SHORT COMMUNICATION

Reduction of Mosquito (Diptera: Culicidae) Attacks on a Human Subject by Combination of Wind and Vapor-Phase DEET Repellent

ERIC J. HOFFMANN AND JAMES R. MILLER 1
Department of Entomology and Center for Integrated Plant Systems, Michigan State University, East Lansing, MI 48824


ABSTRACT In a Central Michigan wetland setting, air drawn through a DEET-impregnated screen using an electric fan and projected toward a human subject significantly reduced mosquito orientation by 74%, landing by 75%, and probing by 70%, relative to no applied wind or DEET. The DEET vapor effect was significant as revealed by a statistically significant wind/DEET interaction. The wind speed at the downwind human subject was 0.6 m/s and the DEET vapor concentration was estimated at 2 μg/liter air. We suggest a combination of directed wind and volatile repellent might be developed as a mosquito deterrent strategy for the backyard setting.

KEY WORDS Mosquito, wind, DEET vapor, human subject

It is well established that environmental factors affect the ability of mosquitoes to find and feed upon their hosts. For example, humidities of 70–80% and temperatures between 37 and 40°C promote peak activity in female Anopheles quadriraculatus (Say) (Platt et al. 1957). Optimal flight temperatures for Aedes aegypti (L.) center around 21°C (Rowley and Graham 1968), whereas rising humidity is a key stimulus for An. gambiae s.s. (Giles) host seeking (Takken et al. 1997). Wind velocity is also a major factor affecting mosquito attraction. Bidlingmayer et al. (1995) documented trap catch reductions of 50% for Deinocerites cancer (Theobald), Culex nigripalpus (Theobald), Ochlerotatus (Aedes) taeniorynchus (Wiedemann), and Anopheles cruciens (Weidemann) at ambient wind velocities of 0.5 m/s, and additional decreases as wind velocity approached or exceeded mosquito flight speeds, estimated in still air to range from 0.4 to 1.6 m/s (Bidlingmayer 1985). Although the potential for controlling mosquitoes by manipulating wind velocity appears real, the benefits of this line of research have not been fully explored.

Currently, dermal application of chemical repellents is the mainstay of personal mosquito control. Although a number of repellent chemicals are available, N,N-diethyl-3-methyl benzamide (DEET) formulations remain the most effective and commonly used (Cockcroft et al. 1998, Fradin 1998). DEET has a high oral LD50 of 1.95 g/kg and an inhalation LC50 of 5.95 g/liter, and its safety has been extensively reviewed. Osmitz and Grothaus (1995) evaluated its toxic risk as “very low.” Despite high levels of effectiveness and a strong safety record, many people still object to dermal application of DEET for protection from mosquito bites. Oily or sticky residues and fear of toxicity are reasons most often cited by those who avoid DEET products (Fradin 1998).

DEET appears to be a behavioral inhibitor for mosquito host seeking. Its apparent repellency has been tied to inhibition of lactic acid sensors (Davis and Sokolove 1976), but there is evidence that DEET may actually attract mosquitoes at some concentrations (Dogan et al. 1999, Mehr et al. 1990). DEET has been shown to be an effective repellent in vapor phase in addition to liquid phase in an olfactometer. Adjacent, rather than mixed, release DEET was effective in reducing the number of mosquitoes attracted to a point source of lactic acid (Dogan et al. 1999). DEET has been shown to have a spatial repellent effect in laboratory bioassays (Schreck et al. 1970, Mcgovern et al. 1967) and in the field via DEET-treated netting (Schreck and Kline 1983). Even though netting in the field experiment was large enough for the insects to pass through, baited traps inside the treated perimeter captured <1% of the number of Culicoides midges compared with controls.

This study was performed to determine whether (1) artificially generated wind might deter nuisance mosquitoes and (2) adding repellent vapor to this moving air would augment a wind effect.

Materials and Methods

Study site and test times. Experiments were conducted between 1 and 29 July 1999 in a 1-ha meadow...
at the Rose Lake Wildlife Research Area in Clinton County, MI (GPS coordinates N 42° 48’ 3.9” W 84° 22’ 24.3”), between 1830 and 2130 hours. The test site was surrounded by trees and shrubs and was <100 m from standing and flowing water sources.

**Chemical plume generation.** N,N-diethyl-m-toluamide (DEET) was applied to a 41 × 51 cm E-Z Flow II air filter (Flanders Precisionaire, St. Petersburg, FL) at 2.4 mg/cm², for a total of 4.75 g per filter. Lower dosages were tried initially, but appeared to offer little benefit. The formulation used was Ben’s 100, 95% DEET (Tender Corp., Littleton, NH) applied via a finger pump. Initial DEET evaporation rates (within 2 h of application) were calculated gravimetrically to be 470 µg/cm²/h at 21°C in laboratory experiments using the same filter materials and wind velocities. The loss rate declined decrementally after this initial period. Air pressures in the field differed by <1.3% from 1,017.0 hPa recorded for laboratory evaporation tests. The filter area was 1.981 cm², yielding a loss of 0.9 g/h of DEET. Air volume treated per hour was 428 kl/h, as determined by at-fan velocities and cross-sectional area of the fan. This information in combination with the maximum evaporation rate yields an estimate of DEET vapor concentration at 2 µg/liter air. We believe that this represents the highest concentration encountered, because temperatures in the field were at or slightly below 21°C. This concentration was detectable by human smell, though it was not judged objectionable by the subject, observer, or two other people who assisted with this research.

**Wind generation.** Wind was generated using one of two identical Cyclone 25-cm radius, 3-speed electric floor fan (Lasko, West Chester, PA). An Onan 4-cycle gasoline-powered generator (Briggs & Stratton, Milwaukee, WI) delivered electrical power (120 V, 12.5 amps); it was situated 15 m from the test subject and perpendicular to the flow of wind from the fan. The “low” fan setting was used; at 1.6 m downwind, the velocity was 0.6 m/s ± 0.15, as determined by a hotwire anemometer (Series 471, Dwyer Instruments, Michigan City, IN). Separate fans were used for DEET treatment and the no-repellent “controls” to avoid contamination.

**Spatial layout of test components.** The furnace filter was placed behind and against the variable-speed electric floor fan so that the fan drew wind through the filter. The wind/DEET vapor plume generated by the fan was projected toward a human subject seated 1.6 m downwind of the fan/filter combination. An assistant was seated just outside of the wind plume to assist with data collection and, as required by Michigan State University human subjects protocol approved for this research, to monitor for overt reactions to the chemical plume or overexposure to mosquito bites. The human subject and observer were required to wear protective clothing, including mosquito-netting headgear. Notably, these guidelines specified that the number of human subjects be minimized until the outcome of preliminary tests could be peer reviewed and judged sufficiently promising and safe for expansion of this research.

**Experimental design, data collected, and analysis.** A 2 × 2 factorial design was used, with the factors being fan on versus off and repellent present versus absent. Each of the four treatment combinations was tested for 10-min intervals separated by a 5-min setup period between treatments. Treatments were blocked (nine total) by 1-h periods; no more than two blocks were completed per evening. Data collected were visual counts of numbers of mosquitoes orienting to, landing on, and probing the subject’s exposed forearms.

Mosquitoes were judged Orienting when <1 m from the subject and directing flight toward or stationkeeping near the subject. Random flight through the test area occurred rarely. Landing was scored when a mosquito alighted on the subject’s exposed forearms, and Probing required lowering the proboscis as if to pierce the skin. Mosquitoes were allowed to freely orient and land, but as soon as they initiated probing behavior they were aspirated into a vial for subsequent identification. Numbers of mosquitoes responding were transformed by (log10 (x + 0.5)) to stabilize variances and analyzed by two-way analysis of variance (ANOVA) using PROC GLM (SAS Institute 1996) for both main effects and interactions.

**Results**

Mosquito pressure was judged high (untreated mean was 15 visits in 10 min) and provided adequate sample sizes for analysis. The most common mosquito species were *Anopheles punctipennis* (Say), *Ochlerotatus texanus*, *Aedes stimulans* (Walker), and *Aedes triitzatus* (Coquillett). A maximum of 46 probing mosquitoes was counted in 10 min, and the average was 6.3 (9.4 SD). Averages for orienting and landing were 13.1 (18.3) and 8.6 (12.9), respectively. With DEET-present and DEET-absent treatments included in the factorial analysis, the main effect of turning the fan on significantly reduced the number of mosquitoes orienting ($F = 8.29; df = 1, 24; P < 0.008$), landing ($F = 9.66; df = 1, 24; P = 0.005$), and probing ($F = 14.45; df = 1, 24; P = 0.001$) (Fig. 1). The effect of repellent located at an inactive fan was not significant for mos-
quito orienting ($P = 0.18$), landing ($P = 0.26$), or probing ($P = 0.48$). However, the interaction between the fan and repellent was pronounced for orienting ($F = 4.28; \text{df} = 1, 24; P = 0.050$), landing ($F = 5.55; \text{df} = 1, 24; P = 0.027$), and probing behaviors ($F = 3.87; \text{df} = 1, 24; P = 0.061$). The mean number of mosquitoes was lower for the fan-on, repellent-present combination than for the fan-on, repellent-absent combination for orienting, landing, and probing.

Discussion

Wind carrying DEET vapor can reduce mosquito bites. Administration of DEET repellent to the wind stream generated by an electric fan was relatively simple to accomplish. While it did not completely eliminate visits from mosquitoes, fan-generated wind plus DEET did confer appreciable protection at a wind flow judged “comfortable” by the subject. The lack of a statistical main effect for DEET is to be expected if no vapor enveloped and protected the human subject when the fan was off. The significant interaction between the Fan and DEET factors is attributable to the action of the fan delivering DEET vapor to the human subject. This interaction also explains the Fan main effect; the fan–DEET combination dramatically reduced the numbers of mosquitoes observed and lowered the overall statistical cell mean for the wind-on analysis in the global ANOVA. Although the fan-on, DEET-absent combination was not significantly different from the fan-off, DEET-absent treatment in this experiment, other experiments with higher fan velocities strongly suggest that winds without DEET can confer substantial protection from mosquitoes (unpublished data). Although not significantly different, there was a noticeable trend toward increased mosquito visitation of the subject when DEET was present at an inactive fan. Perhaps low concentrations of DEET are slightly attractive to mosquitoes (Mehr et al. 1990). Alternatively, mosquitoes moving out of the treated zone might have slightly increased pest density in the surrounding areas.

Wind likely affects mosquito host-seeking success via at least two mechanisms. Mosquitoes might desist from plume following because of an inability to progress up-wind at a rate sufficient to satisfy a built-in optomotor requirement (Kennedy 1939, Klassen and Hocking 1964, Snow 1980, Gillies and Wilkes 1981). Another potential effect of wind is dilution of chemical attractants from the host. A given rate of emanating volatiles (such as CO$_2$ and lactic acid) would be expected to become less stimulatory as wind velocity increased. The concentration, and thus dosage delivered to chemosensory organs, of odorsants would fall as a decay function where a doubling of wind velocity over the constant release source would half the in-air concentration of chemicals. Increasing turbulence associated with rising wind velocities would likely intensify attractant dilution.

Safety considerations. Chemical suitability is an important issue for this and any repellent study. Although DEET has an acceptable safety record (Robbins and Cherniak 1986, Osimitz and Grothaus 1995, Goodyer and Behrens 1998), careful attention must be paid to dosage. We estimate that maximum DEET uptake for a 10-min exposure in this study could have reached 100 mg if the subject, inhaling 5 liter/min of plume air, absorbed all of the volatized chemical inhaled. By comparison, Robbins and Cherniak (1986) analyzed available DEET application data and estimated that an Everglades park worker averaged 4.25 g of dermally applied DEET per day, while the average DEET user in the general population was found to apply 1.65 g/d. Given a mean cutaneous absorption rate of 5.6% (Osimitz and Grothaus 1995), the worker would be absorbing 238 mg of DEET per day, and an average user 92 mg/d. Thus, an extrapolated daily rate of DEET used in the current study was high compared with these measures. Before wind-vaporized DEET use is implemented, the dosages and effects of DEET absorbed through the respiratory system need to be carefully quantified and found to be nonproblematic.

While DEET’s use as a vapor-phase repellent requires further study, we suggest that this strategy of using a fan to project a repellent plume has a place in personal protection from mosquitoes. Electric fans are readily available, comfortable, and could serve a dual purpose of deterring pests and cooling on warm evenings. Tests of this strategy should be expanded to other repellents such as the emerging piperidine compounds.

Acknowledgments

We thank E. Walker and R. Isaacs for improving this manuscript, the Michigan Department of Natural Resources for permission to use Rose Lake facilities, and the Graduate School of Michigan State University for fellowship support of EJH.

References Cited


Received for publication 5 November 2001; accepted 11 April 2002.