Abstract. Insecticide treated nets (ITNs) represent a powerful means for controlling malaria in Africa. This usefulness is due to the fact that the principal malaria vectors, from the Giles Anopheles gambiae and An. funestus species complexes, primarily feed indoors at night. Thus, the proportion of human exposure that occurs indoors (πi), when persons are asleep and can conveniently use ITNs, is very high. Recent evidence suggests behavioral changes by malaria mosquito populations to avoid contact with ITNs by feeding outdoors in the early evening. We adapt an established mathematical model of mosquito behavior and malaria transmission to illustrate how ITNs can achieve communal suppression of malaria transmission exposure, even where mosquito evade them and personal protection is modest. We also review recent reports from Tanzania to show that conventional mosquito behavior measures can underestimate the potential of ITNs because they ignore the importance of human movements.

Insecticide-treated nets (ITNs) represent a powerful means for controlling malaria in Africa. This usefulness is due to the fact that the principal malaria vectors, from the Giles Anopheles gambiae and An. funestus species complexes, primarily feed indoors at night. Thus, the proportion of human exposure that occurs indoors (πi), when persons are asleep and can conveniently use them, is very high. Recent evidence suggests behavioral changes by malaria mosquito populations to avoid contact with ITNs by feeding outdoors in the early evening. We adapt an established mathematical model of mosquito behavior and malaria transmission to illustrate how ITNs can achieve communal suppression of malaria transmission exposure, even where mosquito evade them and personal protection is modest. We also review recent reports from Tanzania to show that conventional mosquito behavior measures can underestimate the potential of ITNs because they ignore the importance of human movements.

The definition of relevant terms in the model are shown in Table 1. The reduction in relative rate of exposure (RRE) to malaria transmission achieved by individual-level personal protection (ITN users), community-level protection (ITN non-users), and combined individual and communal protection (ITN users) was estimated by fixing the additional mortality probability of mosquitoes encountering an ITN at 0.85 and ITN coverage at the achievable level of 0.5, equivalent to 50% use as recorded in typical household surveys and specified by internationally agreed targets.

Otherwise, the model...
is formulated, parameterized, and applied exactly as previously described. Based on these published field data, simulations predict only a slight suppression in personal relative rate of exposure to transmission (RRE = 0.59), equivalent to a 1.7-fold reduction (Figure 2). However, much greater decreases in exposure to transmission for ITN users (communal plus personal protection; RRE = 0.19) and non users (communal protection only; RRE = 0.32) are predicted at 50% community-wide coverage. Thus, even non-users receiving only communal protection can expect 3.1-fold reduction of exposure to transmission and users enjoy a 5.3-fold reduction. Extrapolating this level of communal protection horizontally across Figure 2 shows that this is equivalent to the personal protection provided when mosquitoes feed predominantly at times when most resident are indoors (π_i = 0.77). Once reasonably high use rates are attained, communal protection achieved is greater than personal protection because even modest reductions of mosquito survival and feeding success per gonotrophic cycle result in much larger impacts upon proportion of mosquitoes surviving the multiple blood feeds required to reach an age where they can transmit mature sporogonic-stage parasites.

Conventional mosquito behavior measures can underestimate the potential of ITNs because they ignore the importance of human movements indoors and outdoors. Anopheles gambiae s.s. also prefers to bite outdoors in Dar es Salaam (Figure 1C), but surveys of human malaria prevalence confirm that ITNs confer valuable personal protection...
and reduce infection risk by 23.6% (95% confidence interval = 61.4–95.1%, *P = 0.016*). This finding is due to the fact that because persons sleep indoors during peaks of mosquito activity, this location is where most human exposure occurs (*π* = 0.73; Figure 1D), and can be prevented by using an ITN.7

Plotting *π* versus the proportion of mosquitoes that are caught indoors by conventional field methods (Figure 3) shows that in all cases, the latter consistently underestimates the former. Even for highly exophagic populations of mosquitoes, most bites (Figure 3) can be confined to times when most humans are likely asleep, obtained by dividing the total catch indoors across all times (*I* → 24 hours) by total catch occurring outdoors (*O* → 24 hours) and indoors (*I* → 24 hours). The open triangles represent the proportion of mosquitoes that are caught at times when most humans are likely asleep, obtained by dividing the total catch occurring indoors and outdoors from 9:00 pm to 5:00 am (*I* → 9:00 pm to 5:00 am + *O* → 9:00 pm to 5:00 am) by total catch indoors and outdoors across all times (*I* → 24 hours + *O* → 24 hours). The filled circles represents a crude estimate of the proportion of exposure occurring indoor (*π*), obtained by dividing the total catch occurring indoor from 9:00 pm to 5:00 am hours (*I* → 9:00 pm to 5:00 am) by itself plus the total outdoor catch from 5:00 am hours to 9:00 pm (*O* → 5:00 am to 9:00 pm).

However, the number of mosquitoes caught indoors during sleeping hours, expressed as a proportion of itself plus the number mosquitoes caught outdoors outside of sleeping hours, closely matches formal estimates of *π* (Figure 3). Although the level of exophagy and endophagy of vector populations influences the efficacy of ITNs for preventing malaria transmission, human movement patterns and the extent to which vector activity patterns match them may often be more important. These examples from Dar es Salaam1 illustrate how two exophagic vector populations can avoid ITNs to different extents because of differences in their peak times of activity and the degree to which these coincide with human behavioral patterns. In simple terms, it is more important that persons are asleep and can conveniently use an ITN when vector activity peaks than that the place they sleep is preferred by those mosquitoes.

We therefore caution that ITNs should not be automatically discarded as a priority vector control measure just because vector mosquitoes are observed to prefer feeding outdoors. Explicit estimates of *π* values for locally relevant populations should first be obtained in the field and the potential community-level benefits, which are rarely captured by standard survey designs, should be carefully considered. Personal protection measures such as spatial repellents5,6,9 may be required to protect against outdoor bites in the morning or early evening,6,9,29,32 but should only be considered a supplement to ITNs unless proven otherwise. If the equitable, population-wide benefits of communal protection are ignored, potential opportunities for effective malaria control with a well-proven existing technology may be missed because the requirements for behaviorally-susceptible vector populations may be overestimated or overemphasized.
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