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 ($\pi_i$), when persons are asleep and can conveniently use ITNs, is very high (Figure 1A–D). Such estimates of $\pi_i$, which take into consideration the movement patterns of persons are obtained in the field by weighting the observed indoor and outdoor biting rates at each period of the night by the proportion of humans that are typically in these two compartments at that time.

When reasonable levels of community-wide coverage are achieved, with approximately half of the population using them each night, ITNs not only confer personal protection against infectious bites but can also reduce the survival, feeding frequency, feeding success, and density of vector mosquito populations. This finding means that ITNs not only prevent malaria in protected persons, but can also reduce the exposure of unprotected persons by suppressing transmission across entire communities.

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 because the mosquito vectors feed primarily indoors at night. The proportion of human exposure that occurs indoors, when people are asleep and can conveniently use ITNs, is therefore 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.

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 ($\pi_i$), when persons are asleep and can conveniently use them, is very high (Figure 1A–D). Such estimates of $\pi_i$, which take into consideration the movement patterns of persons are obtained in the field by weighting the observed indoor and outdoor biting rates at each period of the night by the proportion of humans that are typically in these two compartments at that time.

When reasonable levels of community-wide coverage are achieved, with approximately half of the population using them each night, ITNs not only confer personal protection against infectious bites but can also reduce the survival, feeding frequency, feeding success, and density of vector mosquito populations. This finding means that ITNs not only prevent malaria in protected persons, but can also reduce the exposure of unprotected persons by suppressing transmission across entire communities.

Recent evidence suggests behavioral changes by malaria mosquito populations to avoid contact with ITNs by either feeding predominantly outdoors or in the early part of the evening. Such changes can drastically reduce the level of personal protection conferred by ITNs for obvious reasons. These behavioral changes might have resulted from the selection of genetically inherited traits or, more directly, from plastic phenotypic adaptation in response to increased coverage of ITNs or indoor residual spraying. Such intervention pressure may even be strong enough to cause changes in species composition of vector populations by selectively eliminating the most susceptible species and leaving those that are less vulnerable. For instance, An. arabiensis Patton, which is typically more exophagic, zoophagic, and exophagic than its sibling species An. gambiae sensu stricto, already dominates malaria transmission in parts of western Kenya where widespread use of ITNs has progressively diminished the importance of An. gambiae s.s as the main malaria vector.

Although it is commonly perceived that ITNs are ineffective against outdoor-biting mosquitoes based on conventional measures of mosquito behavior, we adapt an established mathematical model of mosquito behavior and malaria transmission to examine the possibility that ITNs can achieve communal suppression of malaria transmission exposure, even where mosquito evade them and personal protection is modest. We adapt an existing model that was previously used to establish population-wide coverage thresholds levels of ITNs at which community-level protection is equivalent to or greater than personal protection. Specifically, we modify the model slightly to deal more realistically with vector populations that vary in terms of their feeding behaviors. The probability of mosquitoes surviving their eventual host attack ($P_e$) is adjusted to account for the effect of ITN avoidance behavior, expressed as the proportion of normal exposure that would occur at times during which a human host would normally be under a net ($\pi_i$). This parameter can also be thought of in simple terms as the maximum proportion of normal exposure, which is directly preventable through personal protection by using an ITN. The corrected probability of a mosquito surviving the eventual host attack is calculated with the following modification of equation 13 of the original model, assuming that the proportion of all attacks that end in death is the sum of mortality probabilities for protecting attacked and unprotected hosts, weighted according to the proportion of the availability of all hosts that they represent.

$$P_e = 1 - \left( \frac{(1 - \pi_i) \mu_u + \pi_i \mu_{u+p} a_{h,u} N_{h,u} + \mu_u (a_{h,1} N_{h,1} + a_{h,u} N_{h,u})}{a_{h,1} N_{h,1} + A_{1}} \right)$$

The definitions 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.8

Figure 1E and F show that less than half of all human exposure to An. arabiensis in urban Dar es Salaam, Tanzania occurs in times and places when using an ITNs is feasible (π = 0.46). 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 = 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.26–28

Conventional mosquito behavior measures5,18,24,29–32 can underestimate the potential of ITNs because they ignore the importance of human movements in indoors and outdoors. Anopheles gambiae s.s. also prefers to bite outdoors in Dar es Salaam (Figure 1C),7 but surveys of human malaria prevalence confirm that ITNs confer valuable personal protection

**Table 1**

<table>
<thead>
<tr>
<th>Parameter definitions</th>
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<tbody>
<tr>
<td>P = Mean probabilities of surviving eventual host attack</td>
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<tr>
<td>π = Proportion of normal exposure of unprotected humans lacking nets that occurs at times and places when net users would be protected by sleeping under them</td>
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<tr>
<td>μ = Mortality upon attacking an unprotected host</td>
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<tr>
<td>μ = Overall mortality upon attacking a protected host</td>
</tr>
<tr>
<td>μ = Mean availability of individual unprotected humans</td>
</tr>
<tr>
<td>N = Number of protected humans</td>
</tr>
<tr>
<td>a = Mean availability of individual cattle</td>
</tr>
<tr>
<td>N = Number of cattle</td>
</tr>
<tr>
<td>N = Number of unprotected humans</td>
</tr>
<tr>
<td>N = Number of humans</td>
</tr>
<tr>
<td>A = Total availability of cattle</td>
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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 \( (\pi_i = 0.73; \text{Figure 1D}) \), and can be prevented by using an ITN.\(^7\)

Plotting \( \pi \) 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 \( (\text{Figure 3}) \) can be confined to times when most humans are likely asleep, obtained by dividing the total catch indoors across all times \( (I_{0-24 \text{ hours}}) \) by total catch occurring outdoors \( (O_{5:00 \text{ am} \rightarrow 9:00 \text{ pm}}) \) and indoors \( (I_{0-24 \text{ hours}}) \). 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 \( (I_{0-24 \text{ hours}} + O_{9:00 \text{ pm} \rightarrow 5:00 \text{ am}}) \) by total catch indoors across all times \( (I_{0-24 \text{ hours}}) \). The filled circles represents a crude estimate of the proportion of exposure occurring indoor \( (\pi_i) \), obtained by dividing the total catch occurring indoor from 9:00 PM to 5:00 AM hours \( (I_{9:00 \text{ pm} \rightarrow 5:00 \text{ am}}) \) by itself plus the total outdoor catch from 5:00 AM hours to 9:00 PM \( (O_{5:00 \text{ am} \rightarrow 9:00 \text{ pm}}) \).

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 \( \pi_i \) (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 Salaam\(^7\) illustrates 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 \( \pi_i \) 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 repellents\(^5,6,20\) may be required to protect against outdoor bites in the morning or early evening,\(^5,6,20\) 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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