

Genome-engineering with CRISPR-Cas9 in the mosquito *Aedes aegypti*

Kathryn E. Kistler¹, Leslie B. Vosshall^{1,2}, Benjamin J. Matthews^{1,2}*

1 Laboratory of Neurogenetics and Behavior, The Rockefeller University, New York, NY 10065 USA

2 Howard Hughes Medical Institute, The Rockefeller University, New York, NY 10065 USA

* **E-mail: Ben.Matthews@rockefeller.edu**

1 **Abstract**

2 The mosquito *Aedes aegypti* is a potent vector of the Chikungunya, yellow fever, and
3 Dengue viruses, which result in hundreds of millions of infections and over 50,000 human
4 deaths per year. Loss-of-function mutagenesis in *Ae. aegypti* has been established
5 with TALENs, ZFNs, and homing endonucleases, which require the engineering of
6 DNA-binding protein domains to generate target specificity for a particular stretch of
7 genomic DNA. Here, we describe the first use of the CRISPR-Cas9 system to generate
8 targeted, site-specific mutations in *Ae. aegypti*. CRISPR-Cas9 relies on RNA-DNA base-
9 pairing to generate targeting specificity, resulting in cheaper, faster, and more flexible
10 genome-editing reagents. We investigate the efficiency of reagent concentrations and
11 compositions, demonstrate the ability of CRISPR-Cas9 to generate several different
12 types of mutations via disparate repair mechanisms, and show that stable germ-line
13 mutations can be readily generated at the vast majority of genomic loci tested. This
14 work offers a detailed exploration into the optimal use of CRISPR-Cas9 in *Ae. aegypti*
15 that should be applicable to non-model organisms previously out of reach of genetic
16 modification.

17 Introduction

18 As a primary vector of the serious and sometimes fatal Chikungunya, yellow and Dengue
19 viruses, the mosquito *Aedes aegypti* (*Ae. aegypti*) is responsible for hundreds of millions
20 of human infections annually [1]. To transmit disease, a female mosquito must first
21 bite an infected individual, and, after a period of viral incubation within the mosquito,
22 bite another human. Female mosquitoes use cues such as odor, carbon dioxide, and
23 temperature to locate a host and obtain a blood-meal [2], used to produce a clutch
24 of approximately 100 eggs. Once a mosquito has developed mature eggs, she uses
25 volatile and contact cues to locate and evaluate a body of water at which to lay her eggs,
26 or oviposit. Our long-term goals involve using genome-engineering techniques coupled
27 with quantitative behavioral analysis to investigate the genetic and neural basis of innate
28 chemosensory behaviors in this important disease vector.

29 Clustered regularly interspaced palindromic repeats (CRISPR) and CRISPR asso-
30 ciated (Cas) genes are components of an adaptive immune system that are found in
31 a wide variety of bacteria and archaea [3]. Beginning in late 2012 [4], the bacterial
32 type II CRISPR-Cas9 system has been adapted as a genome-engineering tool in a
33 wide variety of organisms and *in vitro* preparations, dramatically expanding the ability to
34 introduce specific genome modifications [3]. In particular, the ease of designing and
35 generating these reagents at the bench has opened the door for studies of gene function
36 in non-traditional model organisms.

37 The genome of *Ae. aegypti* is relatively large and incompletely mapped [5–8],
38 presenting difficulties in recovering mutations generated by traditional forward genetics.
39 *Ae. aegypti* has a recent history of genetic modification, including transposon-mediated
40 transgenesis [9, 10] and loss-of-function gene editing with zinc-finger nucleases (ZFNs)

41 [2, 11, 12], TAL-effector nucleases (TALENs) [13, 14], and homing endonuclease genes
42 (HEGs) [15]. ZFNs and TALENs are modular DNA-binding proteins tethered to a non-
43 specific FokI DNA nuclease [16], while HEGs are naturally occurring endonucleases
44 that can be reengineered to target novel sequences [17]. Targeting specificity in these
45 classes of genome-engineering reagents is conferred by context-sensitive protein-DNA
46 binding interactions that are not completely understood. It is therefore technically difficult
47 to engineer these proteins to target many sequences of interest.

48 In this paper, we describe methods for site-directed mutagenesis in *Ae. aegypti* using
49 RNA-guided endonucleases (RGENs) based on the type II CRISPR-Cas9 system. RNA-
50 DNA Watson-Crick base pairing is used to target the double-stranded endonuclease
51 Cas9, derived from *Streptococcus pyogenes*, to specific genome locations where it
52 introduces a double-stranded break. In just two years, the CRISPR-Cas9 system has
53 been adapted for precision genome-engineering in dozens of model organisms from
54 bacteria to primates [3, 18]. While many of these efforts have influenced our work, two
55 studies in the vinegar fly *Drosophila melanogaster* [19] and the zebrafish *Danio rerio* [20]
56 were particularly important in guiding our early attempts to adapt CRISPR-Cas9 to the
57 mosquito *Ae. aegypti*.

58 A detailed bench manual with step-by-step guidance for designing, generating, and
59 testing these reagents is available as a supplement to this paper. This work is not an
60 exhaustive exploration of the parameters controlling the efficiency of CRISPR-Cas9
61 mutagenesis in *Ae. aegypti*, but is instead a practical guide for generating mosquito
62 mutants. Given the proven flexibility of the CRISPR-Cas9 system, we believe that
63 the protocols and procedures outlined here and by numerous other laboratories will
64 continue to be optimized and modified for use in many organisms for which precision
65 genome-engineering has not yet been employed.

66 **Materials and Methods**

67 A detailed bench manual is available as Supplemental File S1.

68 **Microinjection and insect rearing**

69 Microinjection into *Ae. aegypti* embryos was performed according to standard protocols
70 [21] at the Insect Transformation Facility at the University of Maryland. Embryos were
71 hatched 3 days post-injection and reared to pupal or adult stages according to previously
72 described rearing procedures [2, 12]. Liverpool IB12 (LVP-IB12) mosquitoes [5] were
73 used both as the injection strain and as the wild-type strain for out-crossing and were
74 obtained through the MR4 as part of the BEI Resources Repository, NIAID, NIH. This *Ae.*
75 *aegypti* LVP-IB12, MRA-735 strain, was originally deposited by M.Q. Benedict. Female
76 mosquitoes were provided with a mouse or human blood source for egg production.
77 All laboratory blood-feeding procedures with mice and humans were approved and
78 monitored by The Rockefeller University Institutional Animal Care and Use Committee
79 and Institutional Review Board, protocols 11487 and LVO-0652, respectively. All humans
80 gave their informed consent to participate in mosquito blood-feeding procedures.

81 **Cas9 mRNA and protein**

82 Cas9 mRNA was transcribed from vector pMLM3613 (plasmid 42251, AddGene) [20]
83 using mMessage mMachine T7 Ultra Transcription kit (AM1345, Life Technologies).
84 Recombinant Cas9 protein was obtained commercially (CP01, PNA Bio).

85 **sgRNA design and construction**

86 sgRNAs were designed by manually searching genomic regions for the presence of
87 protospacer-adjacent motifs (PAMs) with the sequence NGG, where N is any nucleotide.
88 We required that sgRNA sequences be 17-20 bp in length, excluding the PAM, and
89 contain one or two 5' terminal guanines to facilitate transcription by T7 RNA polymerase.
90 sgRNA sequences were checked for potential off-target binding using the following
91 two web tools: <http://zifit.partners.org/ZiFiT/> and <http://crispr.mit.edu>. To
92 minimize the potential for off-target mutagenesis, we avoided sgRNA sequences with
93 closely related binding sites, defined as fewer than 3 mismatched bases to reduce the
94 possibility of cutting, whenever possible. See Table 1 for sgRNA sequences and closest
95 matches.

96 Linear double-stranded DNA templates for specific sgRNAs were produced by a
97 template-free polymerase chain reaction (PCR) with two partially overlapping oligos
98 (primers sgRNA-R and sgRNA-F; Table 2) [19]. In early experiments, sgRNA sequences
99 were cloned into pDR274 [20] and linearized with PmeI (R0560, NEB). In both cases
100 sgRNAs were produced using the MegaScript T7 *in vitro* transcription kit (AM1334,
101 Life Technologies) overnight at 37°C. Transcribed sgRNA was purified with MegaClear
102 columns (AM1908, Life Technologies).

103 **Extraction of genomic DNA**

104 Genomic DNA was extracted from individual or pools of mosquitoes using either the
105 DNEasy Blood and Tissue Kit (69581, Qiagen) or a 96-well plate extraction protocol [22].

106 **Sequencing and analysis of CRISPR-Cas9 induced mutations**

107 A two-step PCR protocol was used to amplify amplicons surrounding the putative
108 CRISPR-Cas9 cut site from genomic DNA of G_0 mosquitoes (those that were injected
109 as embryos and allowed to develop to pupal or adult stages) or G_1 individuals (the
110 progeny of G_0 individuals crossed to LVP-IB12). First, genome-specific primers were
111 designed with the following tails:

- 112 • Forward: 5'-TCGTCGGCAGCGTCAGATGTGTATAAGAGACAG-GENESPECIFIC-FORWARD-3'
- 113 • Reverse: 5'-GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAG-GENESPECIFIC-REVERSE-3'

114 20 cycles of PCR was performed using KOD Hotstart polymerase (71086-3, EMD
115 Millipore). The product of the first PCR was used as a template for a second round
116 of PCR with Nextera XT Indexed Primers (item FC-131-1002, Illumina). PCR cycles
117 were kept to a minimum to reduce the non-linearity of PCR amplification that can occur
118 at higher cycle numbers. Samples were purified using Ampure XP magnetic beads
119 at 0.6x volume to separate amplicons from primers, were examined on an Agilent
120 Bioanalyzer to verify purity and sizing, and pooled in roughly equimolar amounts. To
121 ensure high sequencing quality, final amplicon pools were quantitated by qPCR to
122 determine the precise molarity of amplicons containing the adapters need for clustering
123 and sequencing (KK4844, KAPA BioSystems). Samples were sequenced on an Illumina
124 MiSeq following the manufacturer's instructions.

125 Following sequencing, reads were aligned to reference sequences of the PCR am-
126 plicons and examined for the presence of insertions, deletions, or other polymorphisms.
127 Scripts developed for the analysis of this data, including those used to run the align-
128 ments and mutation quantitation for all figures, are available at [https://github.com/](https://github.com/bnmtthws/crispr_indel)
129 [bnmtthws/crispr_indel](https://github.com/bnmtthws/crispr_indel). Other software packages used include GMAP/GSNAP [23]

130 <http://research-pub.gene.com/gmap/>, GATK [24] <https://www.broadinstitute.org/gatk/>, and pysamstats <https://github.com/alimanfoo/pysamstats>.

132 **Donor construction for homology-directed repair**

133 Single-stranded DNA oligodeoxynucleotides (ssODNs) were ordered as 200 bp 'Ul-
134 tramers' from Integrated DNA Technologies (IDT). Plasmids used as double-stranded
135 DNA donors were constructed by PCR-amplifying homology arms from LVP-IB12 ge-
136 nomic DNA and cloning with In-Fusion HD cloning (Clontech) into one of two base
137 plasmids, PSL1180polyUBdsRED (AddGene #49327) and pSL1180-HR-PUBecFP
138 (AddGene #47917). Annotated sequences of oligonucleotides and plasmids used for
139 homology-directed repair are available as Supplemental File S2.

140 **Molecular genotyping of stable germ line alleles by PCR**

141 To verify the presence of exogenous sequences inserted by homology-directed-repair or
142 the presence of insertions and deletions, PCR amplicons surrounding the putative cut
143 site were generated from genomic DNA (see Table 2 for primer sequences). Following
144 purification, amplicons were Sanger sequenced (Genewiz), or used as a template for
145 a restriction digest using the enzyme BamHI (R0136, New England Biolabs [NEB]) or
146 PacI (R0547, NEB).

147 **Genotyping stable germ line alleles by fluorescence**

148 Larvae or pupae were immobilized on a piece of moist filter paper and examined under
149 a dissection microscope (SMZ1500, Nikon) with a fluorescent light source and ECFP
150 and dsRed filtersets.

151 **Results**

152 **Outline of CRISPR and injection components**

153 The bacterial type-II CRISPR system has been adapted in many organisms to generate
154 RNA-guided endonucleases, or RGENs, that are targeted to specific regions of the
155 genome by RNA-DNA base-pairing [3]. The core of this adapted CRISPR/Cas system
156 is comprised of two components: 1) a synthetic single guide RNA (sgRNA), which is a
157 small RNA containing 17-20 bases of complementarity to a specific genomic sequence,
158 and 2) the Cas9 nuclease derived from *Streptococcus pyogenes* (SpCas9). SpCas9
159 forms a complex with the sgRNA and induces double-stranded DNA breaks at regions
160 of the genome that fulfill two criteria: 1) contain a sequence complementary to the
161 recognition site of the sgRNA that is 2) directly adjacent to a protospacer-adjacent motif
162 (PAM). The PAM sequence for SpCas9 takes the form of NGG. These motifs occur
163 approximately once every 17 bp in the *Ae. aegypti* genome, making it possible to target
164 essentially any genomic loci of interest with the CRISPR-Cas9 system.

165 To generate stable mutations that can be transmitted through the germline, CRISPR-
166 Cas9 reagents must be introduced pre-blastoderm stage embryos composed of a
167 syncytium of nuclei prior to cellularization (Figure 1). This early developmental stage
168 offers access of genome-editing reagents to the nuclei of both somatic and germ-line
169 cells. In brief, embryos are microinjected 4-8 hours after egg-laying, and allowed to
170 develop for 3 days before being hatched in a deoxygenated hatching solution [21].
171 Following hatching, pupae are collected for sequencing or allowed to emerge as adults
172 and outcrossed to wild-type LVP-IB12 males or females, as appropriate. Genomic DNA
173 from injected embryos is examined for modification rates. Following blood-feeding, G₁
174 eggs are collected from these outcrosses to screen for germ-line transmission of stable

175 mutations.

176 When faced with a double-stranded DNA break, DNA repair machinery can resolve
177 this break in one of two ways: non-homologous end-joining, which can result in small
178 insertions and deletions, or, less frequently, homology-directed repair, which uses
179 exogenous sequence containing regions of homology surrounding the cut site as a
180 template for repair. Additionally, cutting with multiple sgRNAs can result in large deletions
181 between the two cut sites. In this paper, we will discuss stable germ-line transmission of
182 all three types of these alleles in *Ae. aegypti*.

183 **Identifying optimal injection mixes for CRISPR-Cas9 mutagenesis**

184 The insertions and deletions resulting from non-homologous end-joining act as a signa-
185 ture for evaluating the efficiency of reagents such as ZFNs, TALENs, and CRISPR-Cas9.
186 Quantifying the level of these insertions and deletions can give an indication of the
187 activity of a particular sgRNA/Cas9 combination. A variety of techniques have been de-
188 scribed to evaluate the cutting efficiency of Cas9/sgRNA RNA-guided nucleases. These
189 include enzymatic detectors of polymorphisms such as Surveyor or T7 Endonuclease
190 I [25], high-resolution melting point analysis (HRMA) [26], Sanger sequencing [27]
191 or deep sequencing [28]. Each of these techniques evaluates the level of polymor-
192 phism in a short PCR-generated amplicon surrounding the sgRNA target site. With
193 the exception of deep-sequencing, these approaches provide only semi-quantitative
194 estimates of the effectiveness of mutagenesis in each sample. In addition, the *Ae.*
195 *aegypti* genome is highly polymorphic, and so techniques that are based on detecting
196 sequence mismatches, such as HRMA, T7E1, or Surveyor nuclease assays, are prone
197 to false positives from polymorphisms present in our wild-type strains.

198 For these reasons, we opted to prepare and deep sequence barcoded PCR ampli-
199 cons surrounding putative CRISPR-Cas9 cut sites from small pools of injected animals
200 to accurately determine the rates of cutting at different genomic loci. Briefly, sequencing
201 libraries are prepared using a two-step PCR process that incorporates adapter and
202 barcode sequences necessary for Illumina sequencing (Figure 2A). Many distinct bar-
203 coded amplicons can be pooled together using Illumina-supplied Nextera XT primers.
204 We estimate that 10,000-100,000 reads are ample for this analysis, meaning that at
205 current prices, sequencing of amplicons from 3 sgRNAs per gene, for 10 distinct genes
206 can be run for a cost of approximately \$70 per gene (MiSeq v3 reagents, 150-cycle
207 flowcell, item MS-102-3001).

208 Following sequencing, reads were aligned to a reference sequence using the GSNAP
209 short read aligner [23], and insertions and deletions were quantified using the python
210 package pysamstats. This procedure results in data on the number of polymorphisms,
211 including insertions and deletions, found in reads that span each nucleotide of a ref-
212 erence sequence (Figure 2B). Notably, in injections containing a sgRNA and Cas9,
213 a pattern of elevated insertions and deletions can be observed with a peak 3 bp 5'
214 of the beginning of the PAM, exactly the position at which Cas9 is known to make a
215 double-stranded break (Figure 2C). Importantly, there was high concordance in the
216 mutagenesis rates seen between multiple biological replicates generated from different
217 pools of pupae from a single injection (Figure 2C), suggesting that there is minimal
218 variability in mutagenesis frequency in individual injected animals.

219 We next varied the delivery method and concentration of Cas9 and the concentration
220 of a given sgRNA to determine an optimal injection mix composition that would yield high
221 levels of somatic and germline mutations. We first attempted mutagenesis with plasmid
222 DNA constructed to express Cas9 under the control of an *Ae. aegypti* polyubiquitin

223 (PUB) promoter that can effectively drive TALEN half-sites when microinjected into
224 embryos [13,29]. However, injection mixes containing PUB-Cas9 plasmid and a validated
225 sgRNA did not induce detectable rates of insertions or deletions (data not shown).

226 The failure of Cas9 expressed by plasmid DNA might be due to the temporal
227 dynamics of transcription and translation, so we explored two additional methods of
228 Cas9 delivery: mRNA produced by *in vitro* transcription and recombinant SpCas9
229 protein. When included at 500 ng/ μ L, both Cas9 mRNA and protein induced detectable
230 mutagenesis at two distinct guide RNA sites. However, recombinant Cas9 protein
231 induced mutagenesis at rates 5-10x higher than Cas9 mRNA (Figure 2D). To test
232 whether the concentration of sgRNA or Cas9 mRNA or protein was limiting in these
233 earlier injections, we tried four additional injection mixes (Figure 2E), with a single
234 validated sgRNA, and determined that mixes containing 400 ng/ μ L Cas9 recombinant
235 protein induced the highest rates of mutagenesis. Increasing sgRNA concentration did
236 not dramatically increase mutagenesis rates.

237 **Identifying active sgRNAs for a given genomic target**

238 We reasoned that sgRNAs that show higher somatic cut rates in injected animals would
239 be more likely to result in stable germ-line transformation. We first designed 3 different
240 sgRNAs against 6 different genes using publicly-accessible design tools to minimize the
241 potential for off-target mutagenesis (Figure 3A). These varied in length between 17-20
242 bp [30], and in addition to being adjacent to a PAM sequence, were required to begin
243 with GG or G to facilitate *in vitro* transcription of sgRNA.

244 To test the efficiency of these sgRNAs, we performed a series of 6 small test
245 injections (145-168 embryos each) into *Ae. aegypti* embryos (Figure 3B). Each injection

246 mix was comprised of recombinant Cas9 protein at 333 ng/ μ L and a pool of three
247 sgRNAs (40 ng/ μ L each), each targeted against a different gene. Survival rates were
248 very high for these injections (ranging from 46.1%-63.3%, as compared to a 18.6%
249 average survival in previous experiments with 500 ng/ μ L Cas9 protein or mRNA), and
250 we attribute this marked increase in survival to the reduction in Cas9 (or overall injection
251 mix) concentration. Surviving embryos were reared to pupal stages and collected for
252 PCR amplicon preparation and sequencing analysis (Figure 3B).

253 All 18 sgRNAs induced detectable levels of mutagenesis, although the rates of
254 cutting were highly variable within and between different genomic targets (Figure 3C).
255 Thus, in addition to potential effects of chromatin state or other genome accessibility at
256 a particular genomic locus, there appear to be sequence- or context-dependent effects
257 on sgRNA efficiency that are not yet fully understood. Designing and testing 3 sgRNAs
258 resulted in the identification of at least one highly active sgRNA for the 6 genomic targets
259 tested here. The variability observed between different sgRNAs targeting the same
260 locus underscores the benefits of testing multiple sgRNAs per gene before undertaking
261 large-scale mutagenesis injections.

262 **Germ-line transmission of mutant alleles**

263 We next examined whether somatic mutagenesis detected in adults reared from injected
264 embryos (G_0 animals) could result in transmission of stable mutant alleles through the
265 germline to their offspring (G_1 animals). We designed an sgRNA near the 5' end of
266 *Aaeg-wtrw*, a single-exon gene identified through bioinformatics which bears homology
267 to the *D. melanogaster* TRP channel *water witch* (*wtrw*) [31]. We also included 300
268 ng/ μ L of a 200 bp ssODN donor to act as a template for homology-directed repair. The

269 ssODN comprised homology arms of 87-90 bases on either side of the Cas9 cut site,
270 with an insert containing stop codons in all three frames of translation as well as an
271 exogenous restriction enzyme recognition site. Successful integration of this template
272 would result in a truncated protein of 91 amino acids rather than a full-length protein of
273 908 amino acids (Figure 4A).

274 636 embryos were injected with a mixture of 200 ng/ μ L Cas9 mRNA and 12.5 ng/ μ L
275 sgRNA. Note that these injections were performed prior to the optimization of injection
276 mixes described above. To determine the activity of our injected reagents, we performed
277 amplicon sequencing on 6 pools of 5-6 adult G₀ animals after they were outcrossed
278 and allowed to lay eggs (Figure 4B). After alignment and analysis of reads aligning to
279 the reference sequence, we found that these samples contained a mean maximum
280 somatic insertion or deletion rate of 24.87% centered on the Cas9 cut site (Figure 4C),
281 indicating a high rate of somatic mosaicism at the targeted locus in animals injected
282 with this cocktail. As a control, we sequenced amplicons at the *Aaeg-wtrw* locus from
283 animals injected with an injection mix containing another sgRNA targeting a different
284 region of the genome. These samples contained no detectable insertions or deletions
285 at the *Aaeg-wtrw* locus (Figure 4C). Across the six samples, a mean of 0.71% of reads
286 that aligned to the reference sequence contained sequences corresponding to the
287 exogenous sequence in the single-stranded DNA donor (Figure 4D). This indicated that
288 the ssODN template could drive homology-directed repair in somatic tissue, though
289 at a much lower frequency than insertions or deletions mediated by non-homologous
290 end-joining.

291 To determine whether these mutations were stably transmitted through the germline,
292 we sequenced PCR amplicons derived from pools each containing 5 male and 5 female
293 G₁ offspring that were previously mated together and from which we had already

294 collected F2 eggs. Analysis of resulting insertions and deletions using Genome Analysis
295 Toolkit [GATK; [24]] revealed that there were at least 117 mutant chromosomes spread
296 across 50 pools, meaning that the G_1 mutation rate was at least 117/620, or 18.9%
297 (Figure 4E). Four of these alleles corresponded perfectly to the sequence of the ssODN,
298 meaning that our rate of stable germline transmission of alleles generated by homology-
299 driven repair recombination is at least 0.6% (Figure 4E). Notably, these numbers
300 correlate well with those derived from G_0 animals (Figure 4E), suggesting that assays of
301 somatic mutagenesis can be useful in predicting the efficiency of germ-line mutagenesis.

302 We hatched F2 eggs from a single family containing an allele generated by homology-
303 directed repair. Sequencing of single-pair crosses allowed us to isolate a stable mutant
304 line that can be genotyped by a simple restriction digest with the enzyme site introduced
305 by the ssODN targeting event (Figure 4F). To enable future phenotypic characterization,
306 this line was outcrossed for 8 generations to wild-type mosquitoes to increase genetic
307 diversity in the mutant strain and to reduce the possibility of retaining off-target mutations
308 in this population of animals.

309 **Deletions induced by multiplexed sgRNAs**

310 Double-stranded breaks induced at multiple sgRNA sites can induce large deletions
311 between the two cut sites in *D. melanogaster* [32]. We performed a series of five
312 injections into small numbers of embryos using sgRNAs targeting 3 different genes.
313 All but one of these sgRNAs (AAEL000926-sgRNA4) were previously validated as
314 having high activity in somatic mutagenesis assays. We also included ssODN donors
315 with arms on either side of the two breaks and an exogenous sequence containing
316 stop codons in all 3 frames of translation as well as a restriction enzyme recognition

317 site (Figure 5A). We injected small numbers of embryos and collected G_1 embryos
318 from all female G_0 animals, which were hatched and screened individually (Figure 5B).
319 From these individual families, we screened male pupae in pools via PCR, identifying
320 potential mutations through size-based genotyping on an agarose gel. Individual females
321 were outcrossed, blood-fed, and allowed to lay eggs. PCR amplicons were generated
322 from these animals individually and examined for size-shifted bands on agarose gels
323 (Figure 5C). Candidate alleles were characterized by Sanger sequencing of gel-purified
324 fragments (Figure 5C). We found a wide range of mutant transmission rates in female
325 G_1 animals derived from single G_0 individuals where genotyping male pupae showed
326 the offspring of these G_0 animals to contain at least one mutant G_1 (Figure 5D).

327 Although we did not fully characterize each potential mutant allele, we did note
328 several different types of mutations in those that were characterized. These ranged
329 from simple deletions, to homology-directed repair from the ssODN donor, to more
330 complex modifications, including polymorphisms, inversions, and duplications. This
331 indicates that induction of multiple double-stranded breaks is highly mutagenic. We
332 also note that we were successful in obtaining germ-line mutations at high rates in
333 all 3 injections (Figure 5E), making this a cost-effective and efficient way to generate
334 loss-of-function mutant alleles. The relatively large size of deletions generated by this
335 method makes sized-based molecular genotyping straightforward and greatly facilitates
336 the out-crossing and homozygosing of mutant lines.

337 **Integration and transmission of large fluorescent cassettes**

338 Finally, we asked whether CRISPR-Cas9 could be used to introduce longer cassettes of
339 exogenous sequence via homology-dependent repair. In previous genome-engineering

340 experiments in *Ae. aegypti*, zinc-finger nucleases were used to introduce large cassettes
341 from a plasmid DNA donor with homology arms of at least 800 bp on either side
342 [2, 11]. The insertion of a fluorescent cassette simultaneously creates a null mutant by
343 interrupting the protein-coding sequence and inserts the visible fluorescent reporter.
344 We performed injections with Cas9 protein, a validated sgRNA, and a plasmid donor
345 containing homology arms of 799 bp and 1486 bp. This plasmid contains a cassette
346 comprising the constitutive PUb promoter [29] driving the expression of a fluorescent
347 reporter (Figures 6A-B). These arms were cloned from the strain of mosquito into which
348 injections were performed to maximize homology, and were designed to avoid repetitive
349 sequences such as transposable elements. Following injection, individual female G_0
350 animals were outcrossed to wild-type mosquitoes and G_1 eggs were collected (Figure
351 6A). Past experiences in our laboratory indicate that successful homology-directed
352 repair occurs primarily, if not exclusively, in female G_0 animals in *Ae. aegypti*. We
353 therefore discarded G_0 males and restricted our screening to G_1 families generated
354 from females.

355 G_1 individuals were screened under a fluorescence dissecting microscope as larvae
356 at 3-5 days post-hatching. The expression of the PUb promoter is clearly visible in
357 larvae and pupae (Figure 6C and 7B). Fluorescent individuals were collected and reared
358 to adulthood and crossed again to wild-type animals to establish stable lines. To verify
359 directed insertion of our cassette as opposed to non-targeted integration at another
360 genomic locus, we designed PCR primers spanning both homology arms (Figure 6D). It
361 is critical that these primers are designed outside each arm and that bands obtained
362 are sequenced to verify junctions between genomic and exogenous sequence on each
363 end of the insertion.

364 Lines containing verified targeted insertions were out-crossed to wild-type mosquitoes

365 for 8 generations, at which point a homozygous line was established by mating het-
366 erozygous males and females and selecting putative homozygous individuals from their
367 offspring. Because homozygous individuals show increased levels of fluorescence
368 relative to heterozygotes, the generation of homozygous lines is straightforward. Puta-
369 tive homozygous mosquitoes were separated by sex and used to establish single-pair
370 matings, and the genotype of these single-pair matings were verified by PCR across the
371 integration site of the cassette. In this reaction, PCR primers span the entire cassette,
372 resulting in a large shift in size in homozygous mutant individuals (Figure 6E).

373 We generated verified targeted insertions in two genomic loci with the *Ae. aegypti*
374 PUb promoter driving the expression of ECFP (Figures 6, 7A) or dsRed (Figure 7B).
375 Attempts at two additional loci failed to produce directed insertion of the donor cassette
376 (Figures 7C-D). We conclude that, similar to the rates of ssODN integration, homology-
377 directed repair from with large plasmid donors occurs at a relatively low frequency
378 compared to other forms of CRISPR-Cas9-mediated genome modification. A drastic
379 variance in the efficiency noted in two injections (Figure 7A) suggests that higher rates
380 can be achieved through simple modifications of injection mix component concentration,
381 perhaps at the expense of embryo survival. The presence of non-directed targeting
382 events underscores the necessity of verifying all lines generated by this technique by
383 PCR or other molecular methods (Figure 6).

384 Taken together, these data show that the CRISPR-Cas9 system can be been suc-
385 cessfully adapted for genome-engineering in the mosquito *Ae. aegypti*. Following the
386 generation of a double-stranded break by an RNA-guided Cas9 nuclease, a variety of
387 mutant alleles can be recovered, including frame-shift mutations caused by insertions
388 or deletions, deletion of a region between two sgRNA target sites, and integration of
389 exogenous sequences from a single-stranded oligonucleotide or a double-stranded plas-

390 mid DNA donor. We recommend these methods to any laboratory wishing to generate
391 loss-of-function mutations in *Ae. aegypti*.

392 **Discussion and Conclusions**

393 We have demonstrated that the CRISPR-Cas9 system is a highly effective and efficient
394 tool for precision genome-editing in the mosquito *Ae. aegypti*. Compared to the relatively
395 low throughput and high cost of ZFN- and TALEN-mediated mutagenesis, the ease and
396 efficiency of designing and producing CRISPR-Cas9 reagents in the laboratory has
397 allowed us to generate stable and precise loss-of-function mutations in over 10 genes to
398 date. This protocol provides a step-by-step manual to mutagenesis in *Ae. aegypti* and
399 also provides general principles that will be useful when translated to other species.

400 **Optimal injection mix**

401 We recommend using recombinant Cas9 protein for its reproducibility and observed
402 increased rates of mutagenesis and embryo survival. Recombinant Cas9 protein is
403 likely to be much more stable than mRNA, both at the bench and in injected embryos.
404 Additionally, it is likely that sgRNA and Cas9 protein can form a complex in the absence
405 of any other factors, allowing them to generate pre-formed RGENs prior to injection. This
406 can serve to both stabilize sgRNA/Cas9 complexes [33] and ensure that mutagenesis
407 can occur immediately, rather than waiting for Cas9 mRNA to be translated in the embryo.
408 The specific concentrations suggested here represent a good trade-off between survival
409 and efficiency in our hands. However, it is entirely possible that further modifications to
410 this protocol could result in significant increases in certain types of repair.

411 For CRISPR-Cas9 injections into *Ae. aegypti*, we currently recommend the following

412 injection mix. This mix may also be a good starting point for microinjections into other
413 insect embryos.

- 414 • 300 ng/ μ L recombinant Cas9 protein
- 415 • 40 ng/ μ L sgRNA (each)
- 416 • (optional) donor DNA

- 417 • 200 ng/ μ L single stranded ssODN **or**
- 418 • 500 ng/ μ L double stranded plasmid DNA

419 **Designing active sgRNAs**

420 We observed significant variability in the effectiveness of different sgRNAs, even be-
421 tween sgRNAs targeted to a small genomic region (Figure 3). As in other organisms
422 and cell lines [30, 34], we observed success with sgRNAs ranging in length from 17-20
423 bp, and recommend considering sgRNAs in this size range when screening for the
424 most active target sites. A single genomic target (AAEL001123) has proven resistant
425 to mutagenesis with 6 different sgRNAs, perhaps reflecting an underlying chromatin-
426 state [35]. Aside from this one example, we were able to design effective sgRNAs to all
427 other examined genes. Systematic examination of sgRNA efficiency in *D. melanogaster*
428 suggests that the GC content of the 6 nucleotides adjacent to the PAM contributes to
429 the efficiency of a given sgRNA [34]. We will incorporate these suggestions as well as
430 those generated from further investigations into the sequence or context-dependency
431 of sgRNA activity into our future sgRNA design. However, given the ease of testing
432 sgRNA efficiency *in vivo*, we still recommend the design and testing of multiple sgRNAs
433 targeting a given gene before committing to large-scale injections.

434 **Off-target effects**

435 Off-target effects are a concern with any genome-editing technology. We currently adopt
436 several approaches to try and address these concerns in our experiments. First, we
437 check for the sgRNA specificity using publicly available bioinformatic tools [20, 36, 37],
438 selecting the most specific sgRNAs within the region we wish to target. Second, we
439 design several sgRNAs for a given genomic target. For genes of particular interest,
440 we can generate mutant alleles with multiple sgRNAs and examine their phenotype in
441 transallelic combination, reducing the likelihood that these independent lines will share
442 the same off-target mutations. Third, we have successfully used truncated sgRNAs of
443 less than 20 bp in length, which have been shown in cell culture to reduce the likelihood
444 of off-target modifications [30]. Finally, we subject all lines to at least 8 generations of
445 out-crossing to wild-type mosquitoes, which should reduce the co-inheritance of all but
446 the most tightly linked off-target mutations. While we believe these guidelines reduce
447 the likelihood of significant levels of off-target mutagenesis, we recognize the need
448 for continued efforts to improve and to verify the specificity of all precision genome-
449 engineering technologies.

450 Variants on the traditional CRISPR-Cas9 reagents designed to improve specificity
451 include the use of paired Cas9 'nickases' to generate adjacent single-stranded DNA
452 breaks [38–41]. These dual 'nicks' are proposed to be less mutagenic than a single
453 double-stranded break. This approach should decrease the chance that the binding
454 of a single sgRNA at an off-target site produces a mutation. Another approach fuses
455 a nuclease-dead Cas9 mutant (dCas9) to the FokI nuclease. As in ZFN and TALENs,
456 FokI requires paired binding, within a certain distance, on opposite strands of a target,
457 and this technique aims to combine the specificity of TALENs and ZFNs with the
458 ease-of-targeting of CRISPR-Cas9 [42, 43]. Though we have not investigated these

459 CRISPR-Cas9 variants in our experiments, we believe that their benefits are likely to
460 translate to *Ae. aegypti* and other organisms in the future.

461 **Enhancing the efficiency of homology-directed repair**

462 In our experiments, insertions and deletions mediated by non-homologous end-joining
463 occur at much higher frequency than by homology-directed repair. This is similar to what
464 has been observed in *Ae. aegypti* with other genome-editing tools, such as ZFNs [2, 11],
465 and in other organisms such as *D. melanogaster* [44].

466 Several approaches have been developed to increase rates of homology-directed
467 repair. These include injections in the background of a DNA ligase 4 mutation [45, 46]
468 or schemes that linearize a double-stranded donor template *in vivo*. Finally, many
469 laboratories working with *D. melanogaster* have developed transgenic strains that
470 express Cas9 protein under ubiquitous or germ-line promoters, improving the efficiency
471 of mutagenesis generally and homology-directed repair specifically [34, 44]. Other areas
472 of interest include alternatives to homology-directed repair, such as ObLiGaRe [47] and
473 homology-independent double-stranded break repair pathways [48]. It remains to be
474 seen whether transgenic Cas9 delivery or alternative integration approaches can be
475 effectively implemented in *Ae. aegypti*.

476 We note that we have observed a single round of injection that resulted in high
477 (>30%) rates of homology-directed repair but extremely low survival (Figure 7A). This
478 suggests that we might achieve improvements in insertion efficiency by continuing to
479 examine the effects of modulating the concentrations of the three components of the
480 injection mix. If the rates of homology-directed-repair can be sufficiently improved,
481 CRISPR-Cas9 coupled with transgene insertion via homology-directed repair will likely
482 prove to be a versatile tool to tag gene products and introduce transgenes into specific

483 genomic loci, enabling studies of specific neural circuits and other subsets of cells.

484 **Conclusions**

485 Precision genome-engineering in mosquitoes holds great promise for studies on the
486 genetic basis of behavior [2, 11, 12] and for genetic strategies to control vector population
487 or disease competence [49]. Ongoing efforts to increase the specificity and efficiency of
488 these technologies is critical to their adaptation as routine techniques, and we believe
489 that the protocols outlined here have met those criteria for the generation of loss-of-
490 function mutations in the mosquito *Ae. aegypti*. Reagents based on the CRISPR-Cas9
491 platform have been used successfully in organisms from bacteria to primates. This
492 suggests that the techniques described here can likely be adapted to many other non-
493 model organisms, so long as efficient methods of introducing the reagents into the
494 germline and screening for mutations can be developed.

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505 References

- 506 1. Bhatt, S, Gething, P. W, Brady, O. J, Messina, J. P, Farlow, A. W, Moyes, C. L,
507 Drake, J. M, Brownstein, J. S, Hoen, A. G, Sankoh, O, Myers, M. F, George, D. B,
508 Jaenisch, T, Wint, G. R. W, Simmons, C. P, Scott, T. W, Farrar, J. J, & Hay, S. I.
509 (2013) The global distribution and burden of dengue. *Nature* **496**, 504–507.
- 510 2. McMeniman, C. J, Corfas, R. A, Matthews, B. J, Ritchie, S. A, & Vosshall, L. B.
511 (2014) Multimodal integration of carbon dioxide and other sensory cues drives
512 mosquito attraction to humans. *Cell* **156**, 1060–1071.
- 513 3. Doudna, J. A & Charpentier, E. (2014) Genome editing. The new frontier of
514 genome engineering with CRISPR-Cas9. *Science* **346**, 1258096.
- 515 4. Jinek, M, Chylinski, K, Fonfara, I, Hauer, M, Doudna, J. A, & Charpentier, E. (2012)
516 A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial
517 immunity. *Science* **337**, 816–821.
- 518 5. Nene, V, Wortman, J. R, Lawson, D, Haas, B, Kodira, C, Tu, Z. J, Loftus, B, Xi,
519 Z, Megy, K, Grabherr, M, Ren, Q, Zdobnov, E. M, Lobo, N. F, Campbell, K. S,
520 Brown, S. E, Bonaldo, M. F, Zhu, J, Sinkins, S. P, Hogenkamp, D. G, Amedeo,
521 P, Arensburger, P, Atkinson, P. W, Bidwell, S, Biedler, J, Birney, E, Bruggner,
522 R. V, Costas, J, Coy, M. R, Crabtree, J, Crawford, M, Debruyn, B, Decaprio, D,
523 Eiglmeier, K, Eisenstadt, E, El-Dorry, H, Gelbart, W. M, Gomes, S. L, Hammond,
524 M, Hannick, L. I, Hogan, J. R, Holmes, M. H, Jaffe, D, Johnston, J. S, Kennedy,
525 R. C, Koo, H, Kravitz, S, Kriventseva, E. V, Kulp, D, Labutti, K, Lee, E, Li, S, Lovin,
526 D. D, Mao, C, Mauceli, E, Menck, C. F. M, Miller, J. R, Montgomery, P, Mori, A,
527 Nascimento, A. L, Naveira, H. F, Nusbaum, C, O’leary, S, Orvis, J, Pertea, M,

- 528 Quesneville, H, Reidenbach, K. R, Rogers, Y.-H, Roth, C. W, Schneider, J. R,
529 Schatz, M, Shumway, M, Stanke, M, Stinson, E. O, Tubio, J. M. C, Vanzee, J. P,
530 Verjovski-Almeida, S, Werner, D, White, O, Wyder, S, Zeng, Q, Zhao, Q, Zhao,
531 Y, Hill, C. A, Raikhel, A. S, Soares, M. B, Knudson, D. L, Lee, N. H, Galagan,
532 J, Salzberg, S. L, Paulsen, I. T, Dimopoulos, G, Collins, F. H, Birren, B, Fraser-
533 Liggett, C. M, & Severson, D. W. (2007) Genome sequence of *Aedes aegypti*, a
534 major arbovirus vector. *Science* **316**, 1718–1723.
- 535 6. Timoshevskiy, V. A, Severson, D. W, Debruyne, B. S, Black, W. C, Sharakhov, I. V,
536 & Sharakhova, M. V. (2013) An integrated linkage, chromosome, and genome
537 map for the yellow fever mosquito *Aedes aegypti*. *PLoS Neglected Tropical*
538 *Diseases* **7**, e2052.
- 539 7. Timoshevskiy, V. A, Kinney, N. A, Debruyne, B. S, Mao, C, Tu, Z, Severson, D. W,
540 Sharakhov, I. V, & Sharakhova, M. V. (2014) Genomic composition and evolution
541 of *Aedes aegypti* chromosomes revealed by the analysis of physically mapped
542 supercontigs. *BMC Biology* **12**, 27.
- 543 8. Juneja, P, Osei-Poku, J, Ho, Y. S, Ariani, C. V, Palmer, W. J, Pain, A, & Jiggins,
544 F. M. (2014) Assembly of the Genome of the Disease Vector *Aedes aegypti* onto
545 a Genetic Linkage Map Allows Mapping of Genes Affecting Disease Transmission.
546 *PLoS Neglected Tropical Diseases* **8**, e2652.
- 547 9. Coates, C. J, Jasinskiene, N, Miyashiro, L, & James, A. A. (1998) Mariner
548 transposition and transformation of the yellow fever mosquito, *Aedes aegypti*.
549 *Proceedings of the National Academy of Sciences of the United States of America*
550 **95**, 3748–3751.

- 551 10. Lobo, N. F, Hua-Van, A, Li, X, Nolen, B. M, & Fraser, M. J. (2002) Germ
552 line transformation of the yellow fever mosquito, *Aedes aegypti*, mediated by
553 transpositional insertion of a piggyBac vector. *Insect Molecular Biology* **11**,
554 133–139.
- 555 11. Liesch, J, Bellani, L. L, & Vosshall, L. B. (2013) Functional and genetic charac-
556 terization of neuropeptide Y-like receptors in *Aedes aegypti*. *PLoS Neglected*
557 *Tropical Diseases* **7**, e2486.
- 558 12. DeGennaro, M, McBride, C. S, Seeholzer, L, Nakagawa, T, Dennis, E. J, Goldman,
559 C, Jasinskiene, N, James, A. A, & Vosshall, L. B. (2013) orco mutant mosquitoes
560 lose strong preference for humans and are not repelled by volatile DEET. *Nature*
561 **498**, 487–491.
- 562 13. Aryan, A, Anderson, M. A. E, Myles, K. M, & Adelman, Z. N. (2013) TALEN-based
563 gene disruption in the dengue vector *Aedes aegypti*. *PLoS ONE* **8**, e60082.
- 564 14. Aryan, A, Myles, K. M, & Adelman, Z. N. (2014) Targeted genome editing in
565 *Aedes aegypti* using TALENs. *Methods* **69**, 38–45.
- 566 15. Aryan, A, Anderson, M. A. E, Myles, K. M, & Adelman, Z. N. (2013) Germline
567 excision of transgenes in *Aedes aegypti* by homing endonucleases. *Scientific*
568 *Reports* **3**, 1603.
- 569 16. Carroll, D. (2014) Genome Engineering with Targetable Nucleases. *Annual*
570 *Review of Biochemistry* **83**, 409–439.
- 571 17. Stoddard, B. L. (2014) Homing endonucleases from mobile group I introns:
572 discovery to genome engineering. *Mobile DNA* **5**, 7.

- 573 18. Peng, Y, Clark, K. J, Campbell, J. M, Panetta, M. R, Guo, Y, & Ekker, S. C. (2014)
574 Making designer mutants in model organisms. *Development* **141**, 4042–4054.
- 575 19. Bassett, A. R, Tibbit, C, Ponting, C. P, & Liu, J.-L. (2013) Highly efficient targeted
576 mutagenesis of *Drosophila* with the CRISPR/Cas9 system. *Cell Reports* **4**,
577 220–228.
- 578 20. Hwang, W. Y, Fu, Y, Reyon, D, Maeder, M. L, Tsai, S. Q, Sander, J. D, Peterson,
579 R. T, Yeh, J.-R. J, & Joung, J. K. (2013) Efficient genome editing in zebrafish
580 using a CRISPR-Cas system. *Nature Biotechnology* **31**, 227–229.
- 581 21. Lobo, N. F, Clayton, J. R, Fraser, M. J, Kafatos, F. C, & Collins, F. H. (2006)
582 High efficiency germ-line transformation of mosquitoes. *Nature Protocols* **1**,
583 1312–1317.
- 584 22. Holleley, C & Sutcliffe, A. (2012) *Methods in Anopheles Research*, Chapter 3.12.
585 (Centers for Disease Control).
- 586 23. Wu, T. D & Nacu, S. (2010) Fast and SNP-tolerant detection of complex variants
587 and splicing in short reads. *Bioinformatics* **26**, 873–881.
- 588 24. DePristo, M. A, Banks, E, Poplin, R, Garimella, K. V, Maguire, J. R, Hartl, C,
589 Philippakis, A. A, del Angel, G, Rivas, M. A, Hanna, M, McKenna, A, Fennell,
590 T. J, Kernytzky, A. M, Sivachenko, A. Y, Cibulskis, K, Gabriel, S. B, Altshuler, D,
591 & Daly, M. J. (2011) A framework for variation discovery and genotyping using
592 next-generation DNA sequencing data. *Nature Genetics* **43**, 491–498.
- 593 25. Reyon, D, Tsai, S. Q, Khayter, C, Foden, J. A, Sander, J. D, & Joung, J. K.
594 (2012) FLASH assembly of TALENs for high-throughput genome editing. *Nature*
595 *Biotechnology* **30**, 460–465.

- 596 26. Dahlem, T. J, Hoshijima, K, Juryneć, M. J, Gunther, D, Starker, C. G, Locke, A. S,
597 Weis, A. M, Voytas, D. F, & Grunwald, D. J. (2012) Simple methods for generating
598 and detecting locus-specific mutations induced with TALENs in the zebrafish
599 genome. *PLoS Genetics* **8**, e1002861.
- 600 27. Brinkman, E. K, Chen, T, Amendola, M, & van Steensel, B. (2014) Easy quantita-
601 tive assessment of genome editing by sequence trace decomposition. *Nucleic
602 Acids Research* **42**, e168.
- 603 28. Gagnon, J. A, Valen, E, Thyme, S. B, Huang, P, Ahkmetova, L, Pauli, A, Montague,
604 T. G, Zimmerman, S, Richter, C, & Schier, A. F. (2014) Efficient Mutagenesis by
605 Cas9 Protein-Mediated Oligonucleotide Insertion and Large-Scale Assessment
606 of Single-Guide RNAs. *PLoS ONE* **9**, e98186.
- 607 29. Anderson, M. A. E, Gross, T. L, Myles, K. M, & Adelman, Z. N. (2010) Validation
608 of novel promoter sequences derived from two endogenous ubiquitin genes in
609 transgenic *Aedes aegypti*. *Insect Molecular Biology* **19**, 441–449.
- 610 30. Fu, Y, Sander, J. D, Reyon, D, Cascio, V. M, & Joung, J. K. (2014) Improving
611 CRISPR-Cas nuclease specificity using truncated guide RNAs. *Nature Biotech-
612 nology* **32**, 279–284.
- 613 31. Liu, L, Li, Y, Wang, R, Yin, C, Dong, Q, Hing, H, Kim, C, & Welsh, M. J. (2007)
614 *Drosophila* hygrosensation requires the TRP channels water witch and nanchung.
615 *Nature* **450**, 294–298.
- 616 32. Ren, X, Sun, J, Housden, B. E, Hu, Y, Roesel, C, Lin, S, Liu, L.-P, Yang, Z,
617 Mao, D, Sun, L, Wu, Q, Ji, J.-Y, Xi, J, Mohr, S. E, Xu, J, Perrimon, N, & Ni, J.-Q.
618 (2013) Optimized gene editing technology for *Drosophila melanogaster* using

- 619 germ line-specific Cas9. *Proceedings of the National Academy of Sciences of*
620 *the United States of America* **110**, 19012–19017.
- 621 33. Jinek, M, Jiang, F, Taylor, D. W, Sternberg, S. H, Kaya, E, Ma, E, Anders, C,
622 Hauer, M, Zhou, K, Lin, S, Kaplan, M, Iavarone, A. T, Charpentier, E, Nogales, E,
623 & Doudna, J. A. (2014) Structures of Cas9 endonucleases reveal RNA-mediated
624 conformational activation. *Science* **343**, 1247997.
- 625 34. Ren, X, Yang, Z, Xu, J, Sun, J, Mao, D, Hu, Y, Yang, S.-J, Qiao, H.-H, Wang, X,
626 Hu, Q, Deng, P, Liu, L.-P, Ji, J.-Y, Li, J. B, & Ni, J.-Q. (2014) Enhanced Specificity
627 and Efficiency of the CRISPR/Cas9 System with Optimized sgRNA Parameters
628 in *Drosophila*. *Cell Reports* **9**, 1151–1162.
- 629 35. Wu, X, Scott, D. A, Kriz, A. J, Chiu, A. C, Hsu, P. D, Dadon, D. B, Cheng, A. W,
630 Trevino, A. E, Konermann, S, Chen, S, Jaenisch, R, Zhang, F, & Sharp, P. A.
631 (2014) Genome-wide binding of the CRISPR endonuclease Cas9 in mammalian
632 cells. *Nature Biotechnology* **32**, 670–676.
- 633 36. Hsu, P. D, Scott, D. A, Weinstein, J. A, Ran, F. A, Konermann, S, Agarwala, V, Li,
634 Y, Fine, E. J, Wu, X, Shalem, O, Cradick, T. J, Marraffini, L. A, Bao, G, & Zhang,
635 F. (2013) DNA targeting specificity of RNA-guided Cas9 nucleases. *Nature*
636 *Biotechnology* **31**, 827–832.
- 637 37. Sander, J. D, Maeder, M. L, Reyon, D, Voytas, D. F, Joung, J. K, & Dobbs, D.
638 (2010) ZiFiT (Zinc Finger Targeter): an updated zinc finger engineering tool.
639 *Nucleic Acids Research* **38**, W462–8.
- 640 38. Mali, P, Aach, J, Stranges, P. B, Esvelt, K. M, Moosburner, M, Kosuri, S, Yang,
641 L, & Church, G. M. (2013) CAS9 transcriptional activators for target specificity

- 642 screening and paired nickases for cooperative genome engineering. *Nature*
643 *Biotechnology* **31**, 833–838.
- 644 39. Ren, X, Yang, Z, Mao, D, Chang, Z, Qiao, H.-H, Wang, X, Sun, J, Hu, Q, Cui,
645 Y, Liu, L.-P, Ji, J.-Y, Xu, J, & Ni, J.-Q. (2014) Performance of the Cas9 nickase
646 system in *Drosophila melanogaster*. *G3* **4**, 1955–1962.
- 647 40. Ran, F. A, Hsu, P. D, Lin, C.-Y, Gootenberg, J. S, Konermann, S, Trevino, A. E,
648 Scott, D. A, Inoue, A, Matoba, S, Zhang, Y, & Zhang, F. (2013) Double Nicking by
649 RNA-Guided CRISPR Cas9 for Enhanced Genome Editing Specificity. *Cell* **154**,
650 1380–1389.
- 651 41. Shen, B, Zhang, W, Zhang, J, Zhou, J, Wang, J, Chen, L, Wang, L, Hodgkins,
652 A, Iyer, V, Huang, X, & Skarnes, W. C. (2014) Efficient genome modification
653 by CRISPR-Cas9 nickase with minimal off-target effects. *Nature Methods* **11**,
654 399–402.
- 655 42. Tsai, S. Q, Wyvekens, N, Khayter, C, Foden, J. A, Thapar, V, Reyon, D, Goodwin,
656 M. J, Aryee, M. J, & Joung, J. K. (2014) Dimeric CRISPR RNA-guided FokI
657 nucleases for highly specific genome editing. *Nature Biotechnology* **32**, 569–576.
- 658 43. Guilinger, J. P, Thompson, D. B, & Liu, D. R. (2014) Fusion of catalytically inactive
659 Cas9 to FokI nuclease improves the specificity of genome modification. *Nature*
660 *Biotechnology* **32**, 577–582.
- 661 44. Gratz, S. J, Ukken, F. P, Rubinstein, C. D, Thiede, G, Donohue, L. K, Cummings,
662 A. M, & O'Connor-Giles, K. M. (2014) Highly specific and efficient CRISPR/Cas9-
663 catalyzed homology-directed repair in *Drosophila*. *Genetics* **196**, 961–971.

- 664 45. Beumer, K. J, Trautman, J. K, Mukherjee, K, & Carroll, D. (2013) Donor DNA
665 Utilization during Gene Targeting with Zinc-finger Nucleases. *G3* **3**, 657–664.
- 666 46. Beumer, K. J, Trautman, J. K, Christian, M, Dahlem, T. J, Lake, C. M, Hawley,
667 R. S, Grunwald, D. J, Voytas, D. F, & Carroll, D. (2013) Comparing zinc finger
668 nucleases and transcription activator-like effector nucleases for gene targeting in
669 *Drosophila*. *G3* **3**, 1717–1725.
- 670 47. Maresca, M, Lin, V. G, Guo, N, & Yang, Y. (2013) Obligate ligation-gated recom-
671 bination (ObLiGaRe): custom-designed nuclease-mediated targeted integration
672 through nonhomologous end joining. *Genome Research* **23**, 539–546.
- 673 48. Auer, T. O, Duroure, K, De Cian, A, Concordet, J.-P, & Del Bene, F. (2014) Highly
674 efficient CRISPR/Cas9-mediated knock-in in zebrafish by homology-independent
675 DNA repair. *Genome Research* **24**, 142–153.
- 676 49. Alphey, L. (2014) Genetic control of mosquitoes. *Annual Review of Entomology*
677 **59**, 205–224.

678 **Tables and Figures**

Table 1. Sequences of sgRNAs used in this study. Potential off-target sites were evaluated by two publicly available tools. ZiFIT (<http://zifit.partners.org>) was used to determine the number of potential off-target sites in the *Ae. aegypti* genome with 3 or fewer mismatched bases (mm). The number of distinct sites with the given number of mismatches is noted in parentheses. The CRISPR Design Tool (<http://crispr.mit.edu>) uses an algorithm to evaluate potential off-target sites in the context of the *Ae. aegypti* genome and returns a specificity score for sgRNAs of length 20 bp. Scores above 50 are considered "high quality". * indicates sgRNA targets of 17-19bp that cannot be tested with the CRISPR Design Tool

sgRNA name	length	target sequence	PAM	ZiFit off-targets	CRISPR Design Tool score
AAEL000582-sgRNA1	17bp	GGTTGGCAGTTGAGTCC	CGG	2mm (3)	*
AAEL010779-sgRNA1	17bp	GGTGACGCGCCTTGGTT	CGG	2mm (1)	*
AAEL010779-sgRNA2	20 bp	GGCGGTGACGCGCCTTGGTT	CGG	3mm (1)	97
AAEL010779-sgRNA3	20 bp	GGAACTGACTATTTTCGTCT	CGG	3mm (6)	81
AAEL004091-sgRNA1	20 bp	GAAGTATTTAATTCCATGAA	TGG	3mm (5)	77
AAEL004091-sgRNA2	20 bp	GATAACCGTCGCTTCTGTCCG	TGG	3mm (1)	98
AAEL004091-sgRNA3	20 bp	GGTGGTGACGTTTTCATAT	CGG	3mm (1)	96
AAEL000926-sgRNA1	20 bp	GGTATTTTCGGGTGTCGCGAA	AGG	3mm (1)	96
AAEL000926-sgRNA2	20 bp	GGAACGCTCCAAGGTGCAGT	TGG	3mm (2)	94
AAEL000926-sgRNA3	20 bp	GGCAGAAGCCAAGTGCACCT	TGG	>3mm	95
AAEL000926-sgRNA4	19bp	GGCGTTGAATTTTAACT	TGG	3mm (8)	*
AAEL014228-sgRNA1	17bp	GGGCAAATCGTAACCGC	TGG	2mm (5)	*
AAEL014228-sgRNA2	20 bp	GGATGACTTAACTTTAGTTT	CGG	2mm (1)	83
AAEL014228-sgRNA3	20 bp	GGAGTAGCGTTATACTATTG	TGG	>3mm	96
AAEL002575-sgRNA1	20 bp	GGCGCGAAAATCCTCCTGAT	TGG	>3mm	97
AAEL002575-sgRNA2	20 bp	GGGCGAACGTTTCCACGATG	AGG	>3mm	94
AAEL002575-sgRNA3	20 bp	GGAAGGGAACGTACTTGATG	GGG	3mm (3)	89
AAEL013647-sgRNA1	20 bp	GGCAAACCGTGGCTGCCGGT	CGG	3mm (1)	93
AAEL013647-sgRNA2	20 bp	GGAATCCTCGGTGCATGGTT	TGG	3mm (1)	96
AAEL013647-sgRNA3	20 bp	GACAACAGGTGAGAAATTCAC	TGG	>3mm	97
wtrw-sgRNA1	20 bp	GGATTTGTTAGAGAGCCTAC	TGG	3mm (1)	94

Table 2. PCR primer sequences used in this study

primer name	sequence (5' - 3')
sgRNA-R	AAAAGCACCGACTCGGTGCCACTTTTTCAAGTTGATAACGGACTAGCCTATTTTAACTT-GCTATTCTAGCTCTAAAAC
sgRNA-F	GAAATTAATACGACTCACTATA - sgRNA target sequence - GTTTTAGAGCTAGAAATAGC
AAEL000582-1-F-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGTACAAGTACAGCATGTTCCG
AAEL000582-1-R-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGGTTTCTGGCGTCCATTCAATC
AAEL010779-12-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGGTAGCAATGTCGGTAGTATGGTAGT
AAEL010779-12-R12-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCTACCACAGCCTAGTATGTTTCATCA
AAEL010779-3-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGGTTGCTAACTACCATACTACCG
AAEL010779-3-R1-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGGATTCAAGGAAAACGCATCG
AAEL004091-1-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGGTCGTTCTGCTGGATTGAAAAG
AAEL004091-1-R1F2-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGGTGCAACTTTGAGAATACAGCACATTC
AAEL004091-2-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGCACAAATAGTGCAGCTGACTCGCGTTC
AAEL004091-2-R1-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGTACTTCTCATAGATGGTGCGCCTTTTAC
AAEL004091-3-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGGAATGTGCTGTATTCTCAAAGTTGCAC
AAEL004091-3-R1-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGGTAAGTACTTCTCGTTGAAACTCACAAATC
AAEL000926-1-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGCTTCTGCCGGAGCGAAGGATTTGTTTC
AAEL000926-1-R1-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGGAACTCACAAATCACCAGGTTTGTATC
AAEL000926-23-F13R2-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGCCTACGGCGTTGAATTTTTAATCTTGG
AAEL000926-23-R1-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCGAACTATTGCTACAGTATCCAGGAAC
AAEL014228-12-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGCGCGATCCTATCATTATTAGTTTCGACC
AAEL014228-12-R2-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCGCACACTGGAGAATAGAAAATGATC
AAEL014228-3-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGGTCGAAACTAATAATGATAGGATCGCG
AAEL014228-3-R1-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCAGTGCAAACCAACTGTTGATTGAAC
AAEL002575-1-F2-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGTAAGAAGATCGCGTAACGCCGATACAG
AAEL002575-1-R2-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCCGGTGGAAAATTTATAAATCGCAAG
AAEL002575-2-F12-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGGTGATCAGGGGGTTAGACGTGAAAC
AAEL002575-2-R2-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCCTATGCCATCTTCCACCCATTTCTAG
AAEL002575-3-F2-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGGCGGGCAAGTTCTTCGGCGTAGTGC
AAEL002575-3-R2-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCAGATTGATGTGGCTGATCCTCATC
AAEL013647-1-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGCAACGCAGAAACACTCTTTACATACTTC
AAEL013647-1-R1-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCAACCCTCAGAAGGCAAAAGTTTAAATC
AAEL013647-2-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGCAACCCTCAGAAGGCAAAAGTTTAAATC
AAEL013647-2-R1-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGTAGACAAACCCGTACGAGAAGTAAATAG
AAEL013647-3-F1-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGCTTTGGCCAATATTGATATGCTGGAAG
AAEL013647-3-R1-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGCTACTGTTGTAAGTTATCCCGTATGTTG
wtrw-1-F-miseq	TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGCGACTATCATCAGGAAGAC
wtrw-1-R-miseq	GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGAATCTATGGCATTGACCGTACC
wtrw-1-F-BamHI	GACAAAGATCAAACCCACAAGTTCCG
wtrw-1-R-BamHI	GTAATAAATTCACACACTCGACGTTCCC
AAEL010779-deletion-F	CTACCACAGCCTAGTATGTTTCATCA
AAEL010779-deletion-R	TTCATCGTGCCATTGCTCG
AAEL000926-deletion-F	CCGTGCTTTGCGGAGTTGAGCC
AAEL000926-deletion-R	CTTCCCACCGACAGGACAAACACCAC
AAEL014228-deletion-F	CGCACACTGGAGAATAGAAAATGATC
AAEL014228-deletion-R	CAGTGCAAACCAACTGTTGATTGAAC
AAEL002575-deletion-F	CGCAAGAAAACCGACATTGAAGTTG
AAEL002575-deletion-R	CTTGCGGGCAAGTTCTTCGGCGTAG
AAEL000582-ECFP-Larm-F	GTGAGGGTGGTGTGCAATTAACCTTT
AAEL000582-ECFP-Larm-R	CAAGTGACGTCAACCCTTCTAAATCG
AAEL000582-ECFP-Rarm-F	CTGTACAAGAGATCTCGACCCAAGAA
AAEL000582-ECFP-Rarm-R	CCAGCTCAAAGTCCAAAACGAAACC
AAEL000582-ECFP-both-F	GTGAGGGTGGTGTGCAATTAACCTTT
AAEL000582-ECFP-both-R	GTTAGGTCAGAGGTATCCCTGAACAT

Figure 1.pdf

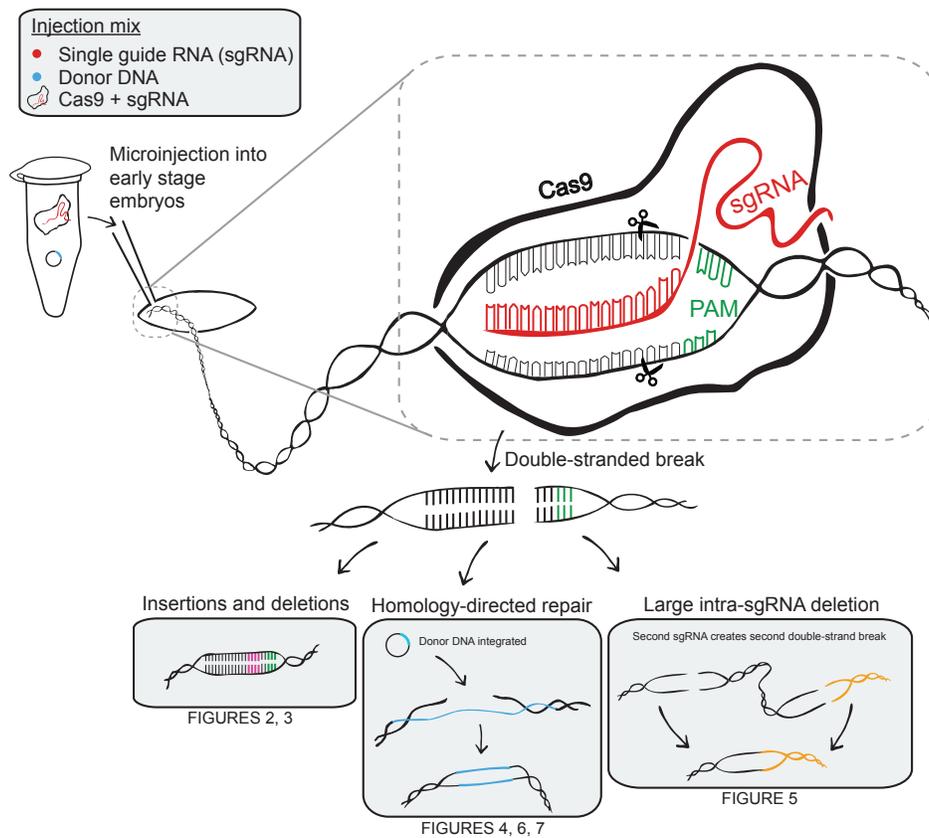


Figure 1. CRISPR-Cas9 genome-engineering system as adapted to the mosquito *Ae. aegypti*.

An sgRNA, donor DNA, and the nuclease Cas9 are microinjected into *Ae. aegypti* embryos. A 17-20 bp sequence of the sgRNA binds to the complementary site in the genome, targeting Cas9 and generating a double-stranded break. These breaks can be repaired in a number of ways, including the following: insertions or deletions resulting from error-prone non-homologous end-joining, insertion of exogenous DNA sequences through homology-directed repair, and generating large deletions between multiple sgRNA/Cas9 double-stranded breaks.

Figure 2.pdf

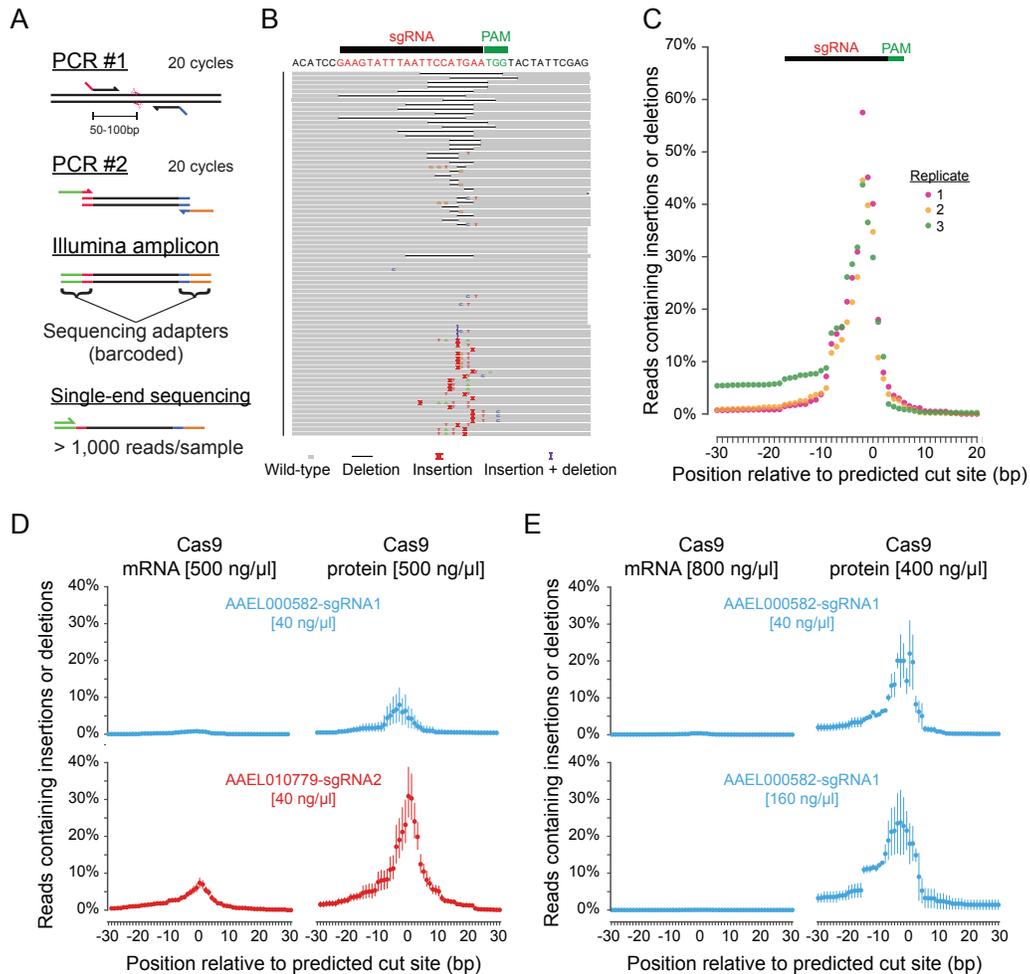


Figure 2. Deep sequencing approach to quantifying CRISPR-Cas9 efficiency

A) Schematic of strategy to generate barcoded PCR amplicons for sequencing. In this example (B-C) amplicons were generated from adults reared from embryos injected with Cas9 and an sgRNA (AAEL004091-sgRNA1) using primers AAEL004091-1-F and AAEL004091-1-R. **B**) Visualization of a subset of alignments to the amplicon reference sequence (top) reveals a heterogeneity of insertions, deletions, and other changes. **C**) Quantification of three replicate libraries, plotted as a percentage of reads aligned to a given base that contain an insertion or deletion at that base, shows reproducibility of mutation rates between individual pools of pupae derived from the same injection. Data are represented as a percentage of reads aligned to a given base that contain an insertion or deletion at that base, and is plotted as mean (circle) and 95% confidence intervals (line). **D**) Summary of sequencing data from animals injected with two different sgRNAs in combination with Cas9 mRNA (left) or Cas9 recombinant protein (right), both at 500 ng/μL. **E**) Increasing Cas9 mRNA concentration to 800 ng/μL (left) did not improve cut rate in conjunction with an sgRNA at 40 or 160 ng/μL. Reducing Cas9 protein concentration to 400 ng/μL (right) increased insertion or deletion rate slightly when combined with an sgRNA at 40 ng/μL. Increasing sgRNA concentration to 160 ng/μL did not dramatically affect the insertion or deletion rate.

Figure 3.pdf

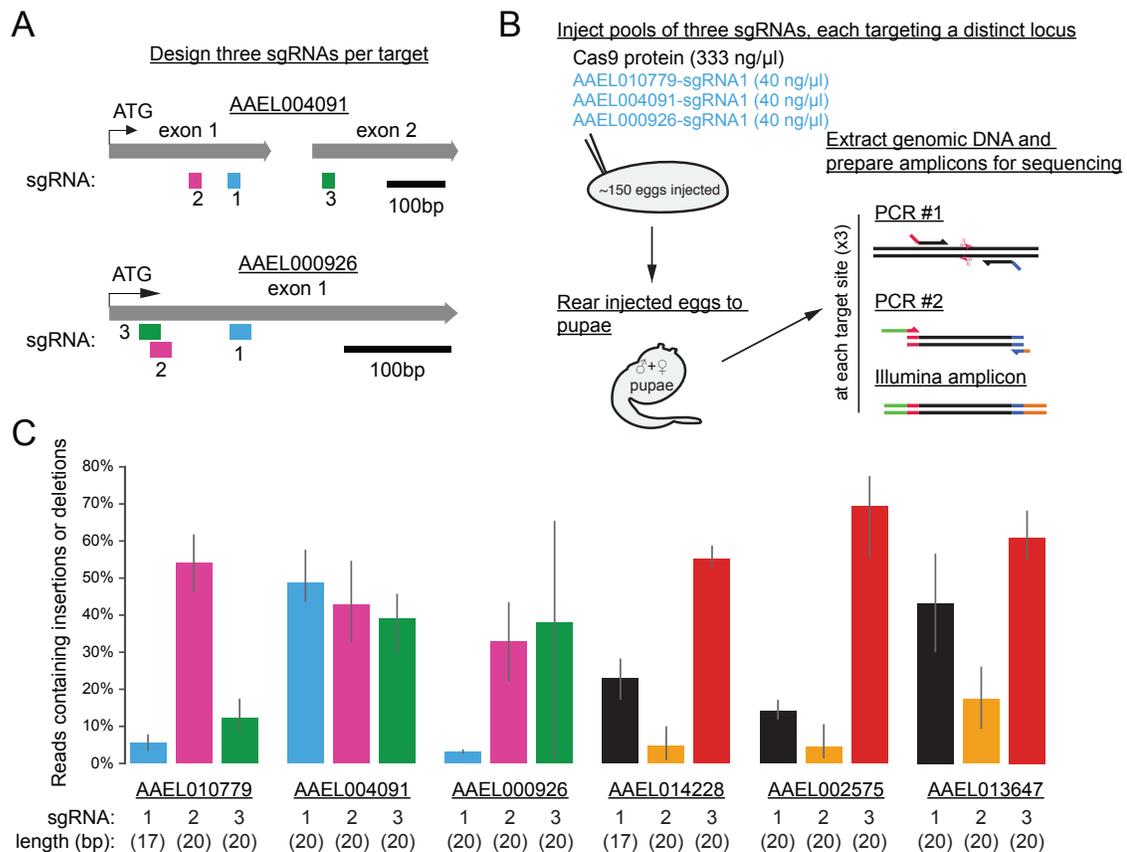


Figure 3. Identifying active sgRNAs

A) Schematic of two target genes in the *Ae. aegypti* genome: AAEL004091 and AAEL000926. Three sgRNAs were designed against the first 500 bp of each gene. **B)** Schematic of the workflow for a small injection (approx. 150 embryos) of Cas9 protein and a pool of three sgRNAs against three distinct target genes. After rearing to pupal stages to synchronize developmental time, genomic DNA was extracted and sequencing amplicons were prepared against each of the three targets. **C)** Sequencing results from 6 small injections (sgRNA sequences can be found in Table 1).

Figure 4.pdf

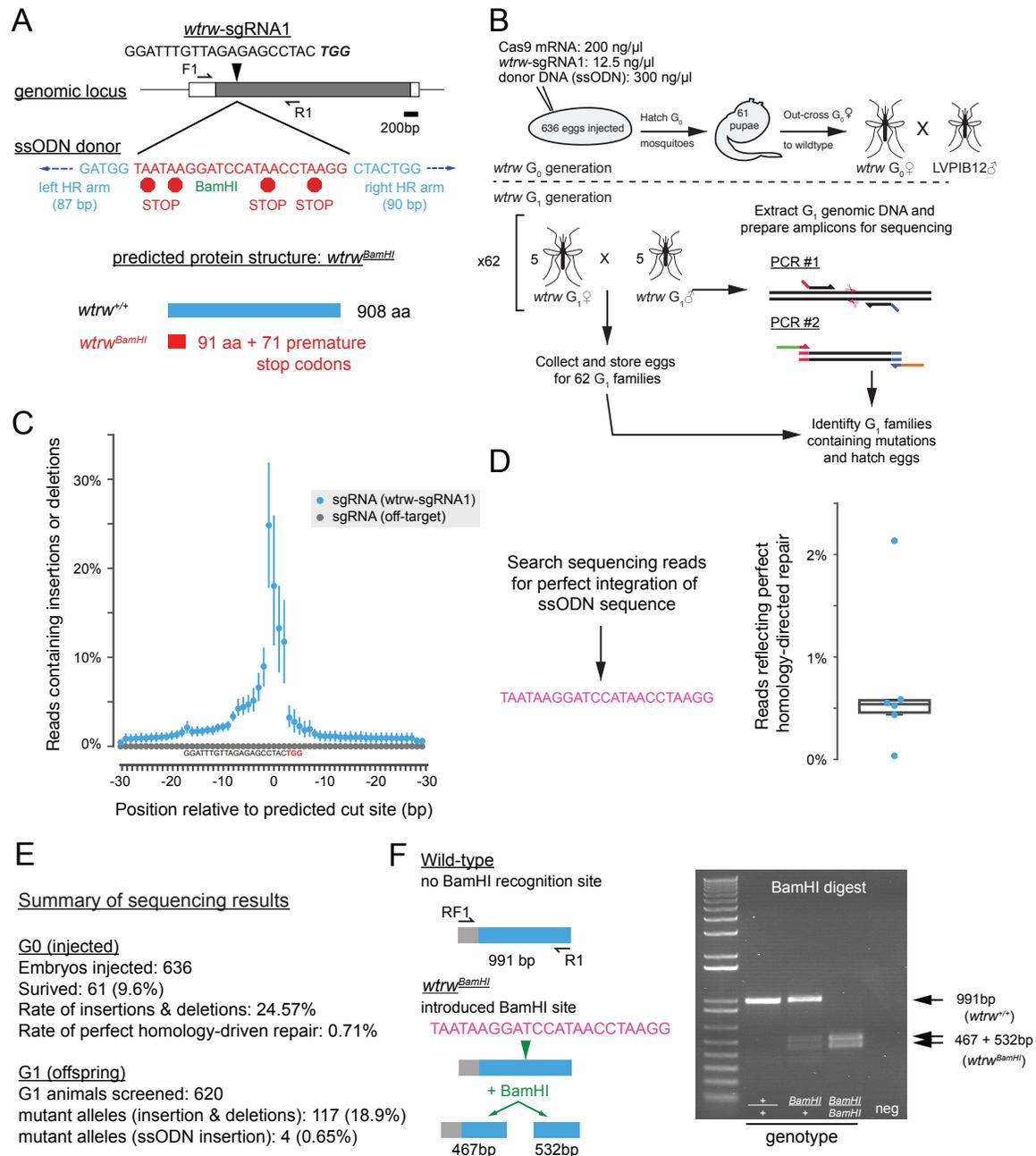


Figure 4. Germ-line transmission of mutant alleles

A) Schematic of the *Ae. aegypti* *wtrw* locus detailing the sgRNA binding site *wtrw*-sgRNA1, the sequence of a 200 bp single-stranded oligonucleotide (ssODN) donor, and the predicted protein structure of a successfully modified locus. **B)** Schematic of injection performed to isolate mutations. Sequencing libraries were generated from both G₀ and G₁ animals after egg-laying. **C)** Summary sequencing data from G₀ adults reveals robust levels of insertion and deletion in injections of *wtrw*-sgRNA1 and Cas9 mRNA. **D)** Exogenous ssODN sequence used as a query for the unix tool grep to identify sequencing reads containing perfect homology-directed repair. A mean of 0.71% of reads contained this insertion. **E)** Summary statistics of sequencing reads from G₀ and G₁ individuals. **F)** Wild-type amplicons contain no BamHI recognition site while mutant alleles are cut into bands of 467 and 532 bp.

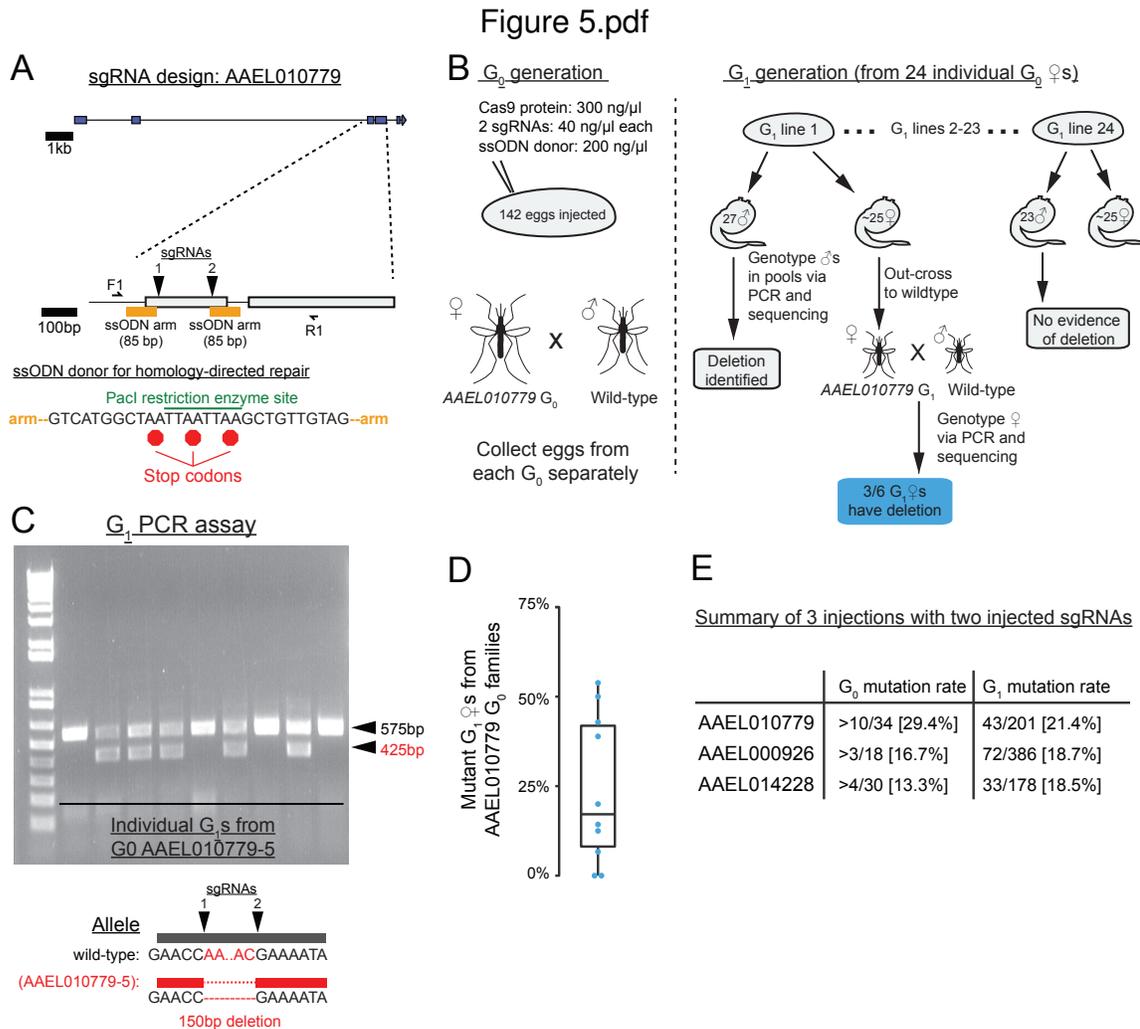


Figure 5. Deletions generated by multiple sgRNAs

A) Schematic of the AAEL010779 genomic locus detailing the design of two sgRNAs and a ssODN donor. **B)** Injection strategy to identify deletion events in G₁ animals with the injection of a small (125-150) number of embryos. **C)** Example agarose gel of 9 G₁ females that are the offspring of a single G₀ female. All individuals contain the wild-type band (black arrowhead). Sanger sequencing verified that the smaller band (red arrowhead) present in 5/9 heterozygous individuals is the result of a clean deletion between the two sgRNA cut sites. **D)** Plot of the proportion of mutant AAEL010779 G₁ females from the 10 G₀ families identified as containing at least one mutant allele. **E)** Summary data from 3 injections of this type show high rates of G₁ mutagenesis across all 3 injections.

Figure 6.pdf

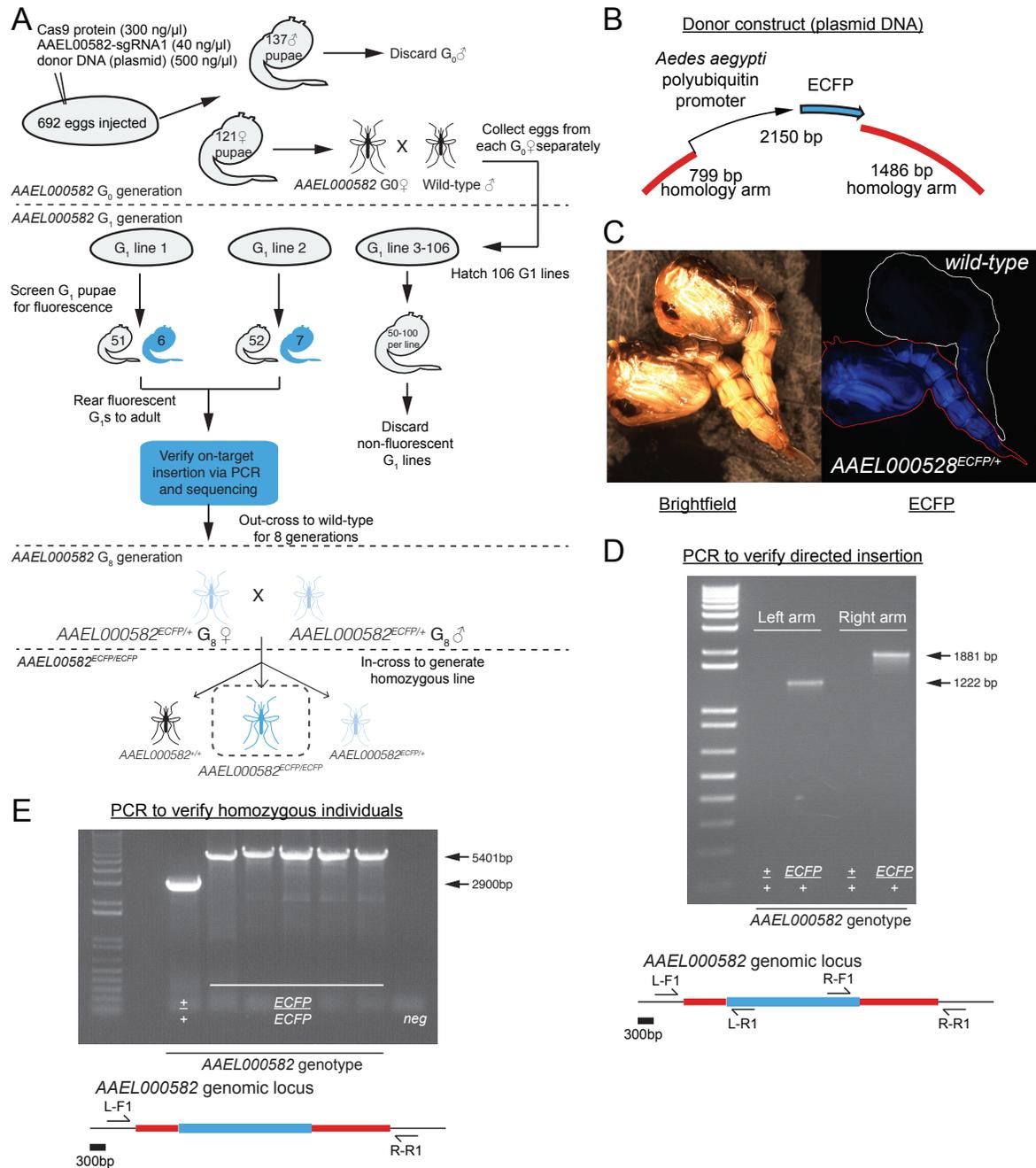


Figure 6. Insertion of fluorescent cassettes by homology-directed repair

A) Schematic of injection and screening strategy to obtain alleles with an insertion of a fluorescent cassette. Blue pupae represent animals with ECFP expression. **B)** Design of the plasmid donor with homology arms of 799 and 1486 bp surrounding a 2150 bp payload of the PUB promoter driving ubiquitous expression of EFCP. **C)** Brightfield and ECFP fluorescence images of two pupae: wild-type (top) and AAEL00582ECFP/+ (bottom). PUB-ECFP is clearly visible in both larval and pupal stages. **D)** PCR strategy to verify directed insertion of the PUB-ECFP cassette. **E)** PCR strategy to identify homozygous individuals.

Figure 7.pdf

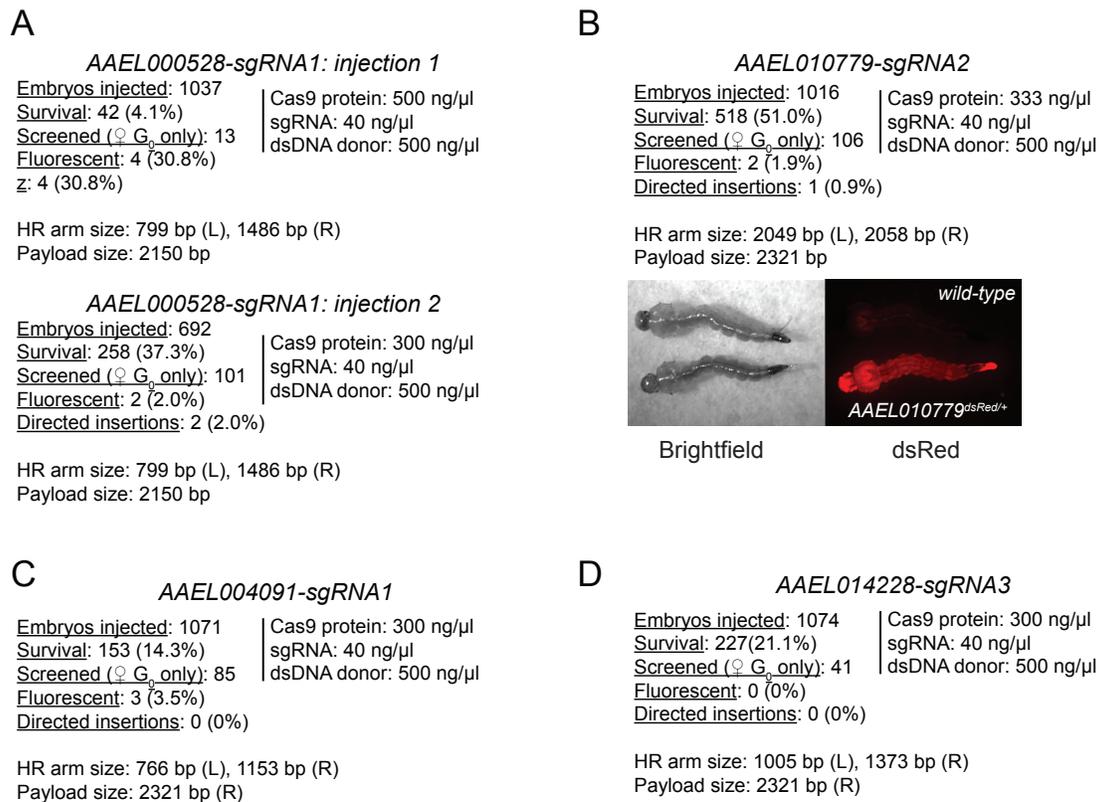


Figure 7. Summary of injections to insert fluorescent cassettes by homology-directed repair

Table of injection statistics for: **A)** Two successful injections to generate fluorescent insertions in AAEL000582. **B)** One successful injection to generate a fluorescent insertion in AAEL010779. At right, brightfield and dsRed images of a wild-type (top) and AAEL010779^{dsRed/+} larva (bottom). **C)** One unsuccessful injection attempt to generate a fluorescent insertion in AAEL004091. **D)** One unsuccessful injection attempt to generate a fluorescent insertion in AAEL014228.