Various applications of TALEN- and CRISPR/Cas9-mediated homologous recombination to modify the *Drosophila* genome

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ABSTRACT

Modifying the genomes of many organisms is becoming as easy as manipulating DNA in test tubes, which is made possible by two recently developed techniques based on either the customizable DNA binding protein, TALEN, or the CRISPR/Cas9 system. Here, we describe a series of efficient applications derived from these two technologies, in combination with various homologous donor DNA plasmids, to manipulate the *Drosophila* genome: (1) to precisely generate genomic deletions; (2) to make genomic replacement of a DNA fragment at single nucleotide resolution; and (3) to generate precise insertions to tag target proteins for tracing their endogenous expressions. For more convenient genomic manipulations, we established an easy-to-screen platform by knocking in a white marker through homologous recombination. Further, we provided a strategy to remove the unwanted duplications generated during the “ends-in” recombination process. Our results also indicate that TALEN and CRISPR/Cas9 had comparable efficiency in mediating genomic modifications through HDR (homology-directed repair); either TALEN or the CRISPR/Cas9 system could efficiently mediate in vivo replacement of DNA fragments of up to 5 kb in *Drosophila*, providing an ideal genetic tool for functional annotations of the *Drosophila* genome.

KEY WORDS: *Drosophila*, TALEN, CRISPR/Cas9, Homologous recombination, Targeted genomic modification

INTRODUCTION

In the past two years, geneticists and molecular biologists have realized the emergence of two fascinating genetic manipulation techniques, which have been shown to be applicable in essentially all animals and plants. The earlier method is based on an arbitrary transcription activator-like effector nuclease (TALEN) system (Cermak et al., 2011; Huang et al., 2011; Liu et al., 2012; Cheng et al., 2013; Friedland et al., 2013; Li et al., 2013; Sung et al., 2013; Wang et al., 2013; Yu et al., 2013a). A pair of customizable TALENs needs to be designed for a particular genomic locus that is designated for modifications (Miller et al., 2011; Zhang et al., 2011). Very recently, another method has been quickly adapted for genomic modifications in many organisms (Friedland et al., 2013; Li et al., 2013; Wang et al., 2013; Yu et al., 2013a), which is based on the Cas9 nuclease and a single guide RNA (gRNA) from the type II bacterial clusters of regularly interspaced short palindromic repeats (CRISPR) system (Jinek et al., 2012). Both of these methods rely on a nuclease, FokI or Cas9, to cut the genomic DNAs, which triggers the cellular repair pathways of double strand DNA breaks (DSBs) via either non-homologous end joining (NHEJ) or homology-directed repair (HDR). The targeted DNA binding specificity is determined by TALE repeats through protein–DNA contact in TALEN-mediated genetic modifications, whereas in the case of a CRISPR/Cas9 system, the specificity is determined by the gRNA binding through RNA–DNA contact (Miller et al., 2011; Zhang et al., 2011; Jinek et al., 2012).

In *Drosophila*, our previous studies and work from other fly labs have successfully established both TALEN and CRISPR/Cas9 techniques in manipulating the fly genome (Liu et al., 2012; Bassett et al., 2013; Gratz et al., 2013; Yu et al., 2013a). Most of these studies have focused on generating indels (insertions and/or deletions) at specific loci, while a few labs have very recently reported HDR mediated genome modifications by either the TALEN (Katsuyama et al., 2013) or CRISPR/Cas9 system (Baena-Lopez et al., 2013; Gratz et al., 2013). The size of indels is not controllable with standard TALEN/Cas9 methods through the NHEJ pathway, and can vary from one nucleotide to over hundreds of base pairs (Huang et al., 2011; Yu et al., 2013a). Although sufficient for generating mutations of a gene, unpredictable sizes of indels are not appropriate for making precise deletions and insertions or making replacement with designed mutations across the genome; modifications that are more useful for *in vivo* functional studies. These goals can be achieved only through the HDR pathway by addition of a homologous donor sequence while injecting either TALEN or CRISPR/Cas9 RNAs.

In this paper, we report a series of efficient applications derived from HDR-mediated genomic modifications by TALEN and CRISPR/Cas9 in manipulating the *Drosophila* genome to precisely: (1) generate deletions of the micro RNAs, specifically, *mir-281*; (2) make genomic replacement of endogenous sequences of *CG4221*, *chameau* and *CG5961* genes with exogenous *loxP* sites or restriction enzyme cutting sites of...
Smal and HindIII, respectively; and (3) insert coding sequences of GFP and Myc to tag the Chameau and CG4221 proteins for tracing their endogenous expressions. We also established an easy-to-screen platform for more convenient genome-wide genetic manipulations and provided a strategy to remove, if necessary, unwanted duplications generated during the “ends-in” recombination process. Comparing with what has been reported very recently in the literature (Gratz et al., 2013), we achieved a much higher efficiency of HDR by using Lig4 mutant flies as recipients for injection; we directly inject DNA plasmids instead of single-strand oligonucleotides, thus our approach is more practical for donor preparation, especially when longer homologous sequences are needed.

RESULTS

TALEN-mediated precise mutagenesis via the HDR pathway

The first application we sought for exploring TALEN and CRISPR/Cas9 induced HDR in Drosophila was to generate precise mutagenesis in the genome. To achieve this purpose, we took advantage of Ligase4 mutant (Lig4^{469}) embryos for microinjection, because loss of function of the Ligase4 gene blocks NHEJ mediated double strand break (DSB) repair and thus promotes the HDR pathway (Beumer et al., 2008; Bozats et al., 2009; Beumer et al., 2013). HDR induced precise mutagenesis is particularly useful for generating null mutations of microRNAs and other non-coding RNAs, and for those genes with multiple splicing isoforms. Here, for the TALEN-mediated HDR mutagenesis, we selected two Drosophila genomic loci, miR-281 and chameau. miR-281 consists of two adjacent miRNAs, pre-miR-281-1 and pre-miR-281-2 (Xiong et al., 2009), the functions of which remain unknown. A mutant allele for the long isoform of chameau has been reported (Grienenberger et al., 2002), in which the short isoform seems to be not affected. We set out to generate a mutant allele that uncovers both the long and short isoforms of chameau in order to get a null mutant of the chameau gene.

In the case of miR-281, a pair of TALENs (see figure legends and supplementary material Table S1 for details) was designed to generate a DSB within the miR-281 loci (Fig. 1A). One pair of homologous arms (HAs) was selected from the flanking genomic regions of the miR-281 loci (as indicated by HA-L, 1.3 kb, and HA-R, 1.9 kb, in Fig. 1A; supplementary material Table S3) and cloned into the pBSK vector to generate the donor plasmid that will be used to mediate the HDR. We expected co-injection of the donor plasmid and the TALEN mRNAs for miR-281 into the Lig4^{469} embryos would precisely delete the genomic DNA segment of both miR-281-1 and miR-281-2. Indeed, three miR-281 deletion-yielding F0 flies were identified from 65 total F0 flies, and four F1 flies were obtained from a total of 520 F1 flies, as assayed by the positive PCR product yielded with the CG5961 primers that reside in the loxP site insertion were identified among 363 total F1 offspring from three independent F0 lines. Further sequencing was performed to confirm the precise replacement (supplementary material Fig. S2).

The statistics of both the precise deletion of miR-281 and precise DNA replacement in chameau are summarized in Table 1. Collectively, we have successfully generated two precise genomic modifications in Drosophila through TALEN induced DSBs and exogenous donor plasmids, which induced the HDR pathway. The frequency of yielding inheritable HDR modifications ranged from 0.8% to 1.4% in F1 flies, and the frequency of homologous recombination (HR) yielding F0 in total fertile F0 ranged from 4.6% to 5.8% in F0 flies.

CRISPR/Cas9-mediated precise mutagenesis via the HDR pathway

Our results described above indicate that the efficiency of TALEN-mediated HDR is relatively low as expected, significantly lower than the efficiency to generate TALEN-mediated indels (Liu et al., 2012). The CRISPR/Cas9 system has been shown to be more efficient than TALEN in mediating genomic indel mutations (Yang, L. et al., 2013). We wondered whether the CRISPR/Cas9 system would also be more efficient in mediating HDR in Drosophila. For this purpose, we chose two Drosophila genomic loci, CG4221 and CG5961, to conduct HR-mediated mutagenesis using the CRISPR/Cas9 system. No mutant alleles have been characterized thus far for either CG4221 or CG5961.

In the case of CG4221 mutagenesis, we used a loxP site to precisely replace the putative 0.12 kb F-box domain of CG4221 (Dui et al., 2012) (Fig. 1C; supplementary material Fig. S3), leading to a disruption of the gene’s coding function. The loxP site can be used for the removal of the unwanted “ends-in” recombination (see Results, last section). The donor plasmid that contains the HA-L (1.5 kb) and HA-R (1.3 kb) (Fig. 1C), and the designed Cas9 mRNA/sgRNA (Fig. 1C; supplementary material Table S2, Table S3), were co-injected into Lig4^{469} embryos to induce HDRs. Successful replacement was detected in 10 out of 230 F1 flies, as assayed by the positive PCR product yielded with primers that reside in the loxP site and the coding exon 2 (Fig. 1C,G; supplementary material Fig. S3; Table S4).

In the case of CG5961 mutagenesis, the strategy was similar to that used for chameau mutagenesis. A HindIII restriction site was designed between two homologous arms (HA-L, 1.3 kb, and HA-R, 1.4 kb) in the donor plasmid (Fig. 1D; supplementary material Fig. S4; Table S2, Table S3) to replace 40 bp of endogenous DNA in the first coding exon of CG5961. Successful replacement of the endogenous DNA with the HindIII site generated a 0.46 kb band that was amplified with two primers as indicated in Fig. 1D, from which two bands were yielded following HindIII enzyme digestion of the PCR products (Fig. 1H). Two mutant F1 flies that showed positive HindIII digestion were obtained from 52 F1 flies.

We have successfully targeted two genomic loci via the CRISPR/Cas9-induced HDR pathway. These results indicate the frequency of inheritable precise mutagenesis induced by CRISPR/Cas9-mediated HDR seems to be higher than that of
Fig. 1. TALEN- and CRISPR/Cas9-mediated precise genomic deletion and nucleotides replacement. (A,E) TALEN-mediated miR-281 deletion and molecular identification. (A) The pair of scissors indicates where the TALENs cut at the miR-281 locus. Dashed red line indicates the deleted genomic region (0.32 kb). (E) The genomic DNAs of two homozygous lines, 17-12 and 200-11, were used as PCR templates. Arrows in opposite directions indicate where the primers are located. The appearance of a 0.31 kb PCR product indicates successful deletion. (B,F) TALEN-mediated SmaI replacement at the chameau locus and molecular identification of positive events. (B) The pair of scissors indicates where the TALENs cut at the chameau locus. (F) Genomic DNAs of two heterozygous F1 lines, 24-1 and 24-6, were used to show PCR and positive SmaI digestion results. Arrows in opposite directions indicate where the primers used for PCR are located (B). PCR products were digested by SmaI; the two cleaved fragments, 0.29 kb and 0.2 kb, represent successful nucleotide replacements. (C,G) CRISPR/Cas9-mediated loxP replacement at the CG4221 locus and molecular characterization. (C) The scissors indicate where the CRISPR/Cas9 cleaves at the CG4221 locus. The empty pentagon box represents the loxP site. (G) Genomic DNAs of two heterozygous F1 lines, 23-1 and 23-7, were used for PCR examination. The primers are indicated by the two opposite arrows in panel C. The appearance of a 0.17 kb band indicates successful loxP replacement. (D,H) CRISPR/Cas9-mediated HindIII replacement at CG5961 and molecular characterization. (D) The scissors indicate where the CRISPR/Cas9 cleaves at the CG5961 locus. (H) Genomic DNAs of two homozygous F1 lines, 23-1 and 23-7, were used for PCR and following HindIII enzyme digestions. The primers for PCR are indicated by the two opposite arrows in panel D. The appearance of two cleaved fragments, 0.26 kb and 0.20 kb, indicates successful HindIII replacement. M: DNA marker; NC: negative control, the corresponding PCR products were amplified from Lig4169 genomic DNA with particular primers in each case. PC: positive control, the corresponding PCR products were amplified from the donor plasmid DNAs with particular primers in each case; k: kilo-base pair; HA-L and HA-R: left homologous arm and right homologous arm; HR: homologous recombination; donor plasmid: circular donor plasmid containing HA-L and HA-R and additional elements if any, the pBSK vector backbone is omitted here; all the dashed black lines indicate the homologous regions in the fly genome and on the donor plasmid; the empty boxes in panel A indicate the genomic regions of miR-281; all the filled boxes with numbers indicate the sequential coding sequences of the corresponding genes in each case, not necessarily representing the full coding sequences.

<table>
<thead>
<tr>
<th>Modifications of specific genes</th>
<th>Fertile F₀</th>
<th>HDR-yielding F₂/fertile F₀</th>
<th>HDR positive F₁/total F₁</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>miR-281 deletion</strong> TALEN-mediated HDR</td>
<td>65</td>
<td>3/65 (4.6%)</td>
<td>4/520 (0.8%)</td>
</tr>
<tr>
<td>chameau SmaI replacement</td>
<td>52</td>
<td>3/52 (5.8%)</td>
<td>5/363 (1.4%)</td>
</tr>
<tr>
<td>white knock-in at the yellow locus</td>
<td>78</td>
<td>1/78 (1.3%)</td>
<td>26/5252 (0.5%)</td>
</tr>
<tr>
<td><strong>CG4221 loxP replacement</strong> Cas9-mediated HDR</td>
<td>28</td>
<td>3/28 (10.8%)</td>
<td>10/230 (4.3%)</td>
</tr>
<tr>
<td>CG5961 HindIII replacement</td>
<td>12</td>
<td>1/12 (8.3%)</td>
<td>2/52 (3.8%)</td>
</tr>
<tr>
<td>Chameau C-terminal eGFP tagging</td>
<td>37</td>
<td>3/37 (8.1%)</td>
<td>8/296 (2.7%)</td>
</tr>
<tr>
<td>CG4221 C-terminal Myc tagging</td>
<td>30</td>
<td>8/30 (26.7%)</td>
<td>24/231 (10.4%)</td>
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</table>
TALEN, ranging from 3.8% to 4.3%, as is also the case of HR yielding F0/total fertile F0, as shown in Table 1, ranging from 8.3% to 10.8%. These observations were also consistent with reports that CRISPR/Cas9 is generally more efficient in mediating normal indels from the non-homologous end joining (NHEJ) pathway (Liu et al., 2012; Yu et al., 2013a).

**Comparison of TALEN- and CRISPR/Cas9-mediated HDR at the same chromosomal region of the yellow locus**

Although a generally higher efficiency of CRISPR/Cas9-induced HDR (3.8–4.3%) was observed compared with TALEN-induced HDR (0.8–1.5%), conclusions cannot be made before the following possibilities are excluded: more accessible local chromatin structure or different donor sequences. To investigate these possibilities, we set out to further compare the efficiency of TALEN- and CRISPR/Cas9-induced HDR at the same yellow locus using the same exogenous donor (Fig. 2A; supplementary material Fig. S5; Tables S1–S3). Here, both the TALENs and the gRNA for the CRISPR/Cas9 have been shown to efficiently induce NHEJ-mediated indels as previously described (Liu et al., 2012; Yu et al., 2013a). The exogenous donor plasmid was designed to delete both the TALENs and the gRNA recognition sequences (boxed for the TALENs and underlined for the gRNA), between HA-L (1.9 kb) and HA-R (1.1 kb), at the yellow locus, which generate a 0.18 kb shorter PCR product than Lig4169 flies (from 0.82 kb to 0.64 kb) with the indicated primers (Fig. 2A,B; supplementary material Fig. S5). This PCR strategy was employed to determine whether any HDR events have occurred after TALEN- or CRISPR/Cas9-induced DSBs. Interestingly, statistical analysis showed the ratio of detected HDR events in F1 was 2.7% for CRISPR/Cas9, whereas the ratio was 3.5% for TALEN; similar results were obtained for mutation-yielding F0/total fertile F0, which was 7.1% versus 8.3% (Fig. 2C). These results suggest that TALENs are likely as efficient as CRISPR/Cas9 to induce HDRs in the *Drosophila* genome, at least at the yellow locus.

**In vivo tagging through CRISPR/Cas9-induced homologous recombination**

After showing that both TALEN and CRISPR/Cas9 can efficiently mediate precise genomic modifications such as deletions and nucleotides replacement, we set out to explore precise insertions. The best example for precise genomic insertions is *in vivo* tagging, which can help to solve several technical problems in biological research such as: (1) Antibodies are widely considered as one of the most important tools to dissect functions of specific genes. However, due to the high cost, low success rate and time-consuming labor, it is still a problem to get ideal antibodies for many proteins; (2) Transgenes with tags often exhibit ectopic expression, whereas *in vivo* tagging leads to the precise tracing of endogenous protein expression; and (3) Proteins with fluorescent tags can be used in live imaging, which is an essential technology for developmental biologists. Here, we thought to take the advantage of HDRs induced by the highly efficient CRISPR/Cas9 technology to tag two endogenous proteins, Chameau and CG4221, with two tags of eGFP (0.72 kb) and Myc (less than 0.1 kb), respectively, that are in different sizes.

For *in vivo* tagging of the chameau gene, we wished to insert an enhanced GFP (eGFP) sequence before the stop codon, resulting in a fused gene, chameau-eGFP (Fig. 3A; supplementary material Fig. S6). The donor plasmid that contains the eGFP sequence between two homologous arms (HA-L, 2.8 kb and HA-R, 1.8 kb) and the Cas9 mRNA/gRNA for

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**Fig. 2. Comparison of TALEN- and CRISPR/Cas9-mediated HDR at the yellow locus.** (A) CRISPR/Cas9- or TALEN-mediated yellow deletion. The CRISPR/Cas9 binding sequence is 5′-GGGTTTGGACACTGGAACCG-3′ (underlined in panel A); PAM sequence is marked in red. One pair of TALEN binding sites is marked by boxes. The pairs of scissors indicate the Cas9 or TALEN cutting site at the yellow locus. The dashed red lines represent the deleted yellow genomic sequence (0.18 kb). (B) Molecular identification of the yellow deletions. The genomic DNAs of two heterozygous F1 lines, 46-3 (CRISPR/Cas9-mediated mutagenesis) and 8-1 (TALEN-mediated mutagenesis) were used as examples. The pair of primers used for PCR is shown in panel A (opposing arrows). The appearance of a 0.46 kb PCR band indicates successful deletion. (C) Frequencies of CRISPR/Cas9- and TALEN-mediated HDR at the yellow locus. The deletion-yielding events in both F0 and F1 are scored based on the appearance of the 0.64 kb short PCR product shown in panel B. The legends for the rest of the elements/labels are the same as in Fig. 1.
Fig. 3. In vivo tagging at the chameau and CG4221 loci. (A,C) chameau C-terminal eGFP tagging. (A) The cartoon scissors represent the CRISPR/Cas9 and indicate where it cuts at the chameau locus. The empty pentagon box indicates loxP site. The filled green box marked with eGFP indicates where the eGFP fragment is fused. The empty box marked by STOP indicates the stop codon of the chameau gene. (C) The genomic DNAs of two heterozygous F1, lines, 15-13 and 15-24 were used for PCR templates. The pair of primers used for PCR is shown in panel A as the two opposing arrows. The appearance of 0.72 kb PCR products indicates successful eGFP tagging (precise insertions). (B,D) CG4221 C-terminal Myc tagging. (B) The cartoon scissors indicate the Cas9 nuclease and its cutting site at the CG4221 locus. The empty triangle indicates the FRT site. The empty box marked with Myc indicates the Myc sequence. The empty box marked by STOP represents the stop codon of the gene CG4221. (D) The genomic DNAs of two heterozygous F1, lines, 55-1 and 55-2 were used as templates for PCR detection. The pair of primers used for PCR is shown as the two opposing arrows in panel B. The positive 0.2 kb PCR band indicates successful Myc tagging (precise insertions). (E–G) Immunostaining detection of the expression of Chameau-eGFP. (E) 3rd instar larval wing discs of line w; chameau-eGFP/vg-Gal4; chameauIR/+ . GFP: green fluorescent protein; eGFP: enhanced green fluorescent protein. (H) Detection of the expression of CG4221-Myc fusion protein by Western blot. Embryos of w1118 and CG4221-Myc line 55-1 were collected for Western blot at 0–3 hours. Anti-Myc antibodies were used to detect CG4221-Myc and tubulin was used as a loading control. See Fig. 1 legend for the common elements or labels that are not explained here.

generating a DSB before the stop codon of chameau coding sequence were co-injected into Lig4169 embryos (Fig. 3A; supplementary material Tables S2, S3). Successful insertion of eGFP was detected by PCR using primers embedded in the inserted sequence and genomic sequences (Fig. 3A,C; supplementary material Fig. S6). RT-PCR was also employed to detect the chameau-eGFP transcripts (supplementary material Fig. S7A,B; Table S4). Expression validation of the Chameau-eGFP protein was performed by immunostaining of eGFP in the wing imaginal discs of 3rd instar larvae. As shown in Fig. 3E, GFP is ubiquitously expressed in the wing imaginal discs of line 15-13, manifesting the pattern of endogenous Chameau. To further demonstrate the existence of the fused chameau-eGFP transcripts, we used vestigial-Gal4 (vg-Gal4) to drive UAS-chameauRNAi to knockdown the transcription of chameau at the vg-Gal4 expressing regions (Fig. 3F,G). Given chameau and eGFP formed a fusion transcript, when chameau was knocked down, the expression of GFP would also be expected to be reduced in the corresponding regions of chameau RNAi. The staining results shown in Fig. 3F indicate that GFP signals were significantly down-regulated where vg-Gal4 driven chameauRNAi was present. Collectively, these results indicate eGFP was successfully inserted into the C-terminus of the gene chameau, leading to a fusion protein that can be detected by the anti-GFP antibody. Since the flies carrying the Chameau-eGFP fusion protein did not exhibit any abnormality, we predict the fusion protein functions normally in vivo.

For in vivo tagging of the CG4221 gene, we wished to insert a Myc tag before the stop codon, resulting in a fused gene: CG4221-Myc. The donor plasmid that contains the Myc sequence and an FRT site (see Discussion) between two homologous arms (HA-L, 1.6 kb and HA-R, 1.8 kb), and the corresponding Cas9 mRNA/gRNA, were again co-injected to the Lig4169 embryos (Fig. 3B; supplementary material Fig. S8; Tables S2, S3). F1 flies that carry successful Myc insertions were screened by PCR using a primer embedded in the Myc sequence (Fig. 3B; supplementary material Table S4). Two positive PCR products from lines 55-1 and 55-2 are shown in Fig. 3D. PCR using primers outside of the homologous arms and RT-PCR were performed to further confirm the insertion and expression (supplementary material Fig. S9; Table S4). To further validate the expression of CG4221-Myc protein, we employed Western blot to detect the Myc tag. As
shown in Fig. 3H, a Myc-band corresponding to the size of CG4221-Myc protein was detected from total embryo lysates of line 55-1 using an anti-Myc antibody, whereas this band was missing in wild-type control embryos.

We have tagged two endogenous genes with two different markers, eGFP and Myc, respectively, via the CRISPR/Cas9-mediated HDR pathway. The efficiency of these kinds of in vivo tagging was sufficiently high for practical utilization. Strikingly, for a 0.72 kb eGFP tagging, the efficiency of getting inheritable germine insertions was 2.7%; and for a smaller tag of Myc the germine efficiency was as high as 10.4%. The summary of the statistical results is shown in Table 1.

The white platform for an easy screen of TALEN- or CRISPR/Cas9-mediated genome-wide mutagenesis

We have shown both TALEN and CRISPR/Cas9 systems are efficient for modifying the fly genome via the HDR pathway. However, it is still relatively time-, labor-, and money-consuming when using PCR based screening strategies to search for correctly modified genomes. Here, we chose to develop an easy-to-screen system using the Drosophila white gene as a marker. In order to set up this system, we first modified the pP[R]3 plasmid (Golic and Golic, 1996) to be a vector that contains the white coding sequence and its minimum regulatory sequence between two multiple cloning sites (MCS) (see Materials and Methods for more details; supplementary material Fig. S10). The specific elements of this vector include: (1) 5’ and 3’ MCSs flanking the white region for the insertion of different homologous arms (HA-L, 3.2 kb and HA-R, 4.2 kb); and (2) two FRT sites (5’TFT and 3’FTT in the same direction) located in the 5’ regulatory region and the intron of the white gene, respectively. The FRTs can be used for further removal of white expression by the Flp recombinase (see Materials and Methods; Fig. 4A; supplementary material Fig. S10). The modified vector was designated pP[R]3\textsuperscript{TM}.

To test how this system works for targeted mutagenesis through the HDR pathway, we employed the same TALENs (supplementary material Table S1) used in Fig. 2A to induce a DSB at the yellow locus. The donor plasmid, pP[R]3\textsuperscript{TM}-white\textsuperscript{-KI}, was designed to contain homologous arms (HA-L and HA-R in Fig. 4A) of the yellow gene that flank the white gene in pP[R]3\textsuperscript{TM} (see Materials and Methods; Fig. 4A). After co-injection of the TALENs and the donor DNAs, successful mutagenesis of the yellow gene was simply screened by following the white\textsuperscript{+} eye phenotype (red eyes), which simultaneously expresses the yellow mutation, leading to yellow phenotypes of the red-eyed flies (Fig. 4D). PCR analysis was used to further confirm the white knock-in (KI) using two pairs of primers (L\textsuperscript{F} and L\textsuperscript{R} and R\textsuperscript{F} and R\textsuperscript{R}), as indicated in Fig. 4A, to yield two positive bands of 3.2 kb and 4.2 kb (Fig. 4B). The efficiency of obtaining the yellow\textsuperscript{+} white-KI flies was 0.5% in germline transmission, and the frequency of HR yielding F\textsubscript{0} in total fertile F\textsubscript{0} was 1.3% as shown in Table 1.

Mutant flies created in this way will carry the white\textsuperscript{+} marker, which can be useful for neurobiologists performing visual behavior experiments, but might be unwanted due to...
differences in genetic backgrounds for other tests. To remove the white marker, the two FRT sites that flank the 5' part of the white gene are used (Fig. 4A). Such mutant flies were crossed with flies carrying the hs-Flp transgene. After a brief heat shock at 37°C, the mosaic white phenotype was observed in offspring flies, indicating the hs-Flp was efficient in removing the FRT cassettes that reside in the yellow mutants (Fig. 4E). With this easy-to-screen white platform, in principle, one can generate (screen for) any precise genomic mutations using only binocular microscopes without high-throughput PCR and enzyme digestion.

Removal of “ends-in” recombination events

In the process of precise modifications of the Drosophila genome through the HDR pathway by co-injection of a circular homologous donor, two ways of holiday-junction resolution lead to two kinds of outcome: “ends-out” and “ends-in” (Fig. 5; supplementary material Fig. S11). The “ends-in” recombination, as in the case of chameau mutagenesis (supplementary material Fig. S12), might be problematic depending on the purpose of the genomic modifications. When the purpose is to mutate a genomic locus, and the “ends-in” recombination yields two mutant alleles at the same locus, it is not a concern for phenotypic analyses. However, if the purpose were to tag an endogenous gene or to make gene corrections, a clean “ends-out” recombination would be favorable. The frequency of getting “ends-in” events can vary from 0 to 100% according to what we observed in this study (Fig. 5C; supplementary material Fig. S12C; data not shown), likely depending on the genomic locus and donor plasmid design, particularly, the distance between the DSB site and the proximal ends of the homologous arms.

Rong and colleagues reported a reduction strategy to remove a duplicated copy resulting from the ends-in recombination (Rong et al., 2002). Here we offer a different solution to remove the “ends-in” recombination and “convert” this kind of event into the “ends-out” outcome, taking advantage of the Flp-FRT or Cre-loxP systems. The CG4221 mutagenesis case will be used again to explain how the system works (Fig. 5). When the HDR pathway is triggered by the presence of both a DSB and a circular homologous donor, two forms of HDR products will be generated (Fig. 5; supplementary material Fig. S11). The “ends-in” HDR event results in a genomic duplication of the targeted CG4221, separated by the vector backbone (vb) of the donor plasmid, whereas the “ends-out” HDR yields only a mutated CG4221 locus (Fig. 5A). To molecularly distinguish these two events, two PCR strategies were again used. A quick examination expects a short PCR product for the “ends-in” event, but not for the “ends-out” event, using one primer located in the T7 of the vector backbone (T7f) and another in the first exon (e1r) (Fig. 5A; supplementary material Table S4). Indeed, a PCR product of 0.36 kb was observed in the “ends-in” recombination, but not in the

Fig. 5. Removal of “ends-in” recombination resultant from CG4221 mutagenesis. (A) “Ends-in” and “ends-out” homologous recombination (HR) were generated via the HDR pathway in the process of CG4221 mutagenesis, leading to either two copies of the CG4221 mutations or one copy of the CG4221 mutation in the fly genome, respectively (see also supplementary material Fig. S11). The Cre recombinase was introduced into the “ends-in” line to remove the duplicated copy of CG4221 by flipping out the DNAs between the two loxP sites, converting the “ends-in” into the “ends-out” events. The short arrows with names indicate the primers used in panels B,D. (B) PCR assays to distinguish the “ends-in” and “ends-out” HR events occurred during CG4221 mutagenesis. The genomic DNAs of heterozygous F1 lines 23-1, 32-5 and 56-7 were used for PCR assays. T7f and e1r detect a corresponding 0.36 kb “ends-in” band, while nothing for the “ends-out”. (C) “Ends-in” and “ends-out” HR ratio of CG4221 mutagenesis, based on the PCR analyses as described in panel B. (D) Molecular confirmation of the removal of the “ends-in” products. Line 32-5 was selected as an example to show successful removal of additional sequences between the two loxP sites by Cre recombinase, as indicated by the loss of the band amplified with T7f and er. Primer pairs used for PCRs are indicated on the right of the gel. Rpl49 genomic primers were used for genomic DNA quality control. See the legends to Fig. 1 for the common elements or labels that are not explained here.
“ends-out” case (Fig. 5B). For further confirmation, a longer, 3.18 kb PCR product extending from the T7f primer to the e1r primer located in the 3′ region of CG4221 locus was obtained from the “ends-in” flies. The longer PCR product disappeared in the same flies when the Cre recombinase was introduced to remove the sequences between two loxP sites, leaving a clean mutation resembling that from the “ends-out” event (Fig. 5A,D).

These results indicate that, introducing a loxP site into the homologous donor to be recombined into the to-be-modified locus of the fly genome, together with a Cre recombinase, can remove the “ends-in” recombination by “converting” the “ends-in” outcome into an “ends-out” outcome, when needed.

**DISCUSSION**

In recent years, genome editing technologies such as the zinc finger nuclease (ZFN), TALEN and CRISPR/Cas9 have emerged to facilitate biomedical research including targeted gene modifications in both basic theoretical research and applied research such as cancer studies (de Souza, 2012; Beumer et al., 2013; Piganeau et al., 2013; Wei et al., 2013). Among them, TALEN and CRISPR/Cas9 systems have been quickly adopted by biologists due to their high efficiencies in DSB induction and easy-to-handle procedures. However, most of the studies thus far have focused on using these two systems in different organisms to generate indel (insertion and/or deletion) mutations via the NHEJ repair pathway or to generate targeted insertion via homology-independent repair (Auer et al., 2014; Maresca et al., 2013; Wei et al., 2013). Despite recent reports of TALEN- or CRISPR/Cas9-mediated HDR in culture cells (Bassett et al., 2014; Yang, H. et al., 2013), application in model organisms has been, thus far, poorly explored. HDR-based genomic modifications include basically three types: (1) precise controllable deletions, which can be applied for deleting specific functional domains of particular genes, or generating precise null alleles of non-coding RNAs or genes with multiple splicing variants; (2) nucleotide replacements, which can be employed for gene corrections and precise point mutations; and (3) insertions, which can be used for in vivo tagging of protein-encoding genes or generating duplicating genes. In this study, we used *Drosophila* as the model organism to test the applications of HDR-mediated genomic modifications through TALEN- and CRISPR/Cas9-based systems. We successfully generated precise deletions, nucleotide replacements and insertions with a germline transmission efficiency of up to 10.4%; we compared the efficiencies of TALEN- and CRISPR/Cas9-mediated HDRs; we established an easy-to-screen platform for precise mutagenesis through TALEN- and CRISPR/Cas9-mediated HDRs; and last but not least, we offered a strategy to resolve the “ends-in” recombination resulting from co-injection of a circular homologous donor. Our results and related tools will be very helpful in facilitating *in vivo* genomic engineering in *Drosophila* as well as *in vivo* functional studies.

Based on our statistical results (Fig. 2C; Table 1), the F1 efficiency of CRISPR/Cas9-mediated genomic modifications via the HDR pathway was between 2.7% and 10.4%, which seemed to be higher than that of TALEN (0.5% to 3.5%). These results suggested CRISPR/Cas9 may be generally more efficient than TALEN in inducing the HDR pathway in *Drosophila*. In principle, this could be due to a higher efficiency in generating DSBs at targeted loci, which has also been supported by recent studies in several different organisms using either CRISPR/Cas9 or TALENs in inducing NHEJ-mediated indel mutations (Liu et al., 2012; Sung et al., 2013; Wang et al., 2013; Yang, L. et al., 2013; Yu et al., 2013a). However, a direct comparison of efficiencies between CRISPR/Cas9- and TALEN-mediated genomic modifications is still lacking both in *in vivo* and *in vitro*. To directly compare the efficiency of TALEN and CRISPR/Cas9 in mediating HDRs, we forced these two enzymes to act on the same locus of yellow (Fig. 2) in the presence of the same donor. Our results suggest the efficiency of TALEN actually was comparable to that of CRISPR/Cas9 in mediating HDRs in *Drosophila*. More cases may be needed to reach a definite conclusion. On the other hand, in all our cases of HDR-mediated applications either by TALEN or by CRISPR/Cas9, the efficiencies seemed to be high enough for practical manipulations in the lab; even in the case of 5 kb white knock-in (Fig. 4; Table 1), the efficiency was still as high as 0.5% in F1 flies. Nevertheless, the CRISPR/Cas9 system should be more convenient in RNA preparations than the TALEN.

NHEJ and HDR are two major pathways to repair DSBs. In this study, we focused on investigations of TALEN- or CRISPR/Cas9-induced HDR in the presence of homologous donor plasmids. To promote HDR versus NHEJ events in all the cases, a Ligase4 mutant (Lig4<sup>–/–</sup>) was employed. However, in the case of yellow deletion, only 20.0% (19/95) and 20.0% (8/40) HDR events were observed in both TALEN- and CRISPR/Cas9-induced yellow mutant F1, respectively. 80.0% of the yellow F1 in each case were non-HDR mutants (as assayed by PCR). Notably, this ratio of HDR versus non-HDR events was apparently lower than that in the case of ZFN-induced HDR (99.1%) at the *roisy* locus reported by Beumer and colleagues (Beumer et al., 2008).

“ends-in” and “ends-out” are two basic recombination events (outcomes) of HDR in the presence of a genomic DSB and a circular homologous donor plasmid. We detected these two outcomes of recombination in some of our mutagenesis cases: *chameau* Smal replacement (supplementary material Fig. S12) and *CG4221* loxP replacement (Fig. 5; supplementary material Fig. S11). To remove the unwanted duplication resultant from the “ends-in” recombination, we took advantage of the Cre/loxP system using *CG4221* mutagenesis as an example (Fig. 5).

Statistical results indicated that 70% of F1 alleles were “ends-in” recombinations in this particular case (Fig. 5B), whereas in *chameau* Smal replacement, the “ends-in” recombinations comprised 100% (supplementary material Fig. S12). Now the question arises: what determines the “ends-in” versus “ends-out” ratio? Although our study has not addressed this question in detail, we believe that the design of the donor plasmid, the relative distance between the proximal ends of the homologous sequences and the cutting site, and the length in between the two homologous arms may play essential roles in determining the outcome of “ends-in” and “ends-out” events. Further systematic experiments are needed to eventually answer this question.

In our study, two different strategies were employed to ensure that the TALEN- and CRISPR/Cas9-mediated HDR events occurred at the target loci: 1) PCR-based molecular analysis using a combination of internal and external primers (supplementary material Fig. S7A,C, Fig. S9A,C, Fig. S12A,B); and 2) expression detection of the fusion protein Chameau-GFP, which is expected to be under the control of the endogenous promoter of the *chameau* gene (Fig. 3). However, possible off-target events cannot be totally excluded at this stage, since technical difficulties in some of the cases, only internal primers, which were embedded in the donor homologous sequences, were used for PCR detections.
MATERIALS AND METHODS

Fly stocks
All flies used in this study were obtained from the Bloomington Stock Center and cultured at 25°C unless otherwise stated. Genotypes of these flies are as follows: w1118, LgD100 (BL28877); w1118, P[70FLP]10 (BL6938); yw, P{Cre,y'1b}; Df/TM3, Sb (BL851); w, vestigial-Gal4; TM2/TM6B, Tb (vg-Gal4, BL6819); yw, P[Trip.HMS00487]attP2 (UAS-chameauRNAi, BL32484).

Design of TALENs, gRNAs and donor plasmids
The target DNA sequences for the left and right TALEs to bind and the spacer DNA in between were designed using the TAL Effector Nucleotide Targeter software (Cermak et al., 2011; https://tale-nt.cacornell.edu). Rules for designing TALE repeats have been described in our previous study (Liu et al., 2012). All the target and spacer DNA sequences selected for this study are listed in supplementary material Table S1. The TALE repeats were constructed according to the “Unit Assembly” procedure described elsewhere (Huang et al., 2011).

Target DNA binding sequences for customized gRNAs in Drosophila were selected according to the rules described in our previous study (Yu et al., 2013a). To simplify the gRNA designing and subsequent in vitro transcription, we followed the target sequence principle: 5′GG-N17–19NGG-3′. The sequences of gRNAs used in this study are listed in supplementary material Table S2.

The pPG[RS3]M plasmid used for our easy-to-screen white platform was modified from pPG[RS3] (Golic and Golic, 1996; Drosophila Genomics Resource Center, Indiana; supplementary material Fig. S10). Briefly, a fragment spanning from the 3′ end of the white gene to the 3′ P element was amplified from the pPG[RS3] vector by standard PCR using one pair of primers: the forward primer, 5′-CTCAAAATGGTTGGAGTTGCT-3′ and the reverse primer, 5′-AAATGGTACAACGGCGTGAGGGCGCGCTTGGGTAACCGAATTTACCAT-3′. The PCR products cut with Ascl and MluI restriction enzymes were inserted at the Bsp1407 site of pPG[RS3] with the correct orientation, establishing the basis of the white platform. Mutagenesis of the yellow gene was employed to demonstrate how to use this white platform. The left (2.5 kb) and the right (3.4 kb) homologous arms (HA), obtained through PCR (Fig. 4A; supplementary material Table S3) with the LgD100 genomic DNA as the template were inserted into the KpnI/NotI and the AscI/MluI sites, respectively, of the pPG[RS3] vector. Donors with correct HAs were chosen for subsequent microinjections. In addition to the HAs, a nFRT sequence and a FRT sequence were added at the 3′ end of chameau and the 5′ end of the flp and Cre recombinase-mediated removal of the unwanted DNAs

To remove the 5′ part of the white gene in between the two FRT sites of the white platform, flies carrying a hs-Flp (BL6938) on the second chromosome were crossed to the red-eyed yellow flies. Heat shock was induced at 37°C for 30 minutes. Images of the mosaic eyes were taken using the Leica stereo microscope. To remove the unwanted elements in CG4221 “ends-in” events of CG4221 mutagenesis were identified by the presence of a positive PCR product using the pair of primers, one located in the T7 promoter of the pBSK vector and the other in the first coding exon of CG4221. A list of primers used in this study is provided in supplementary material Table S4.

The protocols used for the immunostaining of GFP to detect Chameau-eGFP fusion protein, and for the detection of Myc-tagged CG4221 protein by Western blot, are as previously described (Du et al., 2010; Dui et al., 2013). The anti-GFP antibody was from Life Technologies (catalog no. A11122, 1:1000 dilution), anti-Myc was from Cell Signaling Technology (catalog no. 2276, 1:500 dilution), and the anti-tubulin antibody was from CoWin Bioscience (catalog no. CW0098, 1:5000 dilution).

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Competing interests
The authors have no competing interests to declare.

Author contributions
Z.Y., H.C., C.L. and R.J. designed the experiments; Z.Y., H.C., J.L., H.Z., Y.Y., N.Z., Y.G., B.Y., Y.C. and F.D. performed the experiments; Z.Y., H.C.,
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