

Biran A, Smith L, Lines J, Ensink, J and Cameron M (2007). Smoke and malaria: are interventions to reduce exposure to indoor air pollution likely to increase exposure to mosquitoes? *Trans R Soc Trop Med Hyg* Nov;101(11):1065-71

Summary

Indoor air pollution from the domestic use of biomass fuels by poor households in developing countries is known to be harmful to health and efforts are being made to address this problem by changes in fuel type, stove technology, house design and fuel-use practices. However, anecdotal evidence suggests that smoke may play an important role by providing protection from biting insects and that efforts to reduce smoke may increase exposure, particularly to mosquitoes and malaria. This paper reviews the literature relating to the repellent effect of smoke on mosquitoes and finds that there is currently no evidence that smoke from domestic fuel use provides effective protection from mosquitoes and malaria. Given the limited number and quality of studies this finding cannot be interpreted as conclusive. The literature relating to house ventilation and mosquito entry was also reviewed, and an association between eaves spaces and increased indoor mosquito density was noted. Additionally, literature on the effect of soot on the efficacy of insecticide treated bednets was considered, but no direct impact was shown. Efforts to reduce indoor air pollution remain desirable even in areas of malaria transmission.

Key Words:

Indoor air pollution, malaria, mosquito, smoke

Introduction

Biomass fuels such as wood, dung and crop residues or coal are the primary household energy source for an estimated 3.2 billion people (WHO, 2006). It is estimated that exposure to indoor air pollution from these fuels results in around 1.5 million deaths annually from chronic respiratory diseases and acute respiratory infections (Smith et al., 2004; WHO 2002, 2006). Efforts have been made to address this global health problem. Usually these have focussed on reducing smoke through improved stoves that burn fuels more cleanly and more efficiently, cleaner fuels, or on removing smoke through improved house ventilation, chimneys or flues. However smoke is also anecdotally claimed to repel biting insects and house ventilation can provide entry points for insect vectors. It is therefore possible that interventions designed to reduce levels of indoor smoke might exacerbate the threat from malaria (transmitted through biting by infected mosquitoes of the *Anopheles* genus). On the other hand, it is possible that the effectiveness of insecticide treated bednets (ITNs), a cornerstone of modern malaria control, may be impaired by the soot in smoky environments and that removing smoke could be beneficial for preventing malaria.

More than 90% of child malaria deaths occur in poor, rural areas of sub-Saharan Africa (Bryce et al., 2005). The vast majority of African communities depend on biomass fuels for cooking. An estimated 360 000 African children die annually as a result of indoor air pollution (WHO 2006), and this is more than one third of global child deaths from this risk factor. Understanding the possible interaction between interventions to prevent malaria and those to reduce indoor air pollution has important policy implications in this context.

This paper reviews and brings together published studies to consider the following three issues. What is the evidence that smoke from domestic biomass fuels repels mosquitoes and prevents malaria? What is the evidence that increased household ventilation increases exposure to mosquitoes? What is the evidence that soot from domestic biomass fuels impairs the effectiveness of ITNs?

Methods

A search of the Pubmed database was carried out. The terms biomass, burn, combust*, cook*, dung, fire*, indoor air pollution, smoke, stove*, fuel, coal and charcoal were combined with the terms *aedes*, *anophel**, *culex**, *culicidae*, malaria*, mosquito*, *ochlerotatus*, vector*, vector-borne, bite, biting, blood meal, feeding behaviour, feeding pattern*, resting behaviour and resting pattern*. This search was carried out on 12th June 2006. A second search of the Pubmed database was performed to identify literature relating to house construction, ventilation and malaria transmission. The terms house construction, eaves and window* were used in combination with the terms *aedes*, *anophel**, *culex**, *culicidae*, malaria*, mosquito*, *ochlerotatus*, vector*, vector-borne, bite, biting, blood meal, feeding behaviour, feeding pattern*, resting behaviour and resting pattern*. The search was carried out on 20th June 2006. All articles were selected by title in the first instance and abstracts were read. Relevant articles selected on the basis of abstracts were read in full.

Further material came from a search of the Global Health Archive, which covers literature from 1910 to 1972. It is derived from a number of old bibliographic journals and covers a large part of the old vector control literature that is not included in modern databases and

cannot otherwise be searched electronically. Additional material also came from the personal collection of one of the authors (M Cameron) and was identified through discussions with entomologist colleagues at the London School of Hygiene and Tropical Medicine and other experts in the field.

The literature relating to the use of plant-based essential oils is not considered here but has been reviewed by Curtis et al., (1990).

Does smoke repel mosquitoes and prevent malaria?

The search found no randomised controlled trials or systematic reviews of the effectiveness of smoke from wood or plant material to either repel mosquitoes or prevent malaria.

i) Smoke from domestic fuels

One small experimental study was found of the effectiveness of smoke from firewood as a mosquito repellent in Sierra Leone (Bockarie et al., 1994). Significantly more female mosquitoes were caught resting inside the smoke-free room than the room with smoke. However, there was no significant difference in the proportion of mosquitoes that fed on humans. No experimental studies of the repellent effects of smoke from other biomass fuels were found.

Three observational studies (Barber and Forbich, 1933; Danilov, 1928; Kligler and Mer, 1932; from New Mexico, Central Asia, and Palestine respectively), suggested that smoke from domestic fuel-use deterred mosquitoes from resting or hibernating in houses. However, three further observational studies from South and East Africa (De Meillon, 1930; Gibbins, 1933; Symes, 1930) noted that the smoke from domestic fires in traditional houses did not appear to be associated with any reduction in *Anopheles* mosquito numbers. Wilson (1936) also reported no reduction in the numbers of *Anopheles* mosquitoes caught in traditional Kenyan houses without separate kitchens as compared to those with a separate kitchen (presumed less smoky). Ghebreyesus et al (2000) actually reported significantly greater risk of malaria among Ethiopian children living in (presumably smokier) houses without separate kitchens (RR=1.35, P<0.05).

ii) Repellent smoke from specific plant materials

Six, well designed, experimental field studies were found using human biting or landing rates as the outcome measure to investigate the effects of smoke from a variety of traditional mosquito repellent plant materials (see Table 1).

The degree to which the materials were repellent varied according to the species of plant and the species of mosquito. However, all of the test plants significantly reduced biting by 21-84%. A further study in Siberia (Rubtsov, 1939) reported reductions of 85%-90% in rates of mosquitoes and black-fly landing on humans carrying smouldering sticks of thyme (*Thymus serpyllum*) compared with unprotected controls.

It is unclear how much of the observed personal protection in these studies was due to the effect of smoke alone, and how much was due to specific plant-derived volatiles released

through burning specific plants. Thus, the extent to which these results can be generalised to smoke from domestic fuels is not known.

Several observational studies were also identified. However, since people are more likely to employ anti-mosquito practices in contexts where mosquitoes are more numerous and the problem of nuisance biting more severe the results of such studies are hard to interpret. A lack of observed association in this kind of study does not necessarily mean that the repellent was not effective.

In Sri Lanka, van der Hoek et al., (1998) found a significantly lower risk of malaria in households using traditional fumigants compared to those which did not (RR 0.58, 95% C.I. 0.37 – 0.93). On the other hand, a subsequent study by the same team in a nearby location found that reported use of fumigants and relatively high mosquito densities were positively associated with each other and with proximity to a known breeding site (Konradsen et al., 2003).

Similarly, in West Africa the practice of burning *churai* was associated with a significant reduction in biting by *Culex*, *Aedes* and *Anopheles* mosquitoes (Lindsay and Janneh, 1989; Pålsson and Jaenson, 1999a). However, a field study to investigate the effects of burning *churai* on the incidence of malaria in Gambian children where *An. gambiae s.s.* was the main vector found no significant association between *churai* use and malaria (Snow et al., 1998). It is possible that the reduction in biting offered by *churai* is insufficient to result in a reduction in malaria, and/or that the degree of personal protection offered by *churai* is species-specific. On the other hand, it is also possible that the use of *churai* was both effective and more common in houses with relatively high levels of mosquito biting nuisance, so that the human occupants of these houses ended up with approximately average levels of exposure to malaria. The same applies to an observational study in Mexico (Danis-Lozano et al., 1999), which similarly found no decrease in risk of malaria associated with the use of unspecified smoke as a repellent.

Again, these studies do not address the question of whether the protective effect (if any) is provided by plant-specific volatiles within the smoke or by some product of incomplete combustion that is also common to smoke from biomass fuels.

Does increased household ventilation increase exposure to mosquitoes and malaria?

Studies of house-entering habits of mosquitoes in The Gambia have shown that endophagic mosquito species, such as *An. gambiae*, *An. melas* and *Mansonia* spp., fly upwards when they make contact with a vertical wall and enter the house through eaves spaces; on the other hand, more exophilic species such as *An. pharoensis* and *Aedes* spp. are less able to do so and are progressively excluded with increasing wall height (Snow 1987). This trait of flying upwards means that eaves spaces are one of the major routes whereby *An. gambiae* enter houses. Since this is the world's most important malaria vector species preventing it from entering houses could bring major benefits.

Seven studies were identified that reported on the relationship between presence of eaves spaces and indoor mosquito numbers (Adiamah et al., 1993; Charlwood et al., 2003; Gamage-Mendis et al., 1991; Lindsay and Snow, 1988; Lindsay et al., 1995; Lindsay et al., 2003 and Pålsson et al., 2004). With the exception of Adiamah et al., which did not show significance,

all of the studies identified indicated significantly reduced indoor anopheline populations associated with the absence of open eaves spaces. Anopheline numbers were 10 to 60 percent lower in homes without eaves spaces compared to homes with open eaves spaces.

Seven studies were identified that reported the relationship between presence of eaves spaces and malaria morbidity (Adiamah et al., 1993; Gamage-Mendis et al., 1991; Ghebreyesus et al., 2000; Gunawardena et al., 1998; Guthmann et al., 2001; Lindsay and Snow, 1988 and Snow et al., 1998). Five of these studies reported a decreased risk of malaria in houses with closed eaves. In these studies the risk ratios for malaria in households with closed eaves ranged from 0.36 (95% CI 0.18-0.74) to 0.54 (95% CI 0.35-0.84) as compared to households with eaves spaces. The results reported by Snow were not significant after adjustment for confounders using a regression model. Adiamah et al., found an increased risk of malaria in those living in houses with closed eaves spaces but this increase was not statistically significant.

Does soot from domestic biomass fuels impair the effectiveness of ITNs?

The use of ITNs has been established as an effective intervention against malaria (e.g. Lengeler 2004). When ITNs are used in a smoky environment a layer of soot accumulates on the net which might diminish its effectiveness. However, even substantial accumulations of soot on treated netting have been found to have no detectable impact on the effectiveness of the insecticide (e.g. Curtis et al., 1990). These findings led to speculation that insecticide might be absorbed into the sooty layer with the result that washing a sooty net might remove more insecticide than washing a soot-free net. Further investigation has shown that this is not the case (Kayedi et al., 2007).

Sooty nets are perceived as dirty and this can increase the frequency with which nets are washed. Washing ITNs decreases the amount of insecticide remaining on them and therefore decreases the effectiveness with which they kill mosquitoes. A reduction in indoor air pollution might have beneficial effects on malaria control by allowing ITNs to remain unwashed for longer periods.

Discussion

One of the important findings from this study is the dearth of literature relating to the effects of smoke from domestic fuel use on mosquito behaviour. The conclusions and tentative recommendations presented with respect to this are therefore grounded in a somewhat weak evidence base. Keeping this in mind, the main findings drawn from the literature are listed below:

- Smoke from domestic fuel use probably does not have much effect on mosquito feeding, but mosquito feeding is affected by smoke from certain plant products traditionally used as repellents.
- The presence of eaves spaces makes houses more permeable to mosquitoes and has been associated with an increased risk of malaria in observational studies in some contexts.

- Soot from domestic fires, although not toxic to mosquitoes, does not impair the effectiveness of ITNs. It may however increase the frequency with which nets are washed and thus accelerate the loss of insecticide from ITNs.

The potential for indoor smoke to impact on disease transmission presupposes that infective contact with the insect vectors takes place indoors during times when domestic fuel-use is likely. It is therefore of interest to consider what is known about mosquitoes in terms of the timing and location of their feeding behaviour. If indoor smoke has a repellent effect, the species most likely to be repelled are those that feed and rest indoors. Mosquito species with this behaviour pattern include those of the *Anopheles* genus responsible for the transmission of malaria (Lane and Crosskey, 1993).

The relative timings of mosquito biting and domestic fuel use may also be important factors in determining the potential importance of indoor smoke as a repellent. Cooking activities are associated with peaks of smoke production (Ezzati et al., 2000). A common (though not necessarily universal) feature of domestic fuel use is that throughout most of the night cooking activities cease and smoke production is therefore greatly reduced if not absent altogether. For example observations of energy-related behaviours in rural South Africa showed that the last fuel use activity of the day was around 19:30 after which the fire was left to burn out (Barnes et al., 2004). Similarly, in Kenya, the stove was burning only until 20:00 (Ezzati et al., 2000).

A review of studies of mosquito behaviour found that the peak biting time for *Anopheles* is between 24:00 and 04:00 (Gillies and De Meillon, 1968). A more recent review concurred with this finding and further concluded that more than 75% of anopheline bites occurred between 22:00 and 05:00 (Pates and Curtis 2005). These are times at which it is assumed most people in rural areas are in bed. Githeko et al., (1996) also report that biting by *Anopheles* mosquitoes in Kenya peaks after 22:00 while over 90% of villagers retire to bed by 21:00.

Thus it seems likely that the majority of malaria transmission in sub-Saharan Africa, though it occurs indoors, takes place at times when smoke production is expected to be minimal and so is unlikely to be affected by reducing the quantity of indoor smoke produced. However, this general pattern may be subject to local variation.

Research needs

The evidence base relating to the effectiveness of smoke from biomass fuels for repelling insects and preventing disease is inadequate. It should be relatively straightforward to strengthen this evidence through a series of well designed experiments and intervention studies. Questions that need to be addressed include the following:

- What effect does smoke from different biomass fuels (wood, dung, crop residue, charcoal) or coal have on the feeding behaviour of mosquitoes and other insect vectors? Are such effects limited to certain levels of smoke at specific times of day? How do such impacts vary between indoor and outdoor locations?
- What effects do eaves spaces and other aspects of housing design and ventilation have on malaria-transmitting mosquitoes and other insect vectors? Does the use of netting

to protect eaves spaces from mosquito entry prevent the effective escape of smoke through these spaces?

- What, if any, are the health risks associated with burning mosquito-repellent plant materials and plant-based essential oils? What levels of exposure to smoke for what duration and in which population segments result from the use of burning these materials?
- What effect does soot have on the frequency and intensity of washing ITNs?

Qualitative research would also be useful to investigate the health and nuisance perceptions held with regard to smoke and mosquitoes as well as the non-health benefits that may motivate people to reduce their exposure to these risk factors.

Policy Implications

Biomass smoke is known to be harmful to health. There is some evidence that the traditional use of certain aromatic plants which are burned to repel mosquitoes can be effective. However, there is no conclusive evidence that smoke or soot from routine domestic fuel use repels mosquitoes or prevents malaria, and according to some reports published prior to 1940, the presence of cooking smoke has no effect on indoor abundance of African malaria vectors. In any case, under normal conditions of domestic fuel-use, it is likely that most cooking will be done outside of the peak biting times for malaria vectors.

On this basis there seems to be a good health argument for continuing efforts to reduce indoor air pollution, even in areas where malaria is endemic. It is likely that such efforts will have substantial health benefits in reducing respiratory disease, and unlikely that the reduction of smoke per se will have any significant health costs in terms of increased malaria.

However, interventions that seek to change stove or fuel types may need to take into account any existing insect repellent practices that may give effective protection against mosquitoes (such as burning specific, repellent plant materials) although it must be borne in mind that we know very little about the health risks associated with these practices.

Interventions that seek to remove smoke through increased eaves spaces probably run the risk of increasing mosquito densities inside houses. It would seem prudent to take steps to avoid this risk through the use of netting or curtains over additional windows and eaves spaces. However, the extent to which this would prevent effective ventilation is not known. Using flues, hoods and chimneys to reduce indoor smoke is unlikely to carry the same risk.

The use of insecticide treated bednets is known to be very powerful as a means of protection against malaria (Lengeler, 2004) and, unlike smoke, carries little or no health risk. Even untreated nets are partially effective. The effective promotion of insecticide treated bednets in combination with the removal of indoor air pollution would address two major health problems and there may be benefits in taking a more holistic approach to household environmental health.

Table 1: Control trials investigating the effect of burning wood or plant-based material on mosquito human-landing or biting rates.

Reference	Study setting	Plant material	Mosquito species	Mean % reduction in biting versus control (\pm 95% Confidence Intervals)
Lindsay and Janneh 1989	The Gambia	'Churai' = 'santango' (woods and resins from various species, mainly <i>Daniella oliveri</i>) (control = no smoke)	<i>Culex</i> spp	77 (70 - 83)
Vernede et al. 1994	Papua New Guinea	1) Betelnut leaves (<i>Areca catechu</i>) 2) Ginger (<i>Alpina</i> spp.) 3) Coconut husks (<i>Cocos nutifera</i>) (control = no smoke)	<i>An. karwari</i>	1) 84 (62-94) 2) 69 (25-87) 3) 66 (17-86)
Paru et al. 1995	Papua New Guinea	Coffee wood (<i>Coffea robusta</i>) Breadfruit (<i>Artocarpus altilis</i>) Leucina (<i>Leucaena leucocephala</i>) 'Tulip' (<i>Gnetum gnemon</i>) (control = no smoke)	a) Anophelines b) Culicines	a) 76 (50 -88) b) 80 (69-87) (Figures are mean reductions for protected against unprotected individuals. The plant species are not separated in the analyses.)
Pålsson and Jaenson 1999a	Guinea Bissau	1) <i>Hyptis suaveolens</i> 2) <i>Daniellia oliveri</i> bark 3) <i>Azadirachta indica</i> leaves 4) <i>Eucalyptus guineensis</i> infructescences (control = no smoke)	a) <i>An. gambiae</i> s.l. (62%) b) <i>An. pharoensis</i> (24%) c) <i>Culex</i> or <i>Aedes</i> (9%) d) <i>Mansonia</i> (5%)	1.a-d) 84 (82-89) 2.a-d) 78 (76-85) 3.a-d) 76 (73-82) 4.a-d) 69 (65-77)
Sayoum et al. 2002	Kenya	1) <i>Corymbia citriodora</i> leaves 2) <i>Hyptis suavelens</i> leaves and flowers 3) <i>Lippia uckambiensis</i> leaves 4) <i>Ocimum americanum</i> leaves and seeds 5) <i>Ocimum kilimandscharicum</i> leaves and seeds 6) <i>Ocimum suave</i> leaves and seeds (control = burning charcoal)	a) <i>Anopheles gambiae</i> s.s.	1a) 51(39, 61) 2a) 21 (5, 34) 3a) 33 (16, 47) 4a) 21 (3, 36) 5a) 26 (8, 41) 6a) 28 (3, 34)
Moore et al. (submitted)	Bolivia	1) <i>Attalea princeps</i> husks vs charcoal (negative control) 2) <i>A. princeps</i> husks vs 10mg <i>d</i> -allethrin coil (positive control)	a) <i>An. darlingi</i> b) <i>Mansonia</i> spp a) <i>An. darlingi</i> b) <i>Mansonia</i> spp	1.a) 35 (13-82) 1.b) 51 (37-66) 2.a) 60 (36-84) 2.b) 59 (36-82)

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Authors' contributions

AB and MC defined the overall research strategy and refined the questions and designed the initial search strategies; LS, JL, JE and MC refined the initial search strategies and carried out the literature searches; AB, LS, JL, JE and MC reviewed the literature and interpreted the findings; AB and MC wrote the first draft of the manuscript; LS, JL and JE critically revised the manuscript; AB and MC finalised the manuscript. All authors read and approved the final manuscript. AB and MC are guarantors of the paper.

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