

Genetic elimination of dengue vector mosquitoes

Megan R. Wise de Valdez^{a,1}, Derric Nimmo^b, John Betz^a, Hong-Fei Gong^b, Anthony A. James^{c,2}, Luke Alphey^{b,d,2}, and William C. Black IV^a

^aDepartment of Microbiology, Immunology, and Pathology, Colorado State University, Fort Collins, CO 80523-1682; ^bOxitec Ltd., 71 Milton Park, Abingdon, Oxfordshire, OX14 4RX, United Kingdom; ^cDepartment of Microbiology and Molecular Genetics and Department of Molecular Biology and Biochemistry, University of California, Irvine, CA 92697-3900; and ^dDepartment of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, United Kingdom

Contributed by Anthony A. James, January 10, 2011 (sent for review September 29, 2010)

An approach based on mosquitoes carrying a conditional dominant lethal gene (release of insects carrying a dominant lethal, RIDL) is being developed to control the transmission of dengue viruses by vector population suppression. A transgenic strain, designated OX3604C, of the major dengue vector, *Aedes aegypti*, was engineered to have a repressible female-specific flightless phenotype. This strain circumvents the need for radiation-induced sterilization, allows genetic sexing resulting in male-only releases, and permits the release of eggs instead of adult mosquitoes. OX3604C males introduced weekly into large laboratory cages containing stable target mosquito populations at initial ratios of 8.5–10:1 OX3604C:target eliminated the populations within 10–20 weeks. These data support the further testing of this strain in contained or confined field trials to evaluate mating competitiveness and environmental and other effects. Successful completion of the field trials should facilitate incorporation of this approach into area-wide dengue control or elimination efforts as a component of an integrated vector management strategy.

genetic control | sterile insect technique | cage trial

Dengue fever is a rapidly emerging arthropod-borne viral disease threatening one-third of the world's population (1). In the absence of effective drugs and vaccines, mitigation efforts focus on controlling the primary mosquito vector, *Aedes aegypti*. However, current control methods are inadequate and new methods are needed urgently (2, 3). A key challenge in the control of *Ae. aegypti* is finding and treating each of the many breeding sites of this mosquito, which oviposits in diverse natural and artificial containers (4–6). Chemical control is increasingly restricted due to potential human toxicity, mortality in nontarget organisms, insecticide resistance, and other environmental impacts (7–9). Release of insects carrying a dominant lethal (RIDL) is a genetic control strategy derived from classical sterile insect technique (SIT) that provides a new solution to the challenges facing current control efforts (10–14).

SIT is a species-specific, environmentally friendly control method that involves the rearing, sterilization, and release of large numbers of disabled insects (15, 16). These sterile insects mate with wild insects in the target population, thereby reducing the reproductive potential of the target and, if sufficient numbers of sexually competitive insects can be released, achieving local control or even elimination. Large-scale SIT programs have suppressed or eliminated a number of major agricultural pests (15). SIT approaches for mosquito control have been tried (17–19) and continue to be proposed (20, 21). Factors that may have limited the success of these initial mosquito SIT programs and that are of continued concern in proposed SIT applications include reduced mating competitiveness and residual fertility of irradiated males (22, 23), the need to release exclusively males (male mosquitoes do not take blood meals) (20, 24), and reduction of density-dependent larval mortality due to early acting lethality (22, 25, 26). These limitations may be overcome using recombinant DNA technology to engineer repressible dominant-lethal transgenes for an RIDL strategy (4–7).

The *Ae. aegypti* OX3604C strain has the genetic features necessary to produce highly penetrant, dominant, late-acting, female-specific lethality (14). These transgenic mosquitoes carry genes that impose a tetracycline-repressible flightless-female phenotype. This phenotype is effectively lethal because flightless females cannot mate, seek hosts, or avoid predators. Importantly, they cannot serve as vectors for dengue viruses. Here we describe the results of testing this strain for its efficacy in suppressing a target wild-type population of mosquitoes in laboratory-based, large-cage trials.

Results

OX3604C (14) was outcrossed to a genetically diverse laboratory strain (GDLS) of *Ae. aegypti* derived from a mixture of equal numbers of 10 geographically distinct collections made in 2006 from Chiapas, Mexico (27). The outcrossed OX3604C males released in this experiment are expected to be homozygous for the transgene in a genetic background that is approximately 96.9% GDLS. The rationale for the outcrossing procedure was to create an OX3604C strain containing a similar genetic background to that of the target population and to maintain the competitive fitness of OX3604C males (28). The objective of this study is to assess the efficacy of the RIDL strategy using this outcrossed OX3604C strain to eradicate target populations of GDLS *Ae. aegypti* in large (232–504 ft³) laboratory cages.

Target populations of GDLS were established in six cages (Fig. S1) over the course of 12 weeks prior to the release of OX3604C (Figs. 1 and 2). Stable egg and adult densities in all six cages were achieved by Week 6. Three of the six cages were assigned randomly at Week 13 as treatment cages and approximately 900 OX3604C males, representing release ratios of 8.5–10 OX3604C:1 GDLS, were released into them weekly thereafter (Fig. S2). The weekly numbers of larvae returned to the treatment cages were adjusted relative to the weekly return rate in the control cages (held constant at 200 second-instar larvae/week) to reflect any impact of OX3604C release on egg production.

Author contributions: M.R.W.d.V., A.A.J., L.A., and W.C.B. designed research; M.R.W.d.V. and J.B. performed research; M.R.W.d.V., D.N., H.-F.G., A.A.J., L.A., and W.C.B. analyzed data; D.N. and H.-F.G. modeled predicted experimental outcomes; W.C.B. supervised research; and M.R.W.d.V., A.A.J., L.A., and W.C.B. wrote the paper.

Conflict of interest statement: The authors declare a conflict of interest (such as defined by PNAS policy). Those authors affiliated to Oxitec Ltd. (D.N., H.-F.G., and L.A.) are employees of this company, which therefore provided salary and other support for the research program. Also, such employees have shares or share options in Oxitec Ltd. Both Oxitec Ltd. and Oxford University have one or more patents or patent applications related to the subject of this paper. M.R.W.d.V., J.B., A.A.J., and W.C.B. have no patent interests, shares, or share options in Oxitec or any other entity for this technology.

Freely available online through the PNAS open access option.

¹Present address: Texas A&M University, San Antonio, 1450 Gillette Boulevard, San Antonio, TX 78224.

²To whom correspondence may be addressed. E-mail: aajames@uci.edu or luke.alphey@oxitec.com.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1019295108/-DCSupplemental.

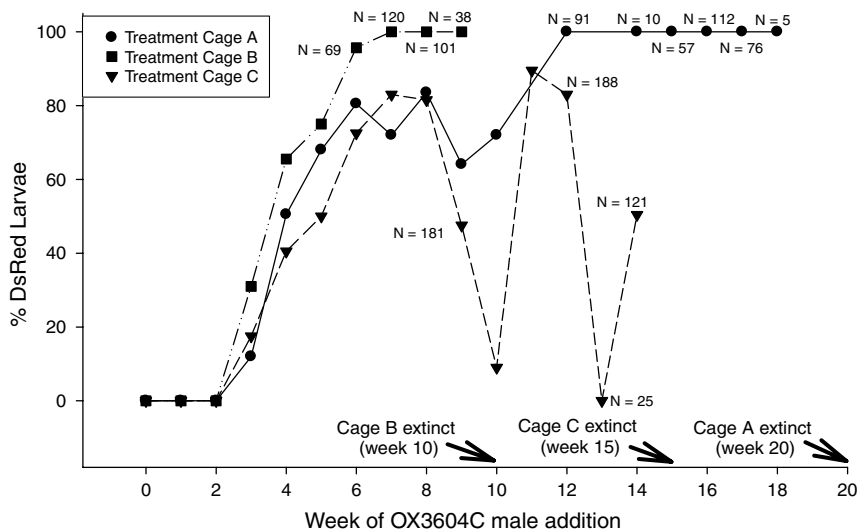


Fig. 3. Progeny genotypes in the treatment cages. Random samples of eggs from each weekly collection were hatched and the larvae screened for DsRed. Two hundred larvae were screened unless otherwise marked. The percentage of DsRed larvae reached 100% in two of the three treatment cages prior to extinction. The percentage of larvae positive for the OX3604C construct in the third cage varied over time and never reached 100%. The missing data from Cage A, Week 19, was due to the eggs collected not hatching. As expected, the frequency of the transgene in the larvae from collected eggs increased before adult female numbers or egg production decreased.

females, and this also is expected to be a key factor in the time scale for suppression. Females typically mate only once and then deposit eggs fertilized by sperm stored in the spermathecae (29, 30). Therefore, the genotype of these eggs reflects the mating choice of the female shortly after her emergence as an adult. Furthermore, with our definition of extinction, a single long-lived female can delay extinction by several weeks, even though she has mated with an OX3604C male and will produce no flying female progeny. This appears to have happened in Cage A where all eggs produced from Week 12 PR were transgenic, but extinction did not occur until Week 20 PR. Alternately, a rare nonhomozygous male in the OX3604 release population could have led to the more protracted extinction time.

We conclude that the release of outcrossed OX3604C males can successfully eliminate target populations of *Ae. aegypti* in a laboratory caged system. We also conclude that OX3604C males competed effectively with target males for target females, as revealed by the production of offspring expressing DsRed. Future field trials need to account for the rate of immigration of wild-type males and females into target populations. This includes movement of mosquitoes from outside the treatment area into it and the emergence in the treatment areas of estivated embryos in seasonally flooded breeding sites. These circumstances represent key differences from a fully contained cage trial. Our data support the transition to field trials with the expectation that release of outcrossed OX3604C or similar mosquitoes will result in a similar significant local suppression or elimination of the target mosquito populations.

Materials and Methods

Outcrossed Homozygous OX3604C. The outcrossed OX3604C homozygous strain of genetically engineered males released in this experiment was established by first outcrossing the OX3604C strain (14) to a GDLS established in 2006 (27). Virgin male OX3604C were caged with virgin female GDLS, and a cage containing the reciprocal cross was established. The resulting F_1 heterozygous adults were allowed to intercross, eggs were hatched, and 1,000 larvae expressing DsRed were collected, reared to adults, and mated individually to virgin GDLS adults. This was repeated for four additional generations so that as much as 96.9% ($1 - (1/32)$) of the genome could consist of GDLS. The frequency of the RIDL construct was increased through selection of DsRed larvae for four generations to generate a homozygous line of the outcrossed OX3604C strain. A total of 250 single-pair families then were established using only DsRed mosquitoes. Eggs were collected and hatched from each family and those families with wild-type larvae discarded. DsRed-

only mosquitoes were reared to adults, sib-mated, and the resulting larvae screened again for the DsRed marker. Any families with even a single wild-type larva were discarded and the remaining families were expected to be homozygous. These families were then intercrossed to provide the outcrossed OX3604C strain.

Target *Ae. aegypti* Population. Target populations were established in each of the six large laboratory cages (Fig. S1) over the course of 12 weeks using a GDLS derived from 10 geographically distinct populations in Chiapas, Mexico, in 2008 (28). Each cage was accessed through a series of three sleeves, two of which opened to shelves, and the third opening to the cage floor, which allowed introduction and removal of a BG-Sentinel Mosquito Trap™ (BGS-Trap Biogents AG; Fig. S1). The shelves in each cage held a total of six oviposition containers (OPs, three on each shelf; Fig. S1), which were glass Pyrex containers. All OPs were filled with 600 ml tap water, which was changed weekly, and were lined with white paper towels (Scott® brand, Kimberly-Clark) for oviposition. The caged populations of mosquitoes were reared and maintained under a 12:12 LD photoperiod at $27^\circ\text{C} \pm 2^\circ\text{C}$ and $82\% \pm 3\%$ humidity. Larvae were fed ground brewer's yeast tablets ad libitum. Adult mosquitoes were provided with raisins and allowed to feed weekly on restrained mice.

The method by which the target populations were established was conducted in two parts, initiation and maintenance. Initiation (Weeks 0–3) consisted of adding 300 second-instar GDLS larvae (50/OPs) for an initial population of 1,200 mosquitoes. Females began to oviposit at Week 3, after which the population was maintained (Weeks 4–12). Eggs laid by existing females were returned to their respective cages as second-instar larvae at a return rate of 200/week (approximately 33/OPs). Egg and adult densities were monitored weekly during target-population establishment. Egg densities were determined by counting the total number of eggs laid weekly in each cage. Adult sample collection commenced in Week 3. Adults were sampled placing a BGS-Trap into each cage for 1 h weekly. Adults were counted and sexed on cold plates and then returned to their respective cages. The adults experienced 5–25% mortality associated with trapping and handling.

Release of OX3604C Males. Weekly releases consisted of hatching 2,100 OX3604C eggs without tetracycline (to produce the flightless-female phenotype) per treatment cage and then rearing these larvae to pupae. Pupae were collected over the course of 3 d and placed in a covered pupal emergence container (PEC; Fig. S1) within each treatment cage. The PEC remained covered to prevent oviposition by females but was uncovered once daily to allow males to escape. Sexing the pupae was unnecessary because emerging females either drowned in the PEC or fell to the floor of the cage, where they died. We estimate that 2,100 OX3604C eggs per week led to the weekly addition of approximately 1,800 total pupae (approximately 900 male pupae) to each treatment cage. This release number was kept constant, and at the

first OX3604C male release (Week 13) it was 8.5–10 times the weekly return rate of 200 second-instar/larvae/week (approximately 100 males). Because the mosquito population decreased over time in the treatment cages, this ratio correspondingly increased, from 8.5–10:1 OX3604C:target males at Week 0 PR to between 600:1 to 900:1 at population extinction (Fig. S2).

Population Maintenance Post OX3604C Release. After OX3604C male release was initiated at Week 13 (Week 0 PR), the number of larvae added back to each cage was adjusted to reflect any impact of OX3604C male release on egg and adult densities. The number of larvae returned to the three control cages remained constant at 200 second-instar larvae/week. However, the number of larvae added back to the treatment cages was changed to a rate proportional to egg densities in the control cages. For example, if a control cage produced 5,000 eggs one week and we returned 200 second-instar larvae to that cage, then we returned 4% (200/5000) of the eggs. If a treated cage in the same week produced 600 eggs, then 24 larvae (600×0.04) would be returned, or, if conversely, a treated cage the same week produced 15,000 eggs then 600 larvae ($15,000 \times 0.04$) would be returned. Consistent with this

methodology, equal numbers of larvae were returned to each cage when egg densities were the same in treated and controls. If egg densities were lower in treated cages then fewer larvae were returned to the treated cage, and if egg densities were greater in treated cages (if for example, there was a greater survival of larvae due to density dependence), then more larvae were returned to the treated cage. If 200 larvae each week had been returned to the treated cages, the return rate would be artificially increased if egg densities in treated cages were low, and, conversely, artificially decreased the return rate when egg densities from treated cages were high.

ACKNOWLEDGMENTS. We thank Thomas W. Scott, Laura Harrington, Fred Gould, Luca Facchinelli, and David M. Brown for their valuable input and Mike Salasek for assistance in GDLS maintenance. This research was funded by a grant to the Regents of the University of California from the Foundation for the National Institutes of Health through the Grand Challenges in Global Health initiative. The use of mice in the blood-feeding of mosquitoes was approved by the Institutional Animal Care and Use Committee at Colorado State University, protocol no. 05-259A-03.

1. WHO-TDR (2006) *Scientific Working Group Report on Dengue* (World Health Organization, Geneva) Report no. TDR/SWG/08.
2. Gubler DJ (2004) The changing epidemiology of yellow fever and dengue, 1900 to 2003: Full circle? *Comp Immunol Microb Infect Dis* 27:319–330.
3. Mackenzie JS, Gubler DJ, Petersen LR (2004) Emerging flaviviruses: The spread and resurgence of Japanese encephalitis, West Nile and dengue virus. *Nat Med* 10:598–5109.
4. Pates H, Curtis CF (2005) Mosquito behavior and vector control. *Annu Rev Entomol* 50:53–70.
5. Juliano SA (2007) Population dynamics. *J Am Mosquito Contr* 23:265–275.
6. Reiter P (2007) Oviposition, dispersal and survival in *Aedes aegypti*: Implications for the efficacy of control strategies. *Vector-Borne Zoonot* 7:261–274.
7. Dorta DM, Vasukai V, Rajavel A (1993) Evaluation of organophosphorus and synthetic pyrethroid insecticides against six vector mosquito species. *Rev Saude Publ* 27:391–397.
8. Denholm I, Devine GJ, Williamson MS (2002) Evolutionary genetics—insecticide resistance on the move. *Science* 297:2222–2223.
9. Teixeira CF, Augusto LG, Morata TC (2003) Hearing health of workers exposed to noise and insecticides. *Rev Saude Publ* 37:417–432.
10. Alphey L, et al. (2010) Sterile-insect methods for control of mosquito-borne diseases—an analysis. *Vector-Borne Zoonot* 10:295–311.
11. Alphey L, Nimmo D, O'Connell S, Alphey N (2008) *Transgenesis and the Management of Vector-Borne Disease*, ed S Aksoy (Landes Biosciences, Austin, TX), 627, pp 93–103.
12. Thomas DD, Donnelly CA, Wood RJ, Alphey LS (2000) Insect population control using a dominant, repressible, lethal genetic system. *Science* 287:2474–2476.
13. Atkinson MP, et al. (2007) Analyzing the control of mosquito-borne diseases by a dominant lethal genetic system. *Proc Natl Acad Sci USA* 104:9540–9545.
14. Fu G, et al. (2010) Female-specific flightless phenotype for mosquito control. *Proc Natl Acad Sci USA* 107:4550–4554.
15. Dyck VA, Hendrichs J, Robinson AS (2005) *Sterile Insect Technique: Principles and practice in Area-Wide Integrated Pest Management* (Springer, The Netherlands).
16. Knipling EF (1955) Possibilities of insect control or eradication through the use of sexually-sterile males. *J Econ Entomol* 48:459–462.
17. Lofgren CS, et al. (1974) Release of chemosterilized males for control of *Anopheles albimanus* in El Salvador II Field Methods and Population Control. *Am J Trop Med Hyg* 23:288–297.
18. Seawright JA, Kaiser PE, Dame DA (1977) Mating competitiveness of chemosterilized hybrid males of *Aedes aegypti* (L) in field tests. *Mosq News* 37:615–619.
19. Lowe RE, Schreck CE, Hobbs JH, Dame DA, Lofgren CS (1975) Studies on flight range and survival of *Anopheles albimanus* in El Salvador. *Mosq News* 35:160–169.
20. Benedict MQ, Robinson AS (2003) The first releases of transgenic mosquitoes: An argument for the sterile insect technique. *Trends Parasitol* 19:349–355.
21. Helsinki ME, et al. (2008) Towards a sterile insect technique field release of *Anopheles arabiensis* mosquitoes in Sudan: Irradiation, transportation and field-cage experimentation. *Malaria J* 7:65.
22. Yakob L, Alphey L, Bonsall M (2008) *Aedes aegypti* control: The concomitant role of competition, space and transgenic technologies. *J Appl Ecol* 45:1258–1265.
23. Helsinki ME, Parker AG, Knols BG (2009) Radiation biology of mosquitoes. *Malaria J* 8:56.
24. Papatathanos PA, et al. (2009) Sex-separation strategies past experience and new approaches. *Malaria J* 8:55.
25. Dye C (1984) Models for the population dynamics of the yellow fever mosquito, *Aedes aegypti*. *J Anim Ecol* 53:247–268.
26. Phuc HK, et al. (2007) Late-acting dominant lethal genetic systems and mosquito control. *BMC Biol* 5:11.
27. Wise de Valdez MR, Suchman EL, Carlson JO, Black WC, eds. (2010) A large-scale laboratory cage trial of the *Aedes Densonucleosis Virus* (AeDENV). *J Med Entomol* 47:392–399.
28. Marrelli MT, Moriera CK, Kelly D, Alphey L, Jacobs-Lorena M (2006) Mosquito transgenesis: What is the fitness cost? *Trends Parasitol* 22:197–202.
29. Clements AN (1999) *The Biology of Mosquitoes. Sensory Reception and Behaviour*, (CABI Publishing, Wallingford, UK), 2.
30. Gwadz RW, Craig GB (1968) Sexual receptivity in female *Aedes aegypti*. *Mosq News* 28:586–594.