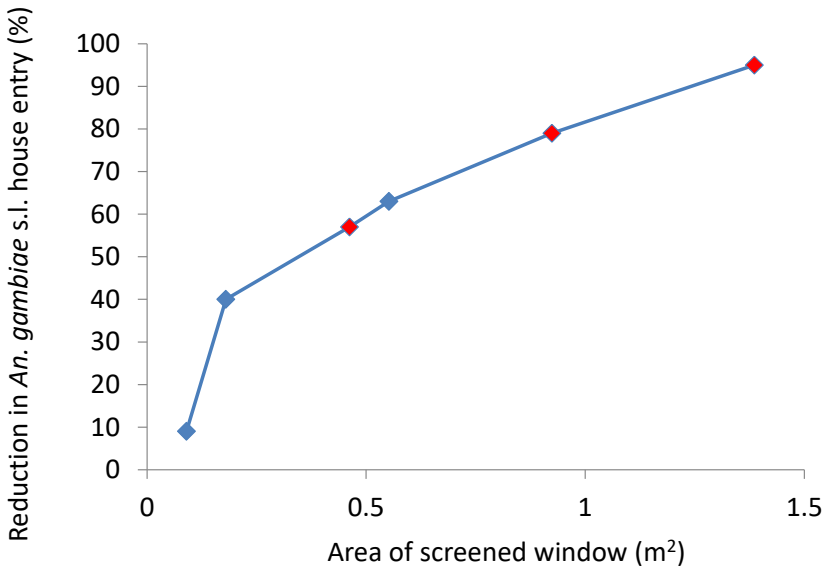


Fig. 3.3 Relationship between surface area of screened windowsand reduction in house entry by *An. gambiae s.l.* Blue diamonds are results from the small window experiment and red diamonds are those from the large window experiment.

3.5 Discussion

The results from this study show that the addition of screened windows to metal-roofed houses with closed eaves reduces the entry of *An. gambiae s.l.* through the gaps around badly-fitting doors. Interestingly my results suggest that there is a curvi-linear relationship between the area of screened window and the reduction in house entry, with mosquito house entry declining as screened surface area increases. Similar relationships were seen with the other taxa of mosquitoes. There are two explanations for this finding. Firstly, the larger the screened surface area, the less carbon dioxide and other host odours will accumulate indoors. Secondly, screened windows act as decoys with host odours emanating from these surfaces attracting mosquitoes to them and away from the gaps around the doors. The larger the surfaces of these decoys, the fewer mosquitoes find the gaps above and below the doors.

Inserting eave tubes into houses may work the same way as installed windows in houses (Waite et al., 2016). The tubes let odours and carbon dioxide pour out of the house attracting mosquitoes to them and away from the door gaps. Mosquitoes are attracted and make contact with the eave tube

surfaces when they are attempting to enter houses. They cannot enter the house due to the netting material.

The importance of house screening is an important finding since most rural houses in The Gambia and other parts of sub-Saharan Africa have badly-fitting doors. The use of screened windows would help reduce malaria transmission, nuisance biting mosquitoes and keep the house cooler at night. The large numbers of houses being built in The Gambia creates an opportunity for advocating screening as a preventive method. Most houses that are built nowadays have sliding windows with screens at the back of the window. During the hot weather, the windows are opened to let air flow into the house while the screens are kept closed to prevent insect entry. Although there are opportunities for introducing screening in The Gambia, one concern would be the durability of the screening material. The plastic netting material does not last long especially in houses with many children. In such houses, frequent replacing of the netting material will be required; failure to do so will defeat the intended purpose.

The effectiveness of house screening in preventing mosquito house entry depends on the interaction between their feeding behaviour and human behavior, especially when and where people spend time either sitting sleeping indoors or outdoors. House screening will only reduce exposure to endophagic mosquito vectors when people are indoors. Since the principal malaria vectors in sub-Saharan Africa are endophagic, house screening should be effective in preventing exposure to vectors. In a randomized controlled trial in The Gambia screened doors and windows were associated with a 54% reduction in indoor vector density and a 47% reduction in anaemia (Kirby et al., 2009). Since many *Culex* species are commonly thought to be predominantly exophagic, it raises concerns whether house screening would be effective against them. However, varying levels of both endophagy and exophagy are observed in different species, and differ from one region to another (Ogoma et al., 2010). In places where *Culex* spp. are more endophagic, and people spend much time indoor especially at night, house screening would be most appropriate in those areas.

Until this study, we did not know how mosquitoes enter the house through the gaps around the door. The results suggest that *An. gambiae s.l.* enter a house through a gap above the door as readily as they enter a gap below the door. Interestingly, even reducing the gaps from two to one did not result in a decline in house entry by this species. The opposite was seen in nuisance biting

mosquitoes where both *Culex* spp. and *Mansonia* spp. declined when there was only one gap above the door, suggesting that these taxa tend to enter houses through gaps lower down in the building. These findings concur with early study conducted by Snow (Snow, 1977) where he looked at the heights at which different mosquitoes fly above the ground. The findings concluded that most unfed host-seeking mosquito species fly below two metres above the ground. Mosquitoes flying low to the ground are more likely to detect host odours and have visual contact with the ground. Support for this findings comes from a study in The Gambia where the importance of eaves for house entry by mosquitoes was examined. The findings concluded that few *Culex* spp. and *Mansonia* spp. enter open eaves and most enter a house through openings around the doors and windows (Njie et al., 2009).

In each of the three experiments we included a thatch-roofed house as a comparator. This was done to repeat the experiments carried out in 2016 where one person slept in each house, whilst in 2017 experiments two people slept in each house. Although it is common to find single males sleeping alone in a house in urban parts of the country, in rural areas, the average household have several people sleeping indoors, thus the experiments conducted in 2017 may be more accurate in reflecting the typical conditions found in Gambian villages. In the first experiment the thatched-roofed house with open eaves and badly fitting doors, a traditional Gambian house, had similar numbers of *An. gambiae s.l.* entering the house as the metal-roofed house with closed eaves and badly-fitting doors, which represented a modern rural house. This result differs from 2016 results where we had significantly more *An. gambiae s.l.* in the metal-roofed house. Nonetheless, the surprising finding here is that closing the eaves does not reduce mosquito house entry as has been demonstrated in thatched-roofs houses (Njie et al., 2009). In the second experiment both the metal-roofed and thatch roofed house were provided with badly-fitting small windows, as well as closed eaves and badly fitting doors. Here there was no difference in the entry of *An. gambiae s.l.*, unlike the experiments in 2016 that showed far fewer mosquitoes in the thatched-roofed house compared with the metal-roofed house. This result may be due to the addition of screened windows becoming important entry points for mosquitoes, irrespective of the roof type. In the third experiment both the metal-roofed and thatched house had closed eaves, badly-fitting doors and badly-fitting large windows. In this case there were fewer mosquitoes entering the thatched-roofed house compared to the metal-roofed house, confirming the results in 2016. The results from the second and third

experiments are clearly contradictory and we have no explanation for this finding, which may have arisen by chance.

3.6 Conclusion

Closed eaves and screened windows provide an effective barrier against *An. gambiae s.l.* and other mosquitoes. *An. gambiae s.l.* did not have a propensity for entering small gaps at the bottom or top of the door. However, the number entering through gaps around the door could be drastically reduced by increasing the surface area of screened windows in the building. Housing improvements such as screened windows may contribute to the reduction of malaria transmission and may have the potential to keep areas malaria free after elimination, when current interventions are scaled back.

Chapter 4 General discussion

4.1 General conclusions

These series of studies were designed to determine how different housing typologies common in The Gambia affect mosquito house entry. Several reviews have described the evidence for housing modifications against mosquito house entry (Lindsay et al., 2002, Tusting et al., 2017). Host-seeking mosquitoes find little or no obstacle to entering a house when openings are available, attracted by carbon dioxide and other host odours emanating from a house (Breugel et al., 2015). However, our understanding of house design as an intervention and how it affects mosquito house entry and human comfort remains poorly understood.

To address this question, I conducted four experiments using five single-roomed experimental houses made from mud blocks. One man slept in each house under a long-lasting insecticidal net (LLIN) in 2016 and in 2017 two men slept under a LLIN. In each experiment, mosquitoes were collected indoors using CDC light traps.

In 2016, five different housing typologies were tested, representing four typologies common in rural Gambia and one novel design with a metal roof and ventilated doors and windows. Mosquito collections were made nightly for five nights each week and the typologies rotated weekly between houses using a replicated Latin rectangle design. Thus at the end of the five week study each treatment had been tested in each location, to adjust for any bias in attractiveness caused by the position of the house.

When the eaves were closed in thatched-roofed houses there was a 94% reduction in *Anopheles gambiae s.l.* compared with a similar house with open eaves. This finding concurs with Njie and colleagues cross-over study where closing the eaves was associated with a 65% reduction of *An. gambiae s.l.* density indoors (Njie et al., 2009). Although closed eaves reduce *An. gambiae s.l.* house entry in thatched-roofed houses, in metal-roofed houses there was an increase in *An. gambiae s.l.* collected indoors. This was surprising since most *An. gambiae s.l.* enter houses through open eaves. One explanation for this finding is that since metal-roofed houses are hotter than thatch roofed houses, sleepers sweat more profusely and produce more body odours in the metal-roofed houses attracting more mosquitoes to enter. Further support for this comes from the higher concentrations of carbon dioxide found in metal-roofed houses than thatch roofed houses. Since carbon dioxide is a major attractant for mosquito house entry (Gillies, 1980) the increased

numbers of *An. gambiae s.l.* found indoors may be a result of the high concentrations of carbon dioxide and other attractants like odours coming out of the gaps around the doors.

In the metal-roofed houses the addition of screened doors and windows were protective, reducing the number of *An. gambiae s.l.* collected indoors by 94% compared to the traditional thatched house with open eaves. Similar reductions were also observed with other *Anopheles* spp., *Culex* spp. and *Mansonia* spp. This finding demonstrates the importance of screening metal-roofed houses. Since temperature play an important role in determining human indoor comfort, the indoor temperature of each house typology was assessed. This was done to find out which house typology will create the most comfortable environment for living. Closing the eaves of a thatched-roofed house increased the temperature by 0.5 ^{o}C in the early evening when people went to bed. But when screening was added to thatch-roofed houses with closed eaves, this made them as cool as houses with open eaves, illustrating the importance of providing a large surface area of screening to allow airflow into the house and keep it cool. In metal-roofed houses closing the eaves resulted in a 1.5 ^{o}C increased in temperature in the early evening compared with the thatched-roofed houses with open eaves. However, even metal-roofed houses can be made cooled by inserting screened windows in the gable ends of the building and adding screened doors. This makes them comfortable as the reference house with thatched roof and open eaves. Thus screening is not only important for keeping out mosquitoes, it also keeps the house cooler at night, increasing the likelihood of the occupants sleeping under a long-lasting insecticidal net during the night.

Whilst mosquito house entry through the eaves is relatively well understood the importance of screened and unscreened doors and windows is not. To answer this question, door gaps were created either at the top or bottom of the doors in metal roofed houses with closed eaves to simulate badly-fitting doors as it is common in rural villages in The Gambia. Whether door gaps were at the top or bottom of the door did not affect house entry by *An. gambiae s.l.*. However, when the door gap was at the top of the door, this reduced the entry of *Culex* spp. by 60% and *Mansonia* spp. by 31%. These findings agree with Njie and colleagues (Njie et al., 2009) who found that nuisance biting mosquitoes were less likely to enter houses through openings higher up a building. The evidence from my study shows that *An. gambiae s.l.* will enter houses through any opening, presumably tracking the host odours that leak from these gaps.

There is evidence that house screening gives protection against mosquito house entry. In a randomized controlled trial in rural Gambia, house screening was associated with a 54% reduction in mosquito density indoor (Kirby et al., 2009). However, the impact of screened windows in houses with closed eaves and badly fitted doors has not been fully explored. The last two experiments examined the effect of screened windows in houses with closed eaves and badly fitting doors. When screened windows with surface area of screened 0.5 m^2 were installed in the houses, a 40% reduction in *An. gambiae s.l.* density indoor was realized. This reduction was observed in other *Anopheles*, *Culex* spp. and *Mansonia* spp. When screened surface area was increased to 1 m^2, a 63% reduction in *An. gambiae s.l.* density indoor was observed. These findings indicate that the larger the screened surface area, the greater percentage reduction in *An. gambiae s.l.* entering the house. Large areas of screened windows have a large surface area for body odours, including carbon dioxide to pour out of the house. Mosquitoes are attracted to these areas but could not get into the house due to the netting material around the window. These findings demonstrated that in houses with closed eaves and badly-fitting doors, mosquito density indoors can be reduced by installing screened windows.

4.2 Further considerations

The important question to consider when evaluating housing features as a supplementary vector control intervention is what features of a house would be effective at reducing mosquito house entry in a wide variety of geographical settings in endemic countries. In different parts of sub-Saharan Africa building designs and the type of building material used for constructing houses will vary. Whilst houses made from light-weight material like wood, thatch and bamboo would keep the occupants cool at night (Knudsen et al., 2013), there is concern about their long-term durability. Short term durability may require frequent modification, which may be costly compared to block walls. In addition, human behaviour is also likely to differ from one geographical location to another. For example, some people might believe in keeping the door closed at night as a good practice, while others might see it as a way of blocking their luck. In parts of The Gambia some people think that shutting the door of a house will prevent good luck entering. Thus differences in behavior may cause the intervention to be ineffective in some areas.

Furthermore, housing interventions that are deemed comfortable in one setting may not necessarily be comfortable in another setting. For example, a study in Tanzania indicated that most people felt comfortable when the indoor temperature was between 22 ^{o}C to 30 ^{o}C (Knudsen et al., 2013). In our study indoor temperatures were often over 30 ^{o}C, yet sleepers mentioned feeling comfortable in the experimental houses. This indicates that indoor temperature comfort differs between regions and what might be a comfortable temperature in one geographical location might not be in another location.

4.2.1 Future research

Since there is evidence that housing features are effective against mosquito house entry in sub-Saharan Africa, malaria control programmes should conduct more operational research on housing to determine which housing interventions work well in their locality and could be scaled up. Again there is a need to conduct more RCTs to see the applicability of house screening in different parts of the region. The studies reported in my thesis, studied mosquito house entry in isolated buildings. In many parts of The Gambia people live in line houses, which are like a terrace of houses side-by-side. Repeating the studies in line houses would be needed to determine whether or not they perform the same function as isolated houses.

4.3 Study limitations

The experimental studies presented in this thesis have a number of limitations. Firstly, only one man slept in each house during 2016, whilst two men slept in each house in 2017. In the study area few men slept on their own. In the local village of Wellingara a single man slept in four out of 30 houses sampled (13.3 %). Usually village houses would have two beds, with two adults, and two or three children sleeping in them. One man sleeping in the house may have limited the number of mosquitoes entering the experimental houses, since there is evidence that mosquito density indoor increases with an increase in the number of people sleeping inside (Kirby et al., 2008). My experiments in 2017 are therefore probably more representative of actual village houses, than those conducted in 2016. Secondly, the small window experiment did not use the average size of windows found in that part of the country. They were of a size typically used in experimental hut

studies (Smith et al., 1965, Miller et al., 1991). Due to the small size of the windows they might limit airflow into the houses causing them to be hotter and raise carbon dioxide levels indoors and other host odours that attract mosquitoes. This may have contributed to the high number of mosquito caught in some of the houses. Therefore, if one is to conduct similar experiments in the future I would recommend using the average window size found in that area. Thirdly, study doors were kept closed, whilst in a village setting, doors open and close much more frequently during the night. Therefore, my experiments did not capture how people in the village use their doors. This may have also limited the number of mosquitoes caught in our experimental houses.

4.4 Major conclusions

The evidence before this study indicated that *An. gambiae s.l.* enter houses through open eaves while nuisance biting mosquito enter through other openings (Njie et al., 2009). When the eaves were closed in thatched-roofed houses, a reduction in *An. gambiae s.l.* density was observed compared to thatched-roofed house with open eaves. This indicates that open eaves were the main portal for house entry by *An. gambiae s.l.*. In marked contrast, when the eaves of a metal-roofed house were closed, there was an increase in *An. gambiae s.l.* density compared to thatched-roofed house with open eaves, probably because of the higher concentrations of carbon dioxide emanating from metal-roofed houses. In addition, in metal-roofed houses with closed eaves, there was no difference in indoor density of *An. gambiae s.l.* in houses with only one gap at the top or bottom of the doors, compared to houses with gaps at the top and bottom of the doors. This finding indicates that *An. gambiae s.l.* can enter houses through any openings around the doors because they are attracted to odours emanating from these sources. Therefore, for house occupants to be protected against malaria vectors, all the openings around the house must be blocked or screened. Finally, the density of *An. gambiae s.l.* indoors can be reduced by increasing the screened surface area of windows in a house, which reduces the number of mosquitoes finding entry points to the house through gaps above and below the door.

Well-built housing with fewer entry points for mosquitoes can help reduce transmission by lowering human exposure to infectious bites. In response to WHO's Global Vector Control Response, it is now widely acknowledged that malaria must be tackled across different sectors, not just in the health sector (WHO, 2017). This provides the opportunity for National Malaria

Control Programmes to engage with other Ministries involved in housing to incorporate housing protective features into new buildings. Since our findings indicate that metal-roofed houses are hotter than traditional thatched houses and can be made cooler by improving the ventilation, there is a need to work with housing programmes and urban planners to incorporate screening into new building designs. In addition, such features can reduce transmission by vectors that have developed resistance to the insecticides currently available for indoor residual spraying and long-lasting insecticidal nets. Therefore, using housing features as preventive measures might provide sustainable means to contribute to malaria elimination.

References

Alonson PL, Lindsay SW, Schellenberg JMA, Gomez P, Hill AG, David PH, Fegan G, Cham K & Greenwood BM (1993). A malaria control trial using insecticide-treated bed nets and targeted chemoprophylaxis in a rural area of The Gambia, West Africa: 2. Mortality and morbidity from malaria in the study area. *Trans. R. Soc. Trop. Med. Hyg*. 1993; 2:37-44.

Ashley EA, Dhorda M, Fairhurst RM, Amaratunga C, Lim P & Suon S. Spread of artemisinin resistance in *Plasmodium falciparum* malaria. *New Engl. J. Med*. 2014; 371: 411–423.

Atieli H. House design modifications reduce indoor resting malaria vector densities in rice irrigation scheme area in Western Kenya, Thesis 2009, Moi University, School of Public Health Kenya.

Bhatt S, Weiss DJ, Cameron E, Bisanzio D, Mappin B, Dalrymple U, Battle KE, Moyes CL, Henry A, Eckhoff PA, Ferqus EA, Lynch M, Lindgren F, Cohen JM, Murray CLJ, Smith DL, Hay SI, Cibulskis RE & Gething PW. The effect of malaria control on *Plasmodium falciparum* in Africa between 2000 and 2015. *Lancet* 2015; 385:117–171.

Boyd MF. The influence of obstacles unconsciously erected against *Anophelines* (Housing and Screening) upon the incidence of Malaria. *Am. J. Trop. Med*. 1926; 6: 157-160.

Breugel FV, Riffell J, Fairhall A & Dickinson MH. Mosquitoes use vision to associate odor plumes with thermal targets. Published in final edited form as: *Curr Biol*. 2015; 25(16): 2123–2129.

Bruce-Chwatt LJ. Alphonse Laveran's discovery 100 years ago and today's global fight against malaria. *Malar. J. R. Soc. Med*. 1981; 74: 531–536.

Caputo B, Nwakanma D, Jawara M, Adiamoh M, Dia I, Konate L, Petrarca V, Conway DJ & Dellatorre A. *Anopheles gambiae* complex along The Gambia river, with particular reference to the molecular forms of *An. gambiae s. s. Malar J*. 2008; 7: e182.

Carter AD. Are housing improvements an effective supplemental vector control strategy to reduce malaria transmission? A systematic review. Thesis 2014, Georgia State University.

Carter R & Mendis KN. Evolutionary and historical aspects of the burden of malaria. *Clin. Microbiol. Rev*. 2002; 15: 564-594.

CDC. About Malaria (n.d.) Centers for Disease Control and Prevention. Retrieved February 4, 2014 from http://www.cdc.gov/malaria/about/index.html.

Celli A. The new preventative treatment of malaria in Latium. In Collected Papers on Malaria. Angelo Celli, 1901; 1899-1912, pp. 1–12, London School of Hygiene and Tropical Medicine.

Charles JW & White NJ. The clinical impact of artemisinin resistance in Southeast Asia and the potential for future spread. *FEMS Microbiol Rev*, 2016; 41: 34–48.

Economist Special Report Emerging Africa. The world's fastest-growing continent. Aspiring Africa. Mar 2nd 2013 from print edition www.economist.com/special.

Gallup JL & Sachs JD. The economic burden of malaria. *Nature*, 1998; 5:1-2

Gallup JL & Sachs JD. The economic burden of malaria**.** *Am. J. Trop. Med. & Hyg*. 2001; 64: 85-96.

GBoS. Projected population 2017. Gambia Bureau of Statistic, Banjul, The Gambia.

Gatton M, Chitnis N, Churcher T, Donnelly MJ, Ghani AC, Godfray CJ, Gould F, Hastings I, Marshall J, Ranson H, Rowland R, Shaman J & Lindsay SW. The importance of mosquito behavioural adaptations to malaria control in Africa. *Evolution*, 2013; 67: 1218-1230.

Gillies MT. The role of carbon dioxide in host finding by mosquitoes (Diptera: Culicidae); a review. *Bull.bEntomol.bRes.* 1980; 70: 525-32.

Gillies MT & De Meillon B. The anopheline of Africa south of the Sahara. Publication No. 54, South Africa Institute for Medical Research 1968, Johannesburg, South Africa.

Govella NJ, Okumu FO & Killeen GF. Insecticide-treated nets can reduce malaria transmission by mosquitoes which feed outdoors. *Am. J. of Trop. Med. Hyg.* 2010; 82: 415.

Hackett LW. *Malaria in Europe. An ecological study* 1937, Oxford. Oxford University Press. pp. xvi + 336 pp.

Hackett LW & Missiroli A. Malaria control through anti-mosquito measures. *Trans. Roy. Soc. Trop. Med. & Hyg*. 1937; 22: 497.

Hewitt R & Kotcher E. Observations on household Anophelism in a selected group of mosquito-proofed and non-mosquito-proofed homes. *Publ. Health Rep*. 1941; 56: 1055.

Hoek Wvd. How can better farming methods reduce malaria? *Acta Tropica* 2004; 89: 95–97

Huho B, Briet O & Seyoum A. Consistently high estimates for the proportion of human exposure to malaria vector populations occurring indoors in rural Africa. *Int J Epidemiol* 2013; 42: 235-47.

Kiker CC. Housing with reference to malaria control. Symposium on human malaria. pp. 308–314, American Association for the Advancement of Science.

Kirby MJ, Green C, Milligan PM, Sismanidis C, Jasseh M, Conway DJ & Lindsay SW. Risk factors for house-entry by malaria vectors in a rural town and satellite villages in The Gambia. *Malar J*. 2008; 9: 7-27

Kirby MJ, Ameh D, Bottomley C, Green C, Jawara M, Milligan PJ, Snell PC, Conway DJ & Lindsay SW. Effect of two different house screening interventions on exposure to malaria vectors and on anaemia in children in The Gambia: a randomised controlled trial. *Lancet* 2009; 374: 998–1009

Knudsen J & Von Seidlein L. Healthy homes in Tropical zones. Improving rural domestic building in Asia and Africa:Denmark Edition Axel Menges, 2013,

LePrince JA & Orenstein AJ. Mosquito control in Panama. The eradication of malaria and yellow fever in Cuba and Panama, 1916, G.P. Putnams Sons, London

Lindsay SW & Snow RW. The trouble with eaves-house entry by vector of malaria. *Trop. Med. Hyg*. 1988; 82: 645-646

Lindsay SW, Emerson PM & Charlwood JD. Reducing malaria by mosquito-proofing houses, *Trends Parasitol.* 2002; 18: 510-4

Lindsay SW, Jawara M, Paine K, Pinder M, Walrave GE & Emerson PM. Changes in house design reduce exposure to malaria mosquitoes. *Trop. Med. Int. Health* 2003; 8: 512-517.

Lindsay SW, Wilkins HA, Zieler HA, Daly RJ, Petrarca V & Byass P. Ability of *Anopheles gambiae* mosquitoes to transmit malaria during the dry and wet seasons in an area of irrigated rice cultivation in The Gambia. *Trop. Med. & Hyg*. 1991; 94: 313-324

Lindsay SW, Jawara M, Paine K, Pinder M, Walraven GEL & Emerson PM. Changes in house design reduce exposure to malaria mosquitoes. *Trop. Med. Int. Health* 2003; 6: 512–517

Lwetoijera DW, Kiware SS, Mageni ZD, Dongus S, Harris C, Devine GJ & Majambere S. A need for better housing to further reduce indoor malaria transmission in areas with high bed net coverage. *Parasit. Vectors* 2013; 6: 57.

Massebo F & Lindtjørn B. The effect of screening doors and windows on indoor density of *Anopheles arabiensis* in south-west Ethiopia: a randomized trial; *Malar J*. 2013; 12:319.

Miller JE, Lindsay SW & Armstrong JR. Experimental hut trials of bed nets impregnated with synthetic pyrethroid or organophosphate insecticide for mosquito control in The Gambia. *Med. Vet. Entomol.*1991; 15: 465-476.

MoH. Malaria Indicator Survey, Ministry of Health, Banjul, The Gambia 2014.

Njie M, Dilger E, Lindsay SW & Kirby MJ. The importance of eaves to house entry by Anopheline but not *Culicine*, mosquitoes. *J. Med. Entomol.* 2009; 46: 505-510.

Ogoma SB, Lweitoijera DW, Ngonyani H, Furer B, Russell TL, Mukabana WR, Killeen GF & Moore SJ. Screening mosquito house entry points as a potential method for integrated control of endophagic filariasis, arbovirus and malaria vectors. *PLoS Negl. Trop. Dis*. 2010; 4: e773.

Okumu F. The paradigm of eave tubes: scaling up house improvement and optimizing insecticide delivery against disease-transmitting mosquitoes. *Malar J*. 2017; 16: 207.

Orenstein AJ. Demonstrations of malaria control. *Publ. Health Rep*. 1916; 31: 614.

Pinder M, Conteh L, Jeffries D, Jones C, Knudsen J, Kandeh B, Jawara M, Sicuri E, D'Alessandro U, & Lindsay SW. The Roo*Pfs* study to assess whether improved housing provides additional protection against clinical malaria over current best practice in The Gambia: study protocol for a randomized controlled study and ancillary studies. *Trials* 2016; 17

Ranson H, N'Guessan R, Lines J, Moiroux N, Nkuni Z & Corbel V. Pyrethroid resistance in African *Anopheles* mosquitoes: What are the implications for malaria control. *Trend Parasitol.* 2011; 988, 1-8

Ranson H, & Lissenden N. Insecticide resistance in African *Anopheles* mosquitoes: A worsening situation that needs urgent action to maintain malaria control. *Trend Parasitol.* 2016; 32:e3

RBM. Economic cost of malaria, Roll Back Malaria 2010, Geneva, Switzerland.

RBM. Housing and malaria consensus statement, Roll Back Malaria 2015, Geneva, Switzerland.

Sachs J & Malaney P. The economic and social burden of malaria. *Nature* 2002; 415: 680-685.

Sinka ME, Bangs MJ, Manguin S, Rubio-Palis Y, Chareonviriyaphap T, Coetzee M, Mbogo CM, Hemingway J, Patil AP & Temperley WH. A global map of dominant malaria vectors. *Parasit. Vect*. 2012; 5: 69.

Smith A. A verandah-trap hut for studying the house-frequenting habits of mosquitoes and for assessing insecticides. A description of the verandah-trap hut and of studies on the egress of *Anopheles gambiae* Giles and *Mansonia uniformis* (Theo.) from an untreated hut. *Bull. Entomol. Res.* 1965; 56: 161–169.

Snow RW, Amratia P, Caroline W. Kabaria W, Abdisalan MN & Marsh K. The changing limits and incidence of malaria in Africa: 1939–2009; *Adv Parasitol*. 2012; 78: 169–262.

Snow WF. The height and direction of flight of mosquitoes in West African savanna, in relation to wind speed and direction. *Bull. Entomol. Res*. 1977; 67: 271-279.

Spitzen1 J, Koelewijn T, Mukabana WR, & Takken W. Visualization of house-entry behaviour of malaria mosquitoes. *Malar. J*. 2016; 15: 233

Ssempiira J, Nambuusi B, Kissa J, Agaba B, Makumbi F, Kasasa S & Vounatsou P. The contribution of malaria control interventions on spatio-temporal changes of parasitaemia risk in Uganda during 2009-2014. *Parasit. Vectors* 2017; 10: 450.

Tusting LS, Bottomley C, Gibson H, Kleinschmidt I, Tatem AJ, Lindsay SW & Gething PW. Housing improvements and malaria risk in sub-Saharan Africa. A multi-country analysis of survey data, *PLoS Med*. 2017; 14: e1002234.

Tusting LS, Ippolito MM, Willey BA, Kleinschmidt I, Dorsey G, Gosling RD & Lindsay SW. The evidence for improving housing to reduce malaria: A systematic review and meta-analysis. *Malar J*. 2015; 14: 209.

UN-Habitat. 2010. State of African Cities. Governance, inequalities and urban land markets. Nairobi: UN Habitat.

United Nation Center for Human Settlements. 1996. Global report on human settlements. Nairobi. UNCHS.

VCAG. 2016. Overview of new product classes and claims, Vector Control Advisory Group, Geneva, Switzerland.

Von Seidlein L, Ikonomedis K, Mshamu S, Nkya TE, Mukaka M, Christopher Pell C, Lindsay SW, Deen JL, Kisinza WN & Knudsen JB. Affordable house designs to improve health in rural Africa: a field study from northeastern Tanzania. *Lancet Plan. Hlth*. 2017; 1**:** e188–99.

Von Seidlein L, Konstantin I, Bruun R, Jawara M, Pinder M, Knols BG & Knudsen JB. Airflow attenuation and bed net utilization: observations from Africa and Asia. *Malar J*. 2012; 11: 200.

Waite JL, Penelope A, Lynch & Thomas MB. Eave tube for malaria control in Africa. A modelling assessment of potential impact on transmission. *Malar J*. 2016; 15: 449.

Webb JLA. Malaria in Africa. History Compass. *Adv*. *Parasitol*., 2011; 3: 162–170

WHO. 2014. World Malaria Report, World Health Organization, Geneva, Switzerland.

WHO. 2015. World Malaria Report, World Health Organization Geneva, Switzerland.

WHO. 2016. World Malaria Report, World Health Organization Geneva, Switzerland.

WHO. 2017. World Malaria Report, World Health Organization Geneva, Switzerland.

Appendix

1. PARTICIPANT INFORMATION SHEET

Version 1.0 Date 12 August 2016

Study Title:

SCC:	1390	Protocol:	**TOWARDS THE END GAME: OPERATIONAL RESEARCH ON IMPROVING RURAL HOUSING IN SUB-SAHARAN AFRICA AS A STRATEGY TO SUPPORT MALARIA ELIMINATION.**

Sponsor & Funder: Durham University/Halley-Stewart Trust

What is informed consent?

You are invited to take part in a research study. Participating in a research study is not the same as getting regular medical care. The purpose of regular medical care is to improve one's health. The purpose of a research study is to gather information that may be useful in future for the whole population. It is your choice to take part and you can stop any time.

Before you decide you need to understand all information about this study and what it will involve. Please take time to read the following information or get the information explained to you in your language. Listen carefully and feel free to ask if there is anything that you do not understand. Ask for it to be explained until you are satisfied. You may also wish to consult your spouse, family members or others before deciding to take part in the study.

If you decide to join the study, you will need to sign or thumbprint a consent form saying you agree to be in the study. You will receive a copy of this.

Why is this study being done?

This study is designed to find ways of reducing the number of malaria mosquitoes coming indoors at night and to make the house comfortable to live in. The results of the study will be made available to your community.

What does this study involve?

You will need to sleep alone in one house for the duration of the study. Each week we will change the characteristics of the house in which you will sleep so that it may have a straw roof one week and a metal roof the next or the other way round. You will be provided with an untreated mosquito net and a mattress so you should have a comfortable night's sleep. You will have to sleep in the experimental house from 9 pm until 6 am the following morning for 5 consecutive nights, with a 2 night break, for a total of 5 weeks.

What will happen to the samples taken in this study?

No samples will be taken in this study.

What harm or discomfort can you expect in the study?

Some of the building modifications we make to your house may make it slightly hotter at night compared to other modifications.

What benefits can you expect in the study?

You will be paid D200/night at the end of the study. You will also be provided with medicine to stop you getting malaria during the study.

Will you be compensated for participating in the study?

You will be paid D200/night at the end of the study.

Are there other products or treatment?

No

What happens if you refuse to participate in the study or change your mind later?

You are free to participate or not in the study and you have the right to stop participating at anytime without giving a reason.

If you are injured in the study what compensation will be available?

If medical treatment is required as an emergency, please contact the field worker who gave his/her telephone number to you or contact Dr Margaret Pinder at MRC Basse Tel: 5668755 or 5668217.

How will personal records remain confidential and who will have access to it?

All information that is collected about you in the course of the study will be kept strictly confidential. Your personal information will only be available to the study team members and might be seen by some rightful persons from the Ethics Committee, Government authorities and sponsor.

Who should you contact if you have questions?

If you have any queries or concerns you can contact Mr Musa Jawara or Dr Margaret Pinder at MRC Basse Tel: 5668755 or 5668217, and you can always call the personal numbers of the study staff given to you. If you have any concerns you can also contact staff at your health centre or clinic.

Please feel free to ask any question you might have about the research study.

Who has reviewed this study?

This study has been reviewed and approved by a panel of scientists at the Medical Research Council and the Gambia Government/MRC Joint Ethics Committee, which consists of scientists and lay persons to protect your rights and wellbeing.

SLEEPER CONSENT FORM

Participant Identification Number: |__|__|__|__|__|__|__|__|__|__|__|__|

……..

(Printed name of participant)

☐ I have read the written information **OR**

☐ I have had the information explained to me by study personnel in a language that I understand and I

- Confirm that my choice to participate is entirely voluntarily,
- Confirm that I have had the opportunity to ask questions about this study and I am satisfied with the answers and explanations that have been provided,
- Understand that I grant access to data about me to authorized persons described in the information sheet,
- Have received sufficient time to consider to take part in this study,
- Agree to take part in the study.

Participant's signature/thumb print :…… Date:……/……../…….. Time:…… (24hrs)

Printed name of impartial witness…….

Signature of impartial witness:……Date:……/……../……Time:…… (24hrs)

Printed name of person obtaining consent:……

I attest that I have explained the study information accurately in …….. to and was understood to the best of my knowledge by, the participant and that he/she has freely given consent to participate in the presence of the above named impartial witness (where applicable).

Signature of person obtaining consent:……Date:……/……../…….Time:…… (24hrs)

Only required if the participant is unable to read or write.

2. SCC 1390 TOWARDS THE END GAME: OPERATIONAL RESEARCH ON IMPROVING RURAL HOUSING IN SUB-SAHARAN AFRICA AS A STRATEGY TO SUPPORT MALARIA ELIMINATION

DAILY LIGHT TRAP COLLECTION (LTC)

	GENERAL INFORMATION (TO BE COMPLETED IN FIELD)	
1	Date of sampling: |___|___|/|___|___|/|___|___|___|___| (dd/mm/yyyy)	
2	House number: EH |___| (e.g. EH 1-5)	
3	House type |___| (e.g. **1**=thatch roof, closed eaves, doors 2cm gaps top & bottom, windows 30cm x 30cm, 1cm gaps top & bottom x 2; **2**= metal roof, closed eaves, doors 2cm gaps top & bottom, windows 30cm x 30cm, 1cm gaps top & bottom x 2; **3**= metal roof, closed eaves, doors 2cm gaps top, 1 screened window 30cm x 30cm front of house only; **4**= metal roof, closed eaves, doors 2cm gaps bottom, screened windows 30cm x 30cm x 2; **5**= metal roof, closed eaves, doors 2cm gaps top & bottom, 2 screened windows 60cm x 30cm (hot side), 30cm x 30cm (cool side)	
4	Sleeper's Names:…….....	
5	Sleeper's ID Numbers: EHS |___| & |___| (e.g. 1-10)	
6	Night Number: |___| (e.g. 1-25)	
7	Week Number: |___| (e.g. 1-5)	
	ROOM DETAILS	
8	Time trap set: |___|___| : |___|___| 24 hours	
9	Time Trap removed : |___|___| : |___|___| 24h hours	
10	Was trap working when removed? (Circle as appropriate)	1- Yes 0- No
11	Was the sleepers using LLIN last night?	1- Yes 0- No

12	Did you leave your house during the night?	1- Yes 0- No
13	If yes, how many times {e. g 1, 2, 3, 4 & 5 }	|___|
14	As the sleepers how comfortable it was last night: *1=comfortable, 2=slightly uncomfortable, 3=highly uncomfortable*	|___|
15	Reasons for uncomfortable *1= cool, 2= very cool, 3= hot, 4= very hot, 5=mosquito bites, 6=mosquito noise*	|___|

Sleeper's ID number: EHS1 = Sleeper 1; SHS2 = Sleeper 2; EHS3 = Sleeper 3; EHS4 = Sleeper 4; EHS5 = Sleeper 5; EHS6 = Sleeper 6; EHS7 = Sleeper 7; EHS8 = Sleeper 8; EHS9 = Sleeper 9; EHS10 = Sleeper 10

3. SCC 1390 TOWARDS THE END GAME: OPERATIONAL RESEARCH ON IMPROVING RURAL HOUSING IN SUB-SAHARAN AFRICA AS A STRATEGY TO SUPPORT MALARIA ELIMINATION

Section 2, to be completed in the lab

Total blood fed *An.gambiae*:……..…… ☐☐

Total unfed *An. gambiae*:…… ☐☐

Total gravid/semigravid *An. gambiae*:……..…….…… ☐☐

Total male *An. gambiae*:……..…….…….……..... ☐☐

Total female other anophelines:.....……..…….…… …. ☐☐

Total male other anophelines:……..……..... ☐☐

Total female *Aedes aegypti*:……..……..…….…….…… ☐☐

Total male Aedes aegypti……☐☐

Total female culicine mosquitoes:……..…….……☐☐☐

Total male culicine mosquitoes:……..……..…….……☐☐☐

Total female mansonia mosquitoes:……..…….……☐☐☐

Total male mansonia mosquitoes:……..…….……☐☐☐

Completed by:…….. Signature:……

4. SCC 1390 End Game: Experimental houses sample storage worksheet

Mosquito Serial ID	Date (dd/mm/yyyy)	Experiment week Number	Experimental House ID Number	Sleeper's ID number	Species (1,2)	Sample Storage		
						Rack position 9X9	Plate/Box No.	Lab Tech Initials
1						1A		
2						2A		
3						3A		
4						4A		
5						5A		
6						6A		
7						7A		
8						8A		
9						9A		
10						1B		
11						2B		
12						3B		
13						4B		
14						5B		
15						6B		
16						7B		
17						8B		
18						9B		
19						1C		
20						2C		
21						3C		
22						4C		
23						5C		
24						6C		
25						7C		
26						8C		
27						9C		

Key:

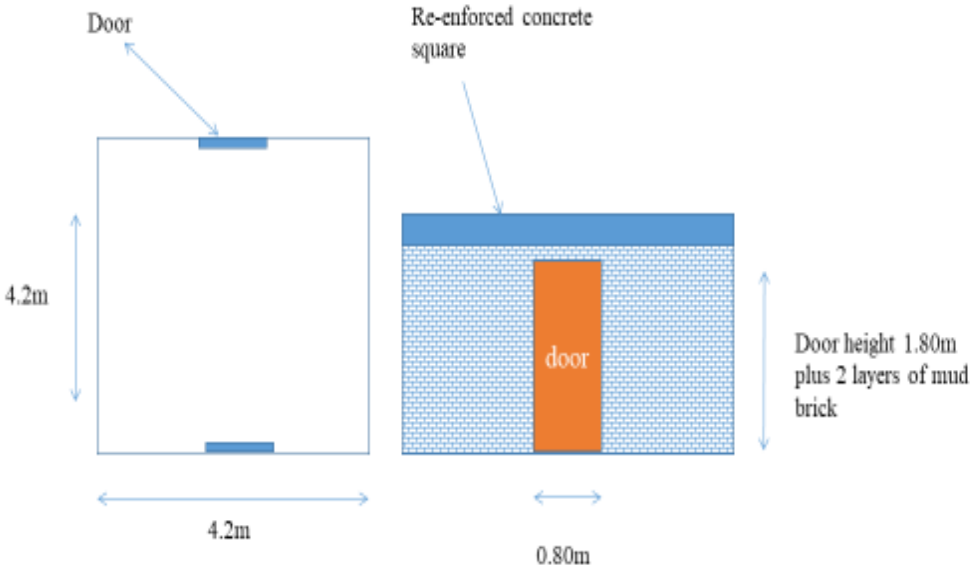
Morphological Species: 1- *An.gambiae s.l.* *2- An. funestus*

Experimental House ID Number: EH1 = House 1; EH2 = House 2; EH3 = House 3; EH4 = House 4 and EH5 = House 5

Sleeper's ID number: EHS1 = Sleeper 1; SHS2 = Sleeper 2; EHS3 = Sleeper 3; EHS4 = Sleeper 4; EHS5 = Sleeper 5

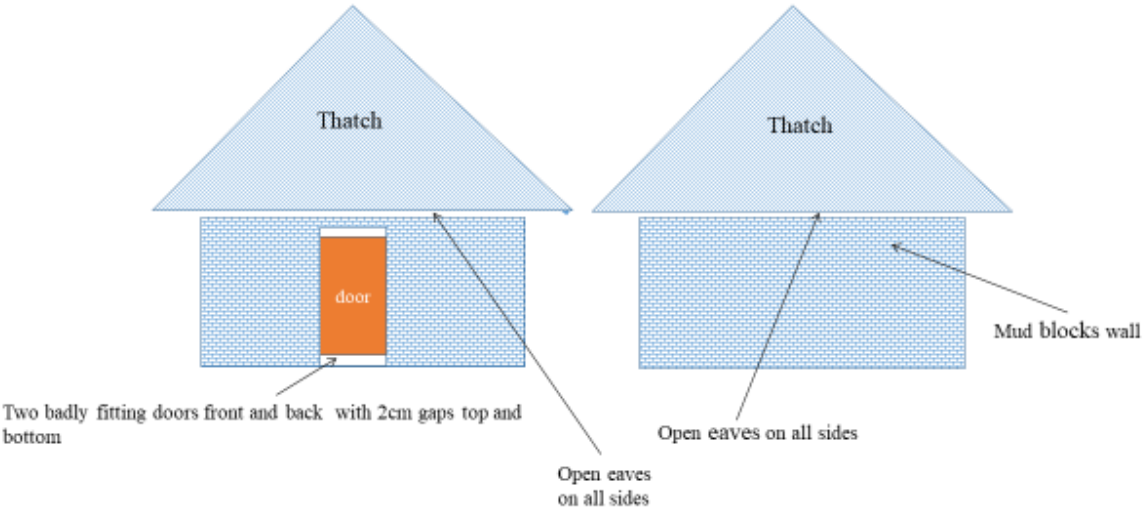
EHS6 = Sleeper 6; EHS7 = Sleeper 7; EHS8 = Sleeper 8; EHS9 = Sleeper 9; EHS10 = Sleeper 10

Floor plan of all the experimental houses

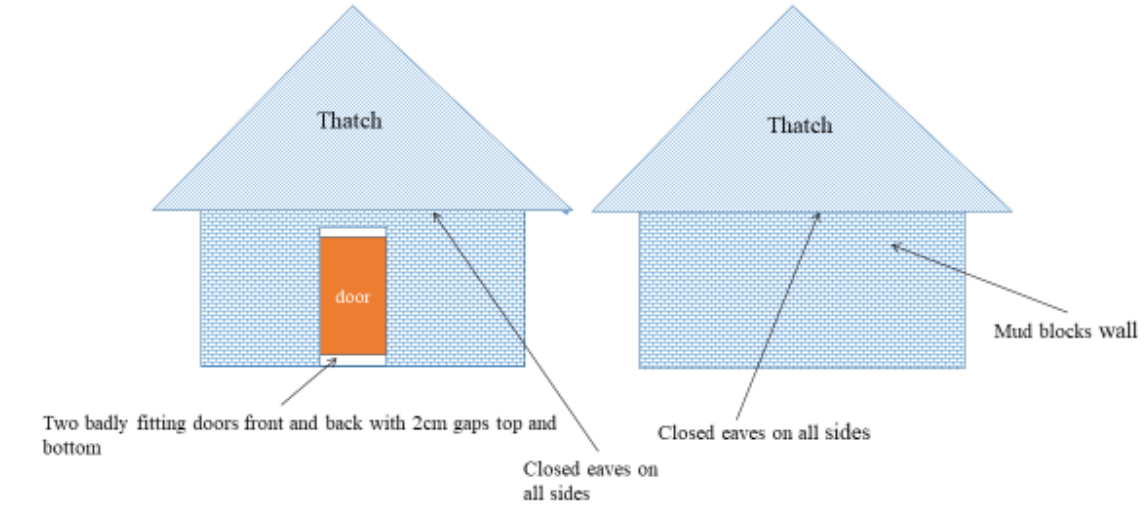


2: Plan of experimental houses used to assess the impact of different building designs on mosquito house entry

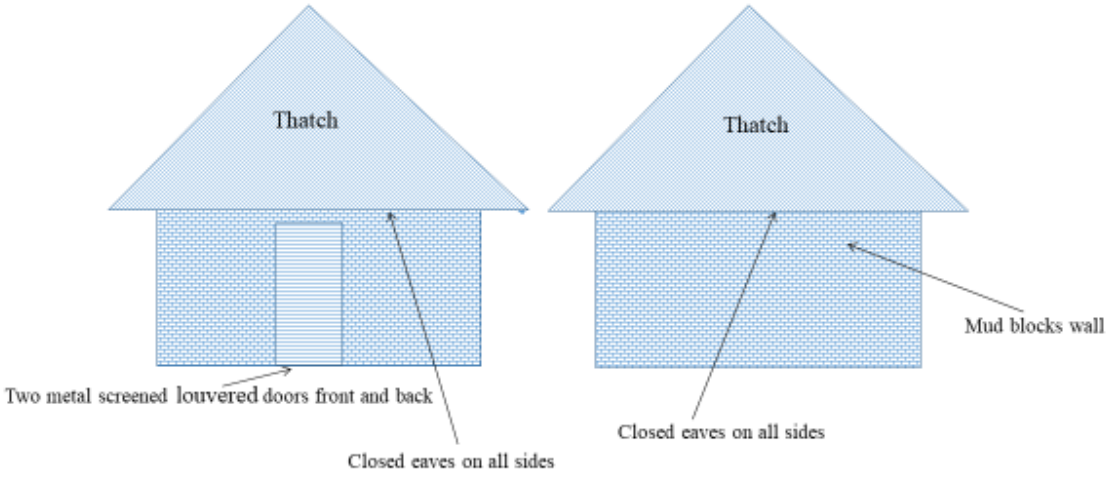
1: Plan of traditional thatch roofed house



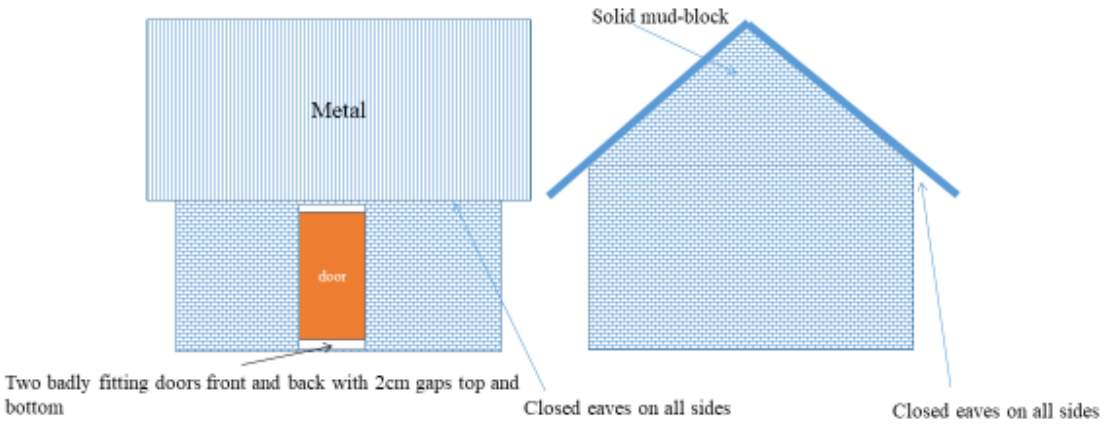
2: Plan of traditional thatch roofed house



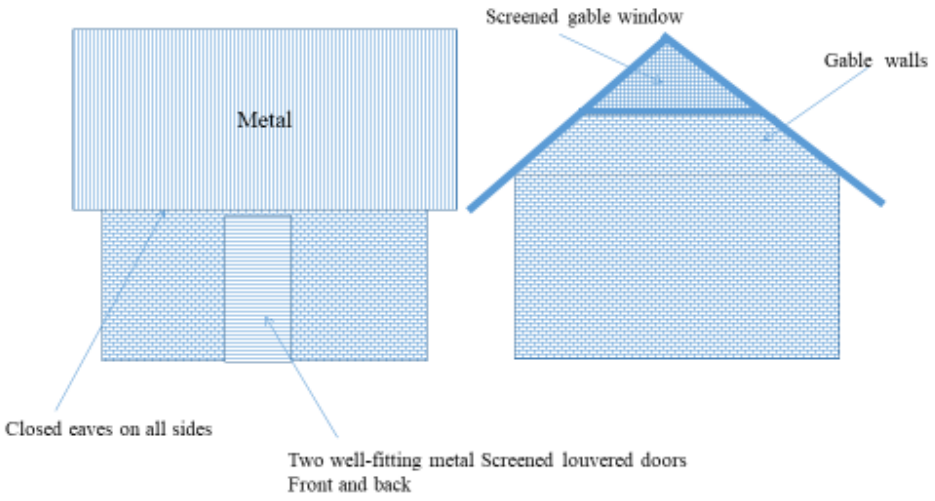
3: Plan of traditional thatch roofed house



4: Plan of traditional metal-roofed house

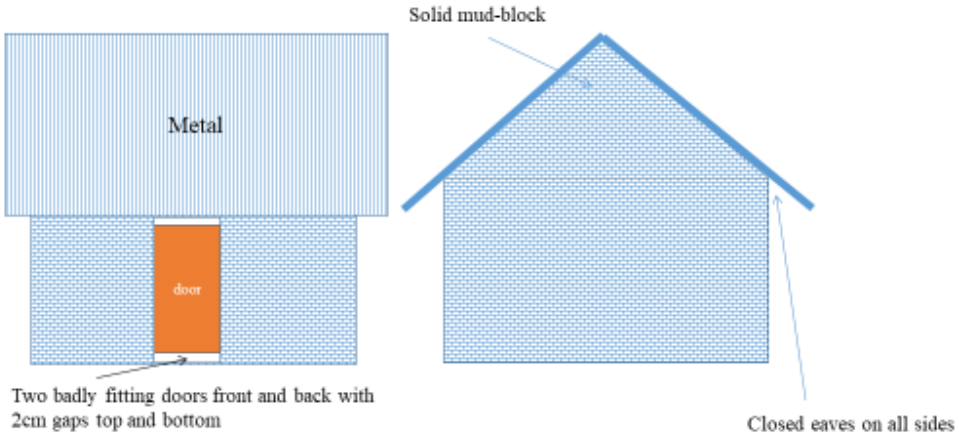


5: Plan of RooPf's house

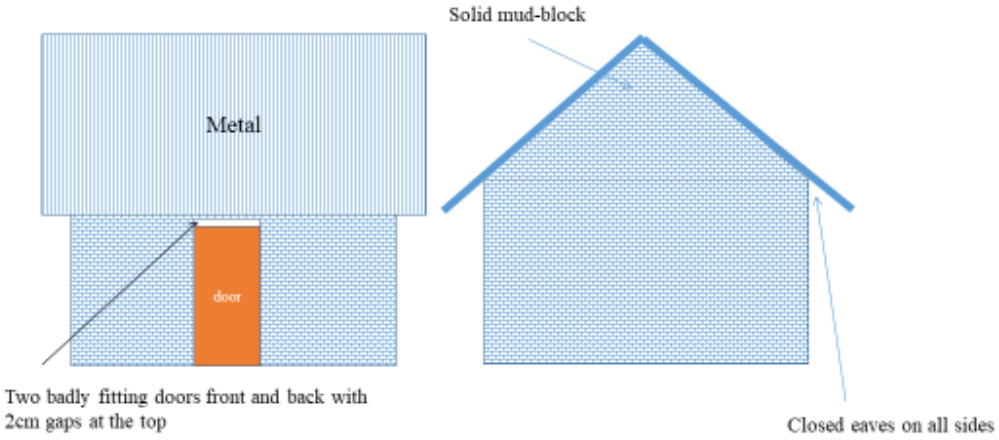


3: Plan of experimental houses used to assess how gaps around the door and addition of screened and unscreened windows affect mosquito house entry in The Gambia

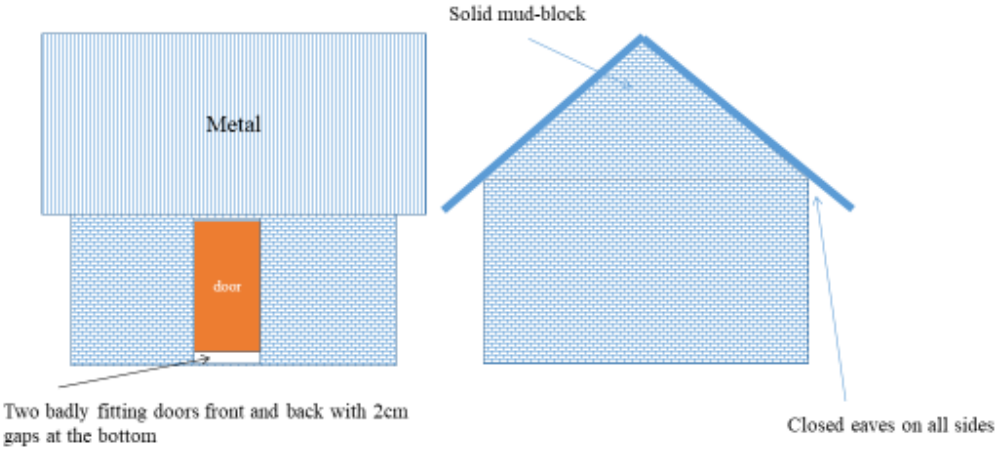
1: Plan of metal-roofed house



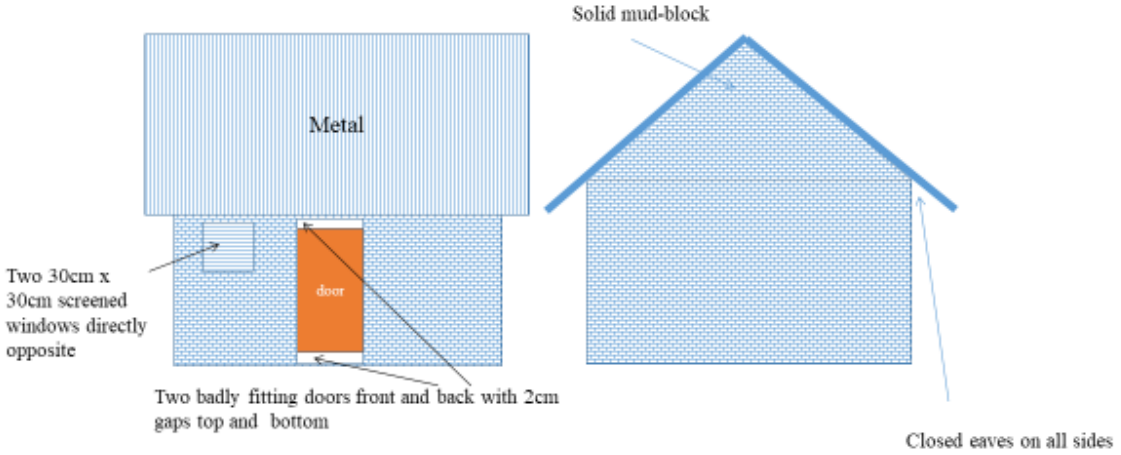
2: Plan of metal-roofed house



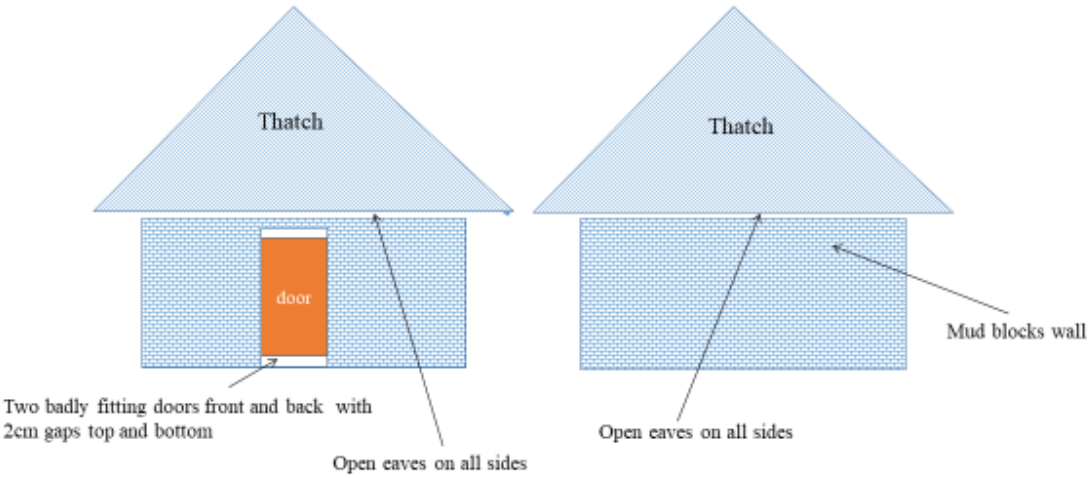
3: Plan of metal-roofed house



4: Plan of metal-roofed house

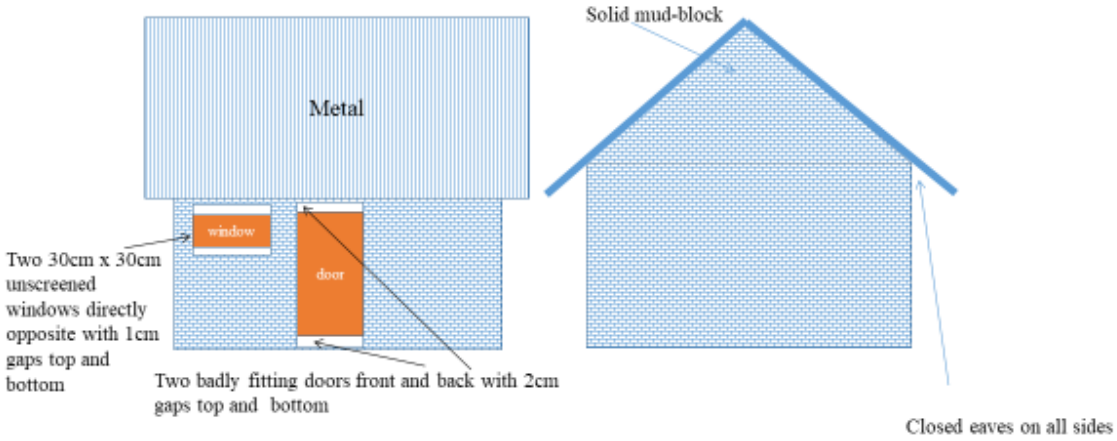


5: Plan of thatch roofed house

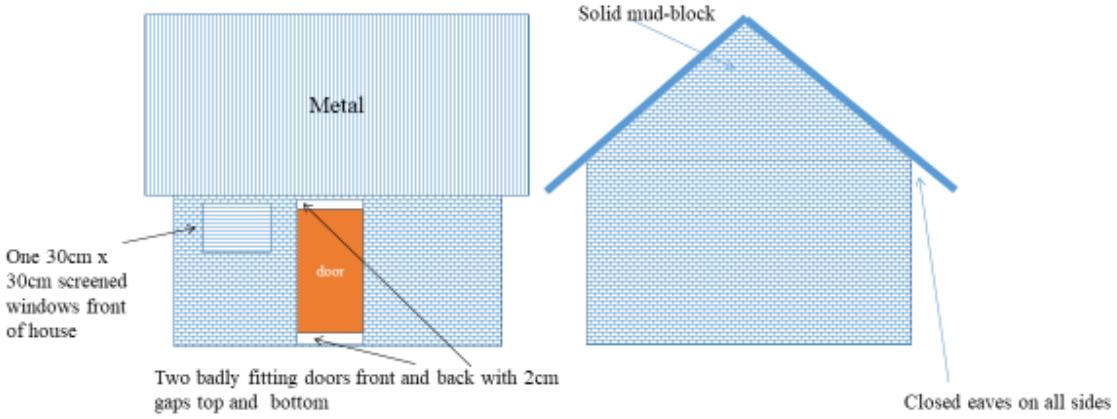


4: Plan of experimental houses used to assess the impact of small windows on mosquito house entry

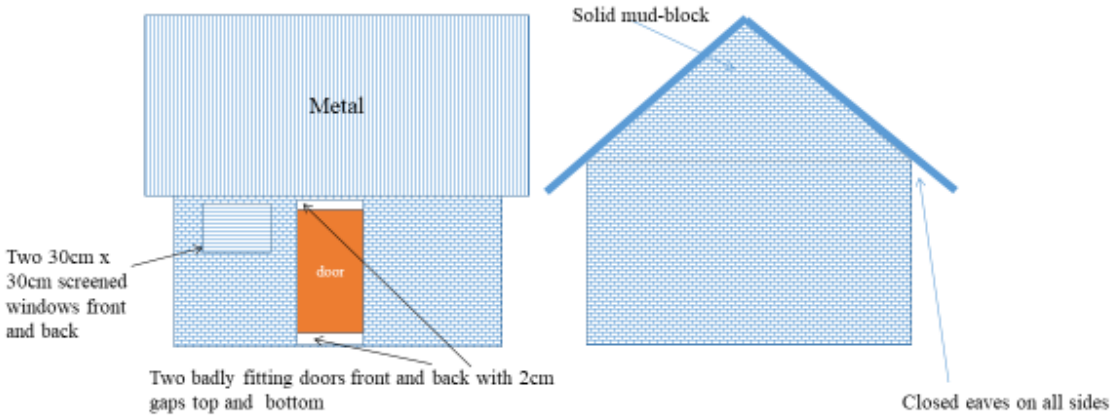
1: Plan of metal-roofed house



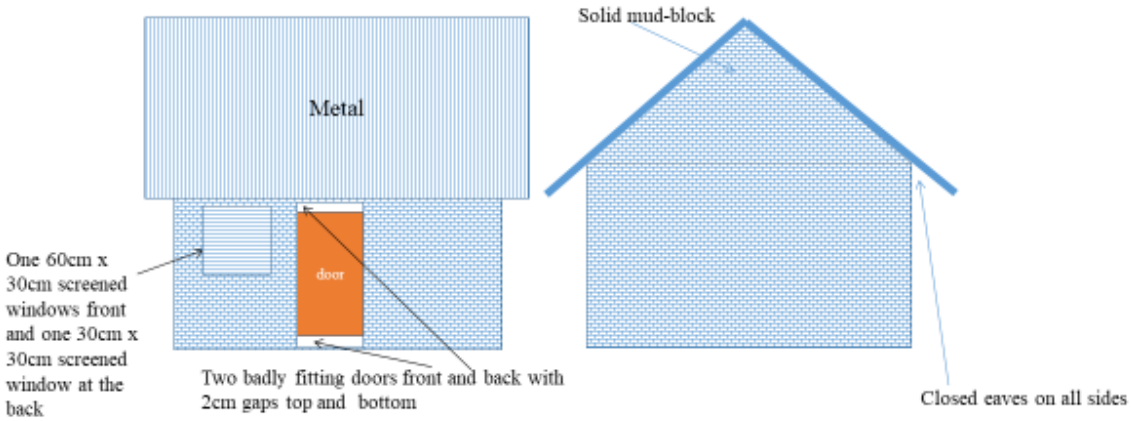
2: Plan of metal-roofed house

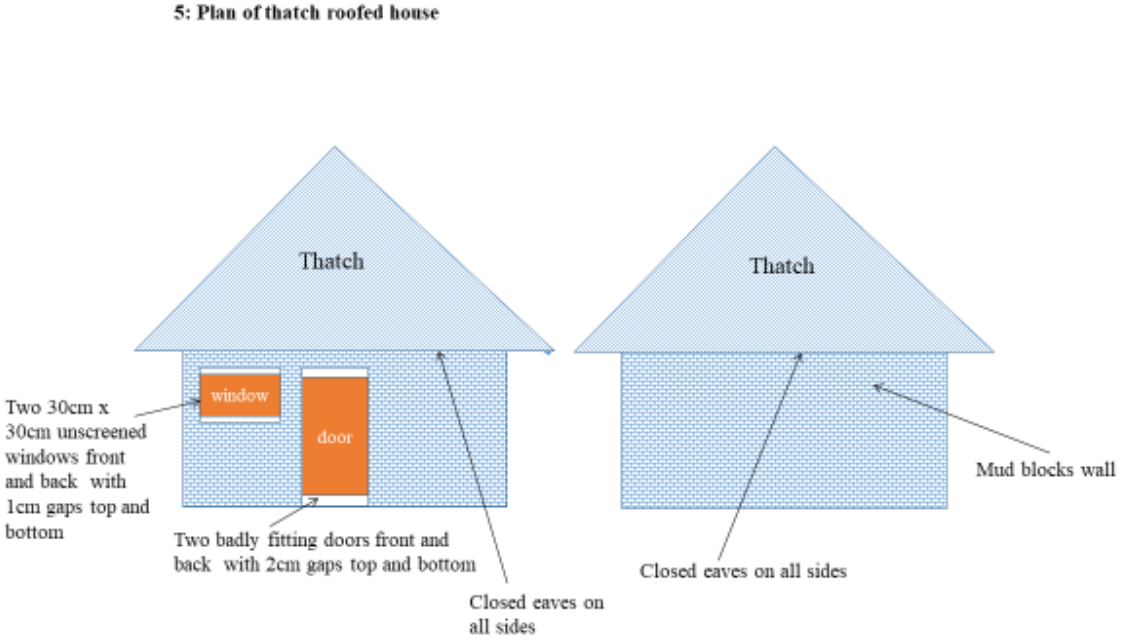


3: Plan of metal-roofed house

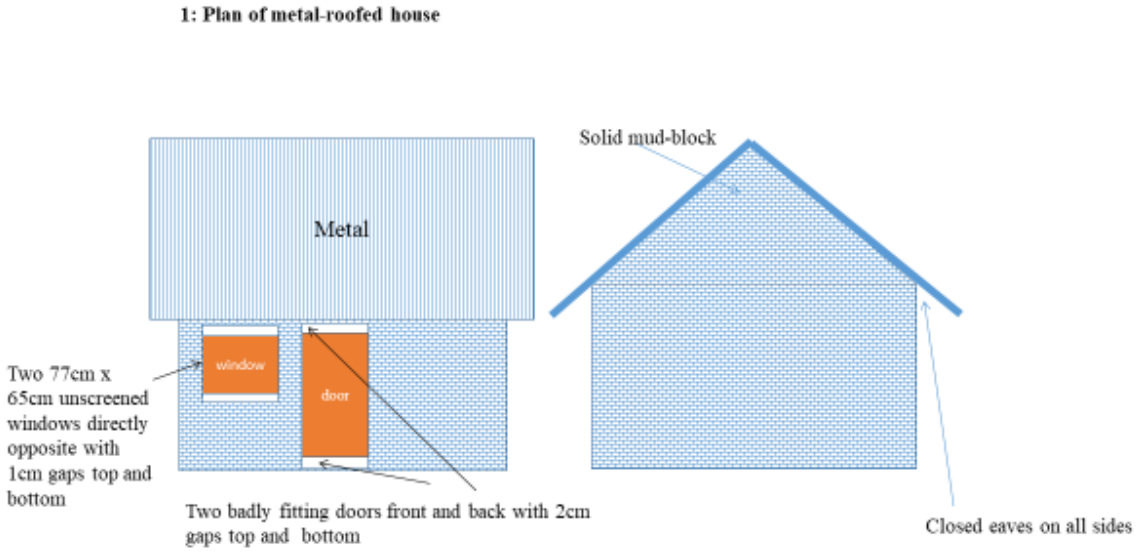


4: Plan of metal-roofed house

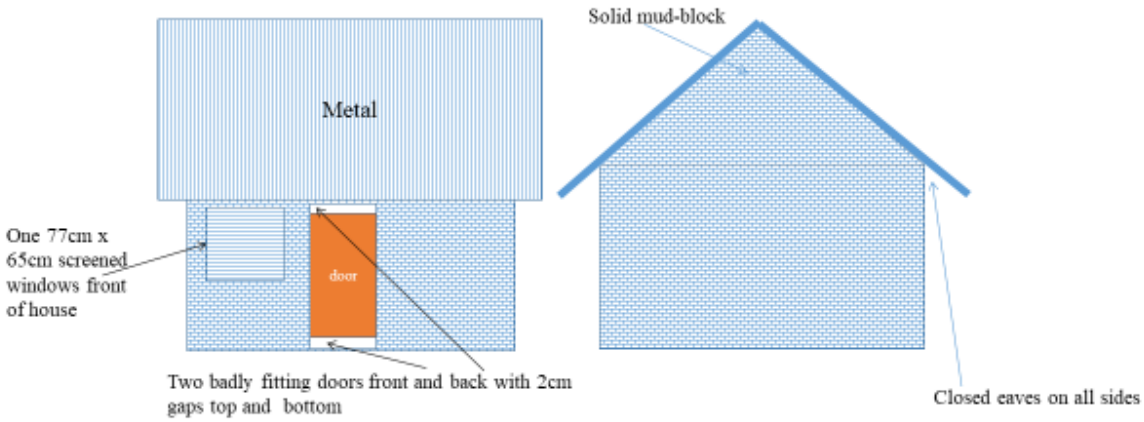




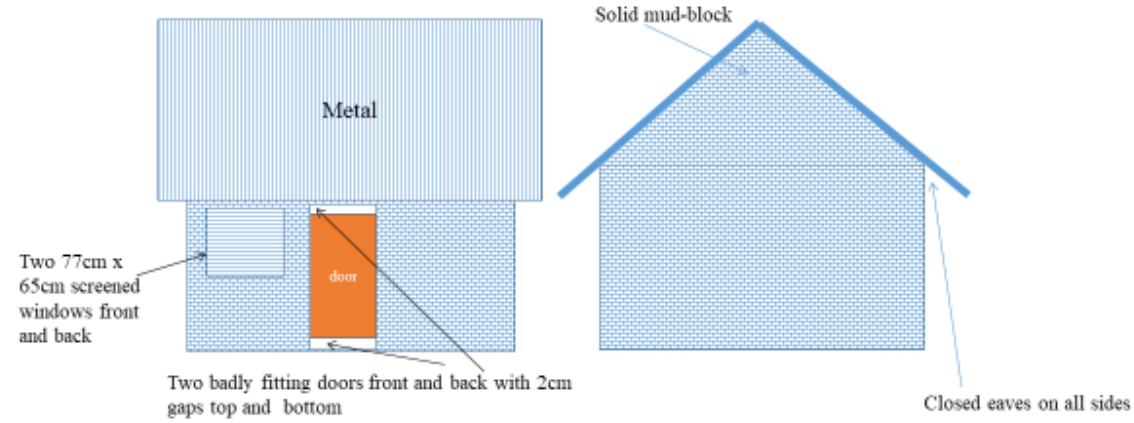
5: Plan of experimental houses used to assess the impact of large Windows on mosquito house entry



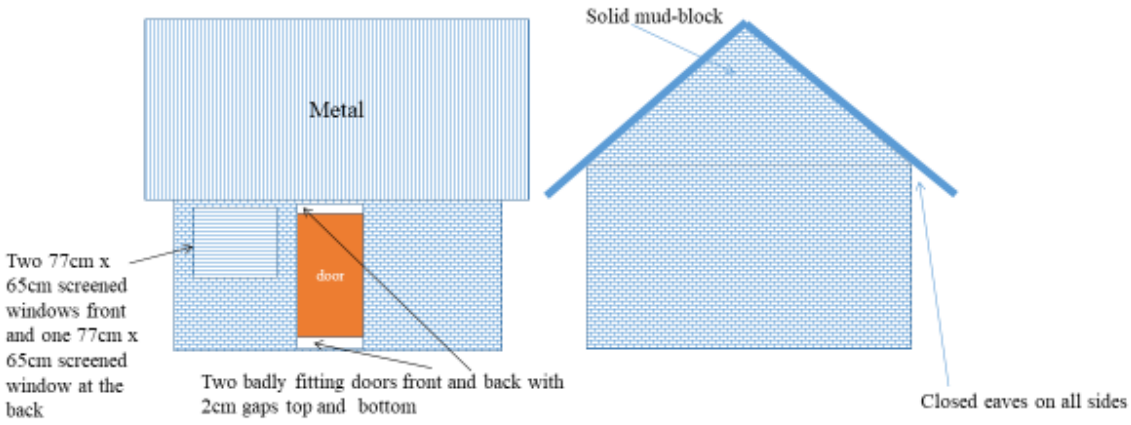
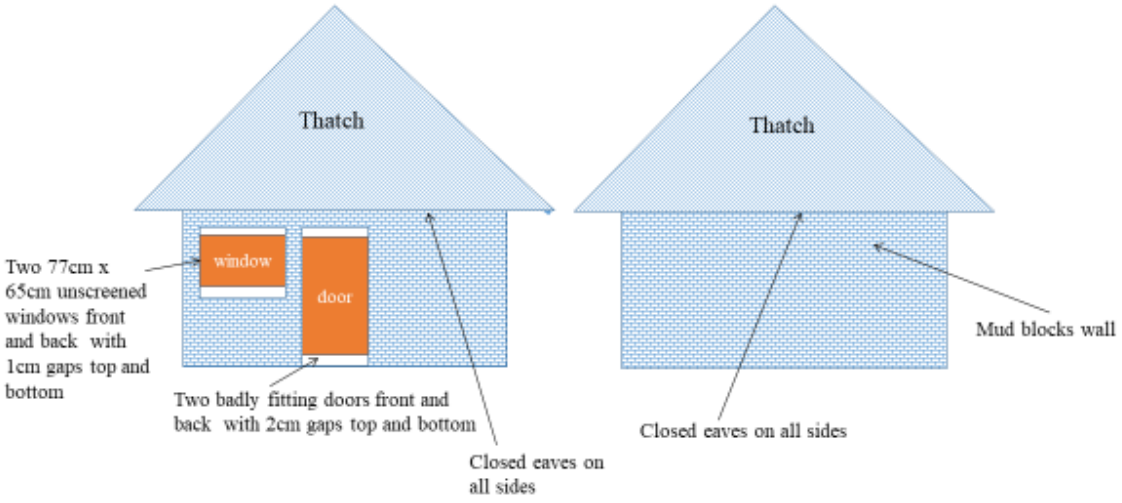
2: Plan of metal-roofed house



3: Plan of metal-roofed house



4: Plan of metal-roofed house



5: Plan of thatch roofed house