CRISPR-induced double-strand breaks trigger recombination between homologous chromosome arms

Erich Brunner1,* Ryohei Yagi2,* Marc Debrunner1, Dezirae Beck-Schneider1, Alexa Burger1, Eliane Escher1, Christian Mosimann1, George Hausmann1, Konrad Basler1

CRISPR–Cas9–based genome editing has transformed the life sciences, enabling virtually unlimited genetic manipulation of genomes: The RNA-guided Cas9 endonuclease cuts DNA at a specific target sequence and the resulting double-strand breaks are mended by one of the intrinsic cellular repair pathways. Imprecise double-strand repair will introduce random mutations such as indels or point mutations, whereas precise editing will restore or specifically edit the locus as mandated by an endogenous or exogenously provided template. Recent studies indicate that CRISPR-induced DNA cuts may also result in the exchange of genetic information between homologous chromosome arms. However, conclusive data of such recombination events in higher eukaryotes are lacking. Here, we show that in Drosophila, the detected Cas9-mediated editing events frequently resulted in germline-transmitted exchange of chromosome arms—often without indels. These findings demonstrate the feasibility of using the system for generating recombinants and also highlight an unforeseen risk of using CRISPR–Cas9 for therapeutic intervention.

DOI 10.26508/lsa.201800267 | Received 6 December 2018 | Revised 29 May 2019 | Accepted 29 May 2019 | Published online 13 June 2019

Introduction

CRISPR–Cas9–based genome editing has revolutionized genetic research, triggering the development of a plethora of technologies and applications that provide unprecedented control over genes in a growing list of model species (1, 2, 3, 4, 5, 6, 7, 8). CRISPR systems allow us to edit, engineer, or regulate genomes, hold great promise for clinical applications, and are likely to be used to treat diseases with genetic underpinnings, including cancer (9, 10). Genome editing is achieved by precisely targeting the nuclease activity of a modified bacterial protein (Cas9) via a user-defined guide RNA to a specific DNA sequence (1). The resulting DNA double-strand breaks (DSBs) are repaired either by the error-prone nonhomologous end joining (NHEJ) or homology-directed repair (11). For refined and precise genome editing purposes, homology-directed repair is harnessed to copy a specific DNA template (single-stranded or double-stranded) into the target site (2, 9, 12, 13). In contrast, NHEJ ligates the two broken ends of the DNA without a donor template, often resulting in random insertions or deletions (indels) that can disrupt coding sequences at the target site (for review see reference 14). However, with directly ligationable ends, NHEJ may lead to accurate repair of close and concurrent DSBs (15, 16, 17, 18), also when induced by Cas9 (19, 20, 21, 22). The ability of CRISPR–Cas9 to introduce several concurrent DSBs at defined positions has enabled engineering of tumor-associated chromosomal translocations resembling those observed in cancers, and hence to establish and test novel in vitro and in vivo tumor models (2, 23, 24, 25). Sadhu et al. (26) leveraged the CRISPR–Cas9 system to produce other chromosomal rearrangements, generating targeted mitotic recombination events in yeast to enable the fine mapping of trait variants. The authors deliberately induced a single DSB in one of the homologous chromosomes in a diploid yeast strain and achieved homologous recombination-based “loss of heterozygosity” events within 20 kb of the target site. Additional reports suggest that recombination in mitotic cells is not restricted to yeast but may also occur in other species such as houseflies (27) and tomatoes (28). What is currently missing is a solid confirmation of such events and data on their frequency in different species.

Here, we set out to examine the occurrence and frequency of genetic exchanges between homologous chromosome arms initiated by Cas9-induced DSBs. We show that Cas9-triggered DSBs induce germline-transmitted recombination between homologous chromosome arms in up to 39% of the CRISPR events in Drosophila. Although these findings expand the tool-box of CRISPR-based genome manipulation in research, they also raise concerns about the use of gene editing in therapeutic settings.

Results

CRISPR/Cas9 cuts induce recombination events

NHEJ is a major repair mechanism triggered by CRISPR–Cas9-induced DSBs in Drosophila (29, 30). Leveraging on this, we developed
a system for activating transgene expression through NHEJ-based repair. The system, which we named CIGAR (CRISPR-Induced Gene Activator), allows activation of transgene expression after CRISPR-induced DSBs. The principle of the CIGAR system is based on activation of gene expression if, and only if, a unique CRISPR–Cas9 target sequence has been cleaved and rearranged by NHEJ (Fig 1). CIGAR consists of four elements: (i) the ubiquitin-p63E promoter to drive gene expression in every cell (31), (ii) a so-called “shifter” sequence, (iii) a flexible linker sequence inserted 3’ of the shifter sequence (32), and (iv) a reporter cDNA (lacking a translational start codon) followed by the 3’UTR of the Drosophila tubulin a1 gene. The functional core of the CIGAR reporter lies within the shifter sequence, which contains optimized translational START codons covering all three frames upstream of a unique 20-nt CRISPR target sequence (33, 34). Each initiation codon is blocked downstream by a corresponding in-frame STOP codon. Importantly, the most 5’ STOP codon, named STOP5 (T for target), is in-frame with the downstream ORF and resides within the unique 20-nt gRNA target, starting 4 nt upstream of the PAM sequence. Activation of CIGAR is achieved by Cas9-induced DNA cleavage within the STOP7 codon. The induced DSBs will then be repaired by NHEJ-mediated repair concomitantly severing or eliminating the STOP5 codon. The resulting indel leads to repositioning of the upstream ATGs relative to the ORF, that is, causing one of the ATGs to be “shifted in-frame” with the ORF.

Two variants of this CIGAR tool box, that is, CIGAR\textsuperscript{gfp} or CIGAR\textsuperscript{mCherry} are depicted in Figs 1 and 2A. Further details of the CIGAR system will be submitted elsewhere. When we molecularly analyzed the shifter sequences in the progeny of females carrying the two CIGAR transgenes in trans (genotype: nos-Cas9, CIGAR\textsuperscript{gfp}/CIGAR\textsuperscript{mCherry}; U6:3-sgRNA\textsuperscript{CIGAR(1,2)}+/+), we found that in some of the F1 animals, the CRISPR target sequence of the CIGAR\textsuperscript{mCherry} reporter became located 5’ of the eGFP ORF and vice versa. Sequence analysis of 84 animals from different crosses revealed a total of 26 animals in which the sequences on one side of the DSB had been exchanged (Figs 2B, S1, and S2 and Table S1). The site of the DSB was in part marked by indels. From these results, we concluded that in these animals, recombination events had occurred at the site of the Cas9-induced DSBs. We would like to emphasize that the term recombination is used here to describe the exchange of genetic material between homologous chromosome arms initiated by CRISPR-induced DSBs. Because Cas9 activity may often cause the break of both homologs, such recombination events may not only be based on homologous recombination but may also result by breakage/fusion events involving NHEJ that lead to a crosswise ligation of the chromosome arms (15, 16, 17, 18, 19, 20, 21, 22). From our results, however, we cannot infer which repair mechanism was involved in the exchange of genetic information between homologous chromosome arms.

In the experiment described above, the CIGAR transgenes were located at position 5D on the X-chromosome that shows native recombination activity in the female germline (35). To further test if CRISPR–Cas9 could induce efficient site-specific recombination, we turned to the fourth chromosome for which normally no naturally occurring recombination is observed (36, 37, 38). We first generated transgenic animals harboring the CIGAR\textsuperscript{gfp} and CIGAR\textsuperscript{mCherry} construct at position 102F on the two homologous arms of chromosome 4, in addition to nos-Cas9 and U6:3-sgRNA\textsuperscript{CIGAR(1,2)}.
individuals were crossed to yw animals, and their offspring were scored for recombination events (Fig 2C, see the Materials and Methods section for details). Animals were randomly picked from 13 crosses immediately after hatching and analyzed for the sequences flanking the target site (Tables S2 and S3). This revealed that in 41 of 156 animals, recombination events had occurred (Fig 2B; for details see the Materials and Methods section). Thus, as described above for the X chromosome, numerous CRISPR-mediated recombination events were observed on the fourth chromosome (39% of the detected Cas9-triggered events, i.e., 41 of 105 CRISPR events).

CRISPR-induced recombination between two distant phenotypic markers

In the above experiments, recombination was induced between homologous chromosome arms for which the nt at the Cas9 target site as well as the flanking sequences (coding for the fluorescent proteins) differed. However, the recombination events could only be demonstrated by sequence analysis of the immediate vicinity of the CRISPR site; more distant phenotypic markers were not present on these chromosomes. Therefore, we could not rule out that, at least in some cases, other mechanisms, such as gene conversion, were responsible for the observed sequence exchange between the two CIGAR reporters in trans (39).

To confirm that indeed a complete exchange of the homologous chromosome arms occurs distal to the CRISPR–Cas9–induced DSBs, we used two visible markers separated by more than 100 kb (Figs 3A and S3): the w+–marked CIGARmCherry,102F, w+ transgene insertion site. To induce recombination at the target site (Fig 3A, TR; see the Materials and Methods section for more experimental details), we injected yw; CIGARmCherry,102F, w+/Dp(1;4)1021,y+; svspa-pol embryos with active Cas9–sgRNA RNP complexes containing recombinant Cas9 and in vitro–translated sgRNA-3 (Fig 3B) (40, 41).

Figure 2. Detailed CIGAReGFP and CIGARmCherry reporter design and illustration of recombination events on the sequence level.

(A) Design and sequence details of un-CRISPRed CIGAReGFP (top) and CIGARmCherry reporters (bottom). The sequences of the sgRNAs and the ORFs are shaded in green and red, respectively. Note that except for the sgRNAs and the ORFs, the sequences of the reporters are identical. The targeted STOP codon (stop); pink differ in sequence. The CRISPR target sites are delineated in the sequence context (pink, open arrows). Analysis of the shifter sequence is performed using primer pairs specific for the Ubi promoter and the 5’ end of the respective ORF (purple arrows). (B) The shifter region of flies harboring a single copy of one of the CRISPR reporters on the X chromosome (attP 5D) was analyzed by single fly PCR and Sanger sequencing. Shown are recombination events from a CIGAReGFP/CIGARmCherry co-targeting experiment visualized on the sequence level. As in (A), the sequences of the sgRNAs and the ORFs are shaded in green and red, respectively. Recombinants exhibit a rearranged sequential arrangement (green-red or red-green) of sgRNA and reporter cDNA. Note that recombination events may or may not be accompanied by indels at the target site. (C) Co-targeting experiments using CIGAR reporters on the fourth chromosome (attP 102F). 172 animals were analyzed by single fly PCR and Sanger sequencing. The yellow sections represent the number of recombinants with or without indel.
animals were crossed with homozygous yw; Dp(1;4)1021,y+,svspa-pol flies to visually detect recombination events in the offspring (i.e., the two visible markers co-segregate upon recombination; see Fig 3B and C and see the Materials and Methods section for details). From 8,604 offspring, we recovered 253 putative recombinants (Fig 3D). Of these 253 animals, we further characterized 57 deriving mostly from independent crosses. 21 of the 57 animals turned out to be true germline-transmitted recombinants that were homozygous viable (TR-A and TR-B in Fig 3E and Tables S4 and S5). Molecular analysis of the Cas9 target site revealed that 19 of these 21 recombinants did not contain an indel lesion at the CRISPR site (sequence traces with indels are shown in Table S4). Extrapolating from the 21 confirmed recombinants (out of 57) to the 253 putative recombinants (out of 8,604 F1 animals), the frequency of CRISPR-mediated targeted recombination in this experiment is estimated to be ~1.1%. This frequency is at least four orders of magnitude higher than that of the rare spontaneous recombination rate predicted for chromosome 4 (37).

CRISPR-induced DSBs may lead to loss of chromosomal structures

The remaining 36 (out of 57) putative recombinants recovered from the above experiment were homozygous lethal and exhibited position effect variegation (PEV; Fig 4A and B) in the adult compound eye. PEV in the eye occurs if the mini-white gene (w'), used as transgene reporter, is juxtaposed to heterochromatic regions via chromosomal rearrangements or translocations (42, 43, 44, 45). In particular, the proximity of the mini-white gene to the heterochromatic telomere regions may lead to PEV (46). We, therefore, reasoned that in animals showing PEV, the Cas9-based editing led to a loss of chromosome structures distal to the DSB and consequently, expression of the mini-white gene of the CIGAR transgene is variably silenced. Similar events have been reported for X-ray–induced DSBs on the fourth chromosome (47). To assess the presence or absence of the most distal part of the chromosomes showing PEV, we tested CIGARmCherry,102F,w+/chromosomes for complementation of the lethal svΔ122 mutation. Independently recovered yw; CIGARmCherry,102F,w+,svΔ122 animals exhibiting PEV were crossed to yw; ciD,svΔ122 animals. Without exception, the tested PEV chromosomes were unable to complement the svΔ122 mutation, indicating that they must have lost distal parts of chromosome 4.

Recombination is triggered by, and confined to the site of, Cas9-induced DSBs

Finally, to exclude that Cas9-induced DSBs merely stimulate nonspecific recombination (NSR) on the fourth chromosome (i.e.,
not at the Cas9 target site), we repeated the experiment using the same experimental conditions, but assessed recombination between a y+ marker on the short left arm of chromosome 4 and the w+-marked CIGARmCherry,102F transgene inserted at 102F of the right arm (Fig 4C–E, NSR; see the Materials and Methods section for more experimental details). Embryos of the genotype yw; CIGARmCherry,102F, w+/Dp(1;4)1021, y+,s vspa-pol were injected with RNPs containing Cas9 protein complexed with in vitro–translated sgRNA-3. The RNPs induce DSBs 39 of toy located distal of CIGARmCherry,102F but should not have any influence on the recombination between the y+ and the w+ markers. G0 animals were crossed with yw animals to score recombination events between the y+ and the w+ marker (Fig 4D). We screened more than 13,000 F1 animals but did not observe a single recombination event between the markers (NSR-A and NSR-B) recovered amongst 13,220 animals screened (see text and the Materials and Methods section for more details).

Discussion

Our results show that a substantial amount of CRISPR–Cas9–induced DSBs result in exchanges between homologous chromosome arms. Importantly, the recombination events we see occur in multiple experimental settings and not only under specific conditions. In this context, it is important to point out that recombination events observed in experiments where Cas9 has been provided as recombinant protein exclusively occurred in mitotic and not in meiotic cells: a study by Burger and colleagues shows that fluorescently labeled Cas9 RNP complexes are detectable until about 18 h after injection (40). In Drosophila, however, the first meiotic divisions occur at much later timepoints (i.e., in males in the...
third instar larvae, about 3–4 d after injection and in females at early pupal stages (48), likely excluding residual activity of Cas9 RNPs.

In experiments where Cas9 protein and the sgRNAs are provided via transgenes (49, 50), Cas9 expression is driven by the nanos (nos) promoter and the Cas9 transgene contains the nos 3’UTR recapitulating germline-specific nos expression, transcript localization, and translational control (49, 51, 52). Hence, Cas9 is maternally provided to the offspring and likely not expressed zygotically during embryogenesis (53). In females, Nos is available during mitotic divisions in the germline stem cells as well as in those that later on form the 16-cell cyst in the germline. It should not be present in the growing oocyte where meiosis would occur (53). In the male germline, nos expression seems to be essential during spermatogenesis (54). Loss of nos expression leads to various phenotypes with strongest effects on the number of primary spermatocytes that are created through mitotic divisions. Together, these arguments suggest that also in case the CRISPR reagents are provided via transgenes, recombination events occurred preferentially in mitotic cells. However, because the nos-Cas9 transgene is not inserted into the nos locus, presence of Cas9 protein and extension recombination events in meiotic cells cannot strictly be ruled out.

One reason why CRISPR-induced recombination has largely remained unnoticed in genetic model organisms is that DSBs are frequently repaired without resulting indels and thus cannot be detected by next-generation sequencing, preventing any follow-up validation of broader effects. When detected using genetic and sequencing validation, we noted variable recombination rates in our experiments. We attribute this variability to three experimental aspects. First, the different Cas9 target sites may have different cutting and recombination efficacy (30, 55). Second, individual crosses may yield different numbers of progeny harboring CRISPR-derived indels (i.e., CRISPRRed (G0) animals transmit a variable number of mutant alleles to the next generation, ranging from 0 to 100% as shown for the recovery of a nonfunctional y allele, see Fig 2 in reference 49). Third, in our experiments, different methods were used to introduce Cas9 and gRNAs, a circumstance that likely contributed to the different frequencies of recombinants recovered (49).

The Cas9-mediated site-specific chromosomal recombination described here opens up a number of new avenues and considerations for genome engineering. We demonstrate that in Drosophila, Cas9-mediated DSBs can be used to generate recombination at a predefined site between chromosomal locations that are in close vicinity. Unlike for site-specific recombination based on Flp (56, 57), no recombinase target sites need to be present. Thus, CRISPR-mediated site-specific recombination enables the combination of two known mutations situated in different alleles of one and the same gene into a single (double-)mutant allele. Moreover, it could be used to study permutations of mutant alleles in tightly linked genes such as members of a Hox gene cluster (58). Especially in vertebrates, such as mouse or zebrafish, CRISPR-induced recombination holds promise for a number of applications, including generation of complex mutant alleles in the same locus (59). Also, in Drosophila, Cas9-mediated recombination enables experiments that were previously impossible because of low or absent recombination rates. For example, by providing sgRNAs or Cas9 activity in a tissue-specific manner, it may become possible to generate specific mutant clones for genes located on the fourth chromosome. Finally, targeted Cas9-mediated recombination could potentially be used in epigenetic studies to determine the effects of swapping promoters, including their epigenetic marks, between maternal and paternal genes.

On the other hand, our findings that recombination between homologous chromosome arms may be triggered upon Cas9-induced DSBs underscore the need for caution in applying CRISPR-based genetic interventions in animals or humans (60). Unrecognized CRISPR-induced recombination events (i.e., no visible indels at the target site) may lead to loss-of-heterozygosity events, generating cells with unnoticed homozygosity for imprinted genes or recessive mutations located distal to the Cas9 target site, which may have unforeseen consequences.

Moreover, we observed that CRISPR-based engineering can lead to loss of chromosome material distal to the locus of the DSB (Fig 4B). We could observe such events in our system because haplo-four animals (harboring only a single copy of the fourth chromosome) are viable (61). Under most circumstances, and likely in most organisms, such events would lead to the death of the affected cells because of haploinsufficiency. In this context, recent work suggested that Cas9 induces mutations in human cells and mice that are larger than anticipated (62). Therefore, it is imperative to routinely consider broader chromosomal alternations as possible outcome when applying CRISPR technologies in translational medicine.

Materials and Methods

Plasmid construction

Unless otherwise noted, the plasmids were constructed by standard molecular cloning methods. When plasmids contain newly synthesized nt sequences via PCR, oligonucleotide synthesis, or mutagenesis, the sequences were verified by DNA sequencing.

pUbiattB

The Stul-ubiquitin p63E promoter (ubi)-EcoRI fragment from pCaSPr3-Up2-RX polyA was subcloned into a pBluescript (pBS) vector between the EcoRI and XhoI sites using blunt-end ligation. The EcoRI-ubi-Acc65I fragment from the resulting plasmid was subcloned into pEPattB (63) using the EcoRI and Acc65I sites.

pUbiattB-CIGAR<sup>GFP</sup>

To create the pUbiattB-CIGAR<sup>GFP</sup> reporter, the shifter sequence (containing optimized translational START codons covering all three frames upstream of a unique 20-nt CRISPR target sequence), a unique gRNA target sequence (referred to as sgRNA-1), the linker sequence, and the eGFP gene were designed (as shown below), synthesized by GenScript, and delivered ligated into the pUC57-Kan vector (pCIGAR-D0).

The pCIGAR-D0 insert:

```
5’-KpnI_CACAATGGTGAAACATGGGTACAGTGGTCGCGAGTGTCGCGACACAGCAAGCTAGCGAGGAGGGAGGGAGGAGGT-
```

CRISPR-Cas9–induced recombination  Brunner et al. https://doi.org/10.26508/lsa.201800267 vol 2 | no 3 | e201800267 6 of 11
gtcatctgcggcggctgtgaaagccgggtgacatggacgagctgtacaagtaa_{EcoRI-3}
tccacaacgaggactacaccatcggTGGAACAGTACGAGCGCGCCGAGGGC-
gcGGCGTGACGGCGGCCACTACGACGCCGAGGTCAAGACCACCTACAAGGCCAAGAA-
cccggagggCGCCCTGAAGGGCGAGATCAAGCAGAGGCTGAAGCTGAAGGTA-
taatgcaagagcatgggctgggAGGCCTCCTCCGAGCGGATGTA-GTTCCATCTACAAGGTGAAGCTGCAGCGGCACCAACTTCCCCTCCGGACGGCCC-
AGGACGGCGGCGTGGTGACCGTGACCCAGGACTCCTCCCTGCAGGACGGCG-
catgtacggctccaaggcctacgtgaagcaccccgccgacatcccccgactac-
gagggcgagggccgcCCCTACGAGGGCACCCAGACCGCCAAGCTGAAGGG-
GTTGACATGGAGGGCTCCGTGAACGGCCACGAGTTCGAGATCGAGGGCC-
AAGGGCAAGGACAACATGGCCATCATCAAGGAGTTCATGCGCTTTAA-

U6-3-sgRNA_{CIGAR(1,2)} (pCFD5-F1)

The pCFD5 vector was a gift from Fillip Top (f73914; Addgene) (50). pCFD5 is the main backbone containing the tRNA assembly prepared to insert multiple gRNAs. For our purposes, sgRNA-1 and sgRNA-2 were inserted via Gibson cloning into the pCFD5 vector (named pCFD5-F1) following the protocol in the supplement method of pCFD5 cloning protocol.

pCFD5 internal tRNA multi-gRNA Scaffold:
5’-GTGGCGGTTTGTAGTTGTAGCATACAGCTGGTTGTCAGTTGG-
TAGAGTTGTCGGCCTGGACGGCGGGGCCGCGGTTGATTCGCTCGAG-
CAGGTTTCTCGTTTTAGACTCAGAAATAGAAGTTAAAATAAGGGT-
GACTTGCTTTAACAATGGAATAAGGGCACCGAGTGGTCGTAACAAGC-
TAGTGGTAGAATAAGTACCCCTCGCAGTCAAGACCCCGGGGGGTGAGTT-
CCGGCTGGACAGAAGCTTTAGTTAGCTCAAAATAGAAGTTAAAATAAGGG-
GACTTGCTTTAACAATGGAATAAGGGCACCGAGTGGTCTGATCTGTT-

Through the process of Gibson cloning, both the sgRNA-1 and sgRNA-2 were inserted into the pCFD5 vector using primer (5’-GCCCGCTTTCGAGTTTCCCGCGGGATACGAGAAGCTTTAGTTAGCT-
CCGGCTGGACAGAAGCTTTAGTTAGCTCAAAATAGAAGTTAAAATAAGGG-
GACTTGCTTTAACAATGGAATAAGGGCACCGAGTGGTCTGATCTGTT-

IVT of sgRNA-3

IVT of sgRNAs were performed as described in reference 40. For IVT, we used MEGAscript (AM1334), and for the purification of the IVT products, we used Purification: MEGAclear (AM1908).

IVT oligo used specific for sgRNA-3:
5’-GAAATTAATACGACTCACTATAGGGTTTCAAGTGGTAATGGGTGCTTTTTT-3’

Complementary sequences of the specific sgRNA primer and the sgRNA-R are shown in bold letters.

Cas9/sgRNA RNP injections

The concentration of SpCas9 injected was about 800 ng/μl SpCas9 (final concentration) and about 300 ng/μl of sgRNA (IVT; final concentration after purification). This corresponds roughly to a 1:2 ratio (SpCas9: sgRNA-3). SpCas9 has about 5× the molecular weight of the sgRNA.

The injection mix is prepared as follows (total volume of 10 μl):

1. sgRNA primer and the IVT primer and the
2. SpCas9 (EnGen Cas9 NLS, NEB #M0646T; 3.22 μg/μl SpCas9 has about 5× the molecular weight of the sgRNA."
3. ddH2O, and 10× incubation buffer NEB and mix thoroughly by pipetting up and down. It is mandatory to add SpCas9 as the last component of the IPRT of SpCas9.
4. Let the mix equilibrate at RT for ~30 min before injection. Never load the mix onto a column (Ultrafree-MC-HV 0.45 μm). Load the mix onto a column (Ultrafree-MC-HV 0.45 μm [Ref: UFC30HV0])
5. Spin for 1 min in a table-top centrifuge @14,000g. Reincubate the flow-through at 37°C for 2 min. Let the mix equilibrate at RT for ~30 min before injection. Never put the mix back on ice.
Fly genetics

Crosses were done at 25°C. Unless noted otherwise, fly lines were obtained from the Bloomington Drosophila Stock Center (see the Acknowledgments section).

Transgenic CIGAR fly lines (integration into ZH-attP 5D [X chromosome] or ZH-attP 102F [fourth chromosome]) were generated by phiC31 integrase-mediated transgenesis (51, 64). Individual strains were confirmed to carry the correct shifter sequence by sequencing the PCR product of the shifter sequence using primers CAACAAAGTTGGCGTCGATA CIGAR-reGFP, 102F, w+/ZH-attP 5D; w+/ZH-attP 102F (452 bp; for CIGAR-reGFP; 102F, w+/ZH-attP 5D; w+/ZH-attP 102F, respectively. PCR settings were as follows: 95°C, 5 min; 35 cycles of 95°C, 25 s; 60°C, 25 s; and 72°C, 30 s; final elongation of 72°C, 10 s. The same PCR setting was used to analyze the shifter sequence of the CIGAR reporters by single fly PCR.

The pCFD5-F1 containing U6:3-sgRNA-CIGAR(12) was made to carry the correct shifter sequence by sequencing the PCR product of the shifter sequence using primers CIGAR-fwd: CAACAAAGTTGGCGTCGATA and CIGAR-rev: GAACCTAGGTGACCTTGCA (452 bp; for CIGAR-reGFP, 102F, w+). The PCR product of the shifter sequence was used primers CIGAR-fwd: CAACAAAGTTGGCGTCGATA and CIGAR-rev: GAACCTAGGTGACCTTGCA (452 bp; for CIGAR-reGFP, 102F, w+). The PCR product of the shifter sequence was used to analyze the shifter sequence of the CIGAR reporters by single fly PCR.

The pCFD5-F1 containing U6:3-sgRNA-CIGAR(12) was used to analyze the shifter sequence of the CIGAR reporters by single fly PCR.

Fly images

The images were taken on Axio Zoom V16 (Zeiss) and were processed in Adobe Photoshop or Adobe Illustrator.

CRISPR–Cas9–induced recombination on the fourth chromosome (more detailed description).

To determine if we could also induce CRISPR/Cas9–mediated recombination on the fourth chromosome, we first generated flies harboring either a CIGAR-reGFP or CIGAR-reCherry construct on the fourth chromosome at position 102F (S1). These animals are referred to as CIGAR-reGFP, 102F, w+ and CIGAR-reCherry, 102F, w+, respectively. Activation of the reporters was achieved with the previously used RNA spacer sgRNA-1,2 tandem array (U6:3-sgRNA-CIGAR(12)). To test if CRISPR-Cas9–mediated DSBS also result in recombination, the fourth chromosome, nos-Cas9/y; U6:3-sgRNA-CIGAR(12); w+; CIGAR-reGFP, 102F, w+ / CIGAR-reCherry, 102F, w+; Dp(1;4)1021,y+; w+, svspa-pol, w, y, w, y+ W0 males were crossed to yw females (or nosCas9/+; U6:3-sgRNA-CIGAR(12); w+; CIGAR-reGFP, 102F, w+ / CIGAR-reCherry, 102F, w+; Dp(1;4)1021,y+; w+, svspa-pol, w, y, w, y+ W0 females to yw males). The offspring of such crosses were first scored at the larval stage to identify animals with either an activated CIGAR-reGFP, 102F or CIGAR-reCherry, 102F reporter. This preselection was made to ascertain that DSBS occurred in both constructs enhancing the likelihood of detecting recombination events on the fourth chromosome in case they occur. 17 vials (crosses from 12 G0 males and 5 G0 females) containing GFP and mCherry-positive larvae were selected for further analysis. A total of 172 yw F1 animals harboring either a CIGAR-reGFP, 102F or CIGAR-reCherry, 102F reporter but lacking the sgRNA plasmid U6pCFD5 (to avoid mosaic flies) from 13 of these crosses were randomly picked right after hatching. Single fly PCR of the target as well as part of the fluorophore region for the CIGAR reporters was performed for these 172 animals (Tables S2 and S3). PCR products and readable sequences were obtained in 156 cases.

For the recombination experiments using the CIGAR transgenes on chromosome 4, we estimate the recombination frequency to be 26%; 41 recombinants identified/156 flies analyzed × 100 (see Fig 2C for numbers).

CRISPR–Cas9–induced recombination between two phenotypic markers (TR in Fig 3)

To confirm that indeed recombination between sister chromatids occurs after CRISPR-Cas9–induced DSBS, we tested if we could induce recombination between two visible markers that are separated by about 100 kb (Figs 3A and S3). The markers were w+-marked CIGAR-reCherry, 102F, w+ at 102F and the recessive viable mutation svspa-pol (a mutation in the eye-specific enhancer of the Drosophila Pax 2 gene) located downstream of the w+ marker near the tip of chromosome 4 (65). The Cas9 target site was selected in the 3′ UTR of the toy gene residing about 18 kb downstream of the CIGAR-reCherry, 102F, w+ transgene insertion site (Fig S3). The rough-eye phenotype of svspa-pol is reliably scored (100% penetrance) and is visible if the mutation is homozygous or over a null allele of sv such as sv127 (Sabarinadh Chilaka, Michael Daube, Erich Frei, and Markus Noll, in preparation).

yw; CIGAR-reCherry, 102F, w+/Dp(1;4)1021,y+, svspa-pol embryos were injected with recombinant Cas9 protein complexed with vitro–translated sgRNA-3 targeting the 3′ UTR of the toy gene. From the eclosing G0 animals, a total of 135 crosses were set up. Either five G0 females (29 crosses) or single G0 males (106 crosses) were crossed with homozygous Dp(1;4)1021,y+, svspa-pol flies. F1 offspring were either yw; CIGAR-reCherry, 102F, w+/Dp(1;4)1021,y+, svspa-pol (UR-A: phenotypically w+, y sv) or homozygous Dp(1;4)1021,y+, svspa-pol animals (UR-B; phenotypically w+, y sv)+ (Fig 3E). Recombination events would be phenotypically distinct (Fig 3E; TR-A or TR-B); TR-A is yw; CIGAR-reCherry, 102F, w+; svspa-pol/Dp(1;4)1021,y+, svspa-pol and would be scored as having rough, red eyes (w+, y sv). The second recombination event (TR-B) that would occur would be yw; Dp(1;4)1021,y+, svspa-pol/Dp(1;4)1021,y+, svspa-pol flies having white and smooth eyes (w+, y sv). From a total of 8,604 scored F1 animals, 253 putative recombinant flies were recovered: 216 had rough red eyes (2.5%, from 56 independent G0 crosses) and 37 animals had white and smooth eyes (five independent G0 crosses). Notably, in one cross, 31 w+, y sv animals were present in one tube corresponding to about 25–30% of the offspring. 70 of the 253 putative recombinants (we picked mostly males) were backcrossed to homozygous Dp(1;4)1021,y+, svspa-pol flies to establish stocks. 61 of the 70 putative recombinants were recovered from independent crosses (56 w+, svspa-pol and 5 w, y sv). 13 of the 70 crosses remained without offspring. Most importantly, from 21 putative recombinants, we could generate homozygous viable lines. 17 of the 21 lines showed the y, w, svspa-pol phenotype, whereas four lines were w+, y sv marking all 21 lines as true recombinants. The remaining 36 putative recombinants were homozygous lethal (for more information on these 36 lines see “Cas9–induced DSBS may lead to loss of chromosomal structures” below).

We then investigated these animals by PCR specific for the CRISPR target site. Sequence analysis revealed that with the exception of two animals all CRISPR sites were without any indel (i.e., had a wild-type sequence; Tables S4 and S5). Interestingly, two recombinants from the same cross (G0 male) showed the same CRISPR mark (6-bp deletion). However, they had the complementary phenotype: Whereas one fly showed the y, w, svspa-pol
phenotype, the other was phenotypically w, y+, sv+, indicating that we may have recovered both chromosomes from the same recombination event. A third recombined animal from the same cross showed no CRISPR mark and thus can be counted as independent recombination event.

Recombination experiment between two phenotypic markers (NSR in Fig 4)

To assess if CRISPR–Cas9–induced DSBs in general would enhance the frequency of recombination away from the Cas9 target site, we repeated the experiment and assessed the recombination frequency between a y+ marker on the short, left arm of chromosome 4 and the w+–marked CIGARmCherry,102F inserted at 102F (see NSR in Fig 4C). To use the same experimental conditions and to exclude that the addition of active Cas9 would also induce recombination elsewhere on the fourth chromosome, embryos of the genotype (yw; CIGARmCherry,102F,w+/Dp(1;4)1021,y+,svspa-pol) were injected with Cas9 protein complexed with vitro–translated sgRNA-3. This again would induce DSBs 3' of toy located distal of CIGARmCherry,102F but should not have any influence on the recombination between the y+ and the w+ markers. 60 animals were this time crossed with yw animals to be able to score crossover events between the y+ and the w+ marker (Fig 4D). As expected, F1 animals were phenotypically either yw+ or yw+ because the two markers normally segregate. However, 11 phenotypically y+,w+ flies were recovered from a total of 13,220 analyzed offspring. To assess if the y+,w+ recovered animals were indeed spontaneous recombinants, or represented non-disjunction events (i.e., triplo-4 animals which are viable), we backcrossed such animals again against yw flies. Spontaneous recombination between y+ and w+ could be excluded as the above-mentioned backcross would have only revealed phenotypically y+w+ or yw+ flies. Instead, nondisjunction could be confirmed in all 11 cases because the backcross revealed phenotypically y+w+, yw, y+w, and y+w+ flies. We determined the non-disjunction rate for the fourth chromosome to be 1 in 1,200, which is similar to the one observed for the X chromosome (66).

Supplementary Information

Supplementary Information is available at https://doi.org/10.26508/lsa.201800267.

Acknowledgements

We thank Julia Compart, Angelika Dannert, Madlen Mueller, and Andri Lansel for technical help, Giuseppe Saccone, Daniel Bopp, Alessandro A Sartori, Damian Brunner, Darren Gilmour, Hugo Stocker, Olivier Uwryler, Ernst Hafen, Hirokazu Okada, Markus Noll, Christian Lehner, and Erich Frei for scientific discussions; Fillip Port for reagents; Johannes Bischoff for the ZH attP SD line; Markus Noll for the yw; sv3+/-, cp0, sv3pos-poly by stock; and Martin Jinek and Giuseppe Saccone for recombinant Cas9 protein for testing. This work was supported by the Swiss National Science Foundation (SNF), grant number 310030B_173331 (K Basler), Swiss National Science Foundation, grant number 170623 (C Mosimann), Swiss Bridge Foundation (A Burger), SNF consecutive grants 31003A_162557 and 31003A_182532, and by the SystemsX.ch grant 51RT-0.145725 (to Ernst Hafen; ETH Zurich).

Author Contributions

E Brunner: conceptualization, data curation, formal analysis, supervision, validation, investigation, visualization, methodology, project administration, and writing—original draft, review, and editing.
R Yagi: conceptualization, resources, formal analysis, validation, investigation, visualization, methodology, and writing—original draft, review, and editing.
M Debrunner: validation, investigation, methodology, and writing—review and editing.
D Beck-Schneider: investigation, methodology, and writing—original draft, review, and editing.
A Burger: resources, methodology, and writing—review and editing.
E Escher: investigation and methodology.
C Mosimann: resources, funding acquisition, methodology, and writing—review and editing.
G Hausmann: funding acquisition and writing—review and editing.
K Basler: conceptualization, resources, supervision, funding acquisition, project administration, and writing—review and editing.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References

1. Jinek M, Chylinski K, Fonfara I, Hauer M, Doudna JA, Charpentier E (2012) A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity. Science 337: 816–821. doi:10.1126/science.1218259
2. Doudna JA, Charpentier E (2014) Genome editing. The new frontier of genome engineering with CRISPR-Cas9. Science 346: 1258096. doi:10.1126/science.1258096
3. Hsu PD, Lander ES, Zhang F (2014) Development and applications of CRISPR-Cas9 for genome engineering. Cell 157: 1262–1278. doi:10.1016/j.cell.2014.05.010
4. Bosley KS, Botchan M, Bredenoord AL, Carroll D, Charo RA, Charpentier E, Cohen R, Corn J, Doudna J, Feng G, et al (2015) CRISPR germline engineering: The community speaks. Nat Biotechnol 33: 478–486. doi:10.1038/nbt.3227
5. Sternberg SH, Doudna JA (2015) Expanding the biologist’s toolkit with CRISPR-Cas9. Mol Cell 58: 568–574. doi:10.1016/j.molcel.2015.02.032
6. Chavez A, Tuttle M, Pruitt BW, Ewen-Campen B, Chari R, Ter-Ovanesyan D, Haque SJ, Cecchi RJ, Kowal EJK, Buchthal J, et al (2016) Comparison of Cas9 activators in multiple species. Nat Methods 13: 563–567. doi:10.1038/nmeth.3871
7. Ewen-Campen B, Mohr SE, Hu Y, Perrimon N (2017) Accessing the genotype gap: Enabling systematic investigation of paralog functional complexity with CRISPR. Dev Cell 43: 6–9. doi:10.1016/j.devcel.2017.09.020
8. Sadhu MJ, Bloom JS, Day L, Siegel JJ, Korsu S, Kruglyak L (2018) Highly parallel genome variant engineering with CRISPR-Cas9. Nat Genet 50: 510–514. doi:10.1038/s41588-018-0087-y
9. Sander JD, Joung JK (2014) CRISPR-Cas systems for editing, regulating and targeting genomes. Nat Biotechnol 32: 347–355. doi:10.1038/nbt.2842
20. Ghezraoui H, Piganeau M, Renouf B, Renaud J-B, Sallmyr A, Ruis B, Oh S, Filler Hayut S, Melamed Bessudo C, Levy AA (2017) Targeted...
28. Pannunzio NR, Watanabe G, Lieber MR (2018) Nonhomologous DNA end-joining really an inherently error-prone process? Dev Cell 44: 283–292. doi:10.1016/j.devcel.2018.07.014
34. Kozak M (1986) Point mutations define a sequence flanking the AUG initiation codon that modulates translation by eukaryotic ribosomes. Cell 44: 283–292. doi:10.1016/0092-8674(86)90762-2
35. Bopp D, Schütt C, Puro J, Huang H, Nöthiger R (1999) Recombination and dissociation in female germ cells of Drosophila depend on the germline activity of the gene sex-lethal. Dev Camb Engl 126: 5785–5794.
36. Ashburner M (2011) Drosophila: A Laboratory Handbook. Cold Spring Harbor, NY: Cold Spring Harbor Laboratory Press.
37. Hartmann MA, Sekelsky J (2017) The absence of crossovers on chromosome 4 in Drosophila melanogaster: Imperfection or interesting exception? Fly (Austin) 11: 253–259. doi:10.1093/flyemm/fax181
38. Sandler L, Szauter P (1978) The effect of recombination-defective meiotic mutants on fourth-chromosome crossing over in Drosophila melanogaster. Genetics 90: 699–712.
39. Chen JM, Cooper DN, Chuzhanova N, Ferec C, Patrinos GP (2009) Gene conversion in evolution and disease Encyclopedia of Life Sciences (ELS). Chichester: John Wiley & Sons, Ltd.
40. Burger A, Lindsay H, Felker A, Hess C, Anders C, Chiavacci E, Zaugg J, Weber LM, Catena R, Jinck M, et al (2016) Maximizing mutagenesis with solubilized CRISPR-Cas9 ribonucleoprotein complexes. Dev Camb Engl 143: 2025–2037. doi:10.1242/dev.134809
41. Meccariello A, Monti SM, Romanelli A, Colonna R, Primo P, Inghilterra MG, Del Colsaro G, Ramaglia A, Iazzetti G, Chiareo A, et al (2017) Highly efficient DNA-free gene disruption in the agricultural pest Ceratitis capitata by CRISPR-Cas9 ribonucleoprotein complexes. Sci Rep 7: 10061. doi:10.1038/s41598-017-10347-5
42. Zhimulev IF, Belyaeva ES, Chuzhanova N, Ferec C, Patrinos GP (2009) Gene conversion in evolution and disease Encyclopedia of Life Sciences (ELS). Chichester: John Wiley & Sons, Ltd.
43. Elgin SCR, Reuter G (2013) Position-effect variegation, heterochromatin formation, and gene silencing in Drosophila. Cold Spring Harb Perspect Biol 5: a017780. doi:10.1101/cshperspect.a017780
44. Dohmen JG, Mottus R, Grigliatti TA (2008) Telomeric position effect: A third silencing mechanism in eukaryotes. PLoS One 3:e3864. doi:10.1371/journal.pone.0003864
45. Schoeftner S, Blasco MA (2009) A ‘higher order’ of telomere regulation: Telomere heterochromatin and telomeric RNAs. EMBO J 28: 2323–2336. doi:10.1038/emboj.2009.197
46. Wallrath LL, Elgin SC (1995) Position effect variation in Drosophila is associated with an altered chromatin structure. Genes Dev 9: 1263–1277. doi:10.1101/gad.9.10.1263
47. Dominguez M, Brunner M, Hafen E, Basler K (1996) Sending and receiving the hedgehog signal: Control by the Drosophila gli protein cubitus interruptus. Science 272: 1621–1625. doi:10.1126/science.272.5268.1621
48. Hartenstein V (1995) Atlas of Drosophila Development. Cold Spring Harbor, NY: Cold Spring Harbor Laboratory Press.

49. Port F, Chen HM, Lee T, Bullock SL (2014) Optimized CRISPR/Cas tools for efficient germline and somatic genome engineering in Drosophila. Proc Natl Acad Sci USA 111: E2967–E2976. doi:10.1073/pnas.1405500111

50. Port F, Bullock SL (2016) Augmenting CRISPR applications in Drosophila with tRNA-flanked sgRNAs. Nat Methods 13: 852–854. doi:10.1038/nmeth.3972

51. Bischof J, Maeda RK, Hediger M, Karch F, Basler K (2007) An optimized transgenesis system for Drosophila using germ-line-specific phiC31 integrases. Proc Natl Acad Sci USA 104: 3312–3317. doi:10.1073/pnas.0611511104

52. Crucs S, Chatterjee S, Gavis ER (2000) Overlapping but distinct RNA elements control repression and activation of nanos translation. Mol Cell 5: 457–467. doi:10.1016/s1097-2765(00)80440-2

53. Wang C, Dickinson LK, Lehmann R (1994) Genetics of nanos localization in Drosophila. Dev Dyn 199: 103–115. doi:10.1002/aja.1021990204

54. Bhat KM (1999) The posterior determinant gene nanos is required for the maintenance of the adult germline stem cells during Drosophila oogenesis. Genetics 151: 1479–1492.

55. Liu X, Homma A, Sayadi J, Yang S, Ohashi J, Takumi T (2016) Sequence features associated with the cleavage efficiency of CRISPR/Cas9 system. Sci Rep 6: 19675. doi:10.1038/srep19675

56. Dang DT, Perrimon N (1992) Use of a yeast site-specific recombinase to generate embryonic mosaics in Drosophila. Dev Genet 13: 367–375. doi:10.1002/dvg.102130507

57. Struhl G, Basler K (1993) Organizing activity of wingless protein in Drosophila. Cell 72: 527–540. doi:10.1016/0092-8674(93)90072-x

58. Tschopp P, Duboule D (2014) The genetics of murine Hox loci: TAMERE, STRING, and PANTHERE to engineer chromosome variants. Methods Mol Biol 1196: 89–102. doi:10.1007/978-1-4939-1242-1_6

59. Cunningham TJ, Lancman JJ, Berenguer M, Dong PDS, Duester G (2018) Genomic knockout of two presumed forelimb Tbx5 enhancers reveals they are nonessential for limb development. Cell Rep 23: 3146–3151. doi:10.1016/j.celrep.2018.05.052

60. Ma H, Marti-Gutierrez N, Park SW, Wu J, Lee Y, Suzuki K, Koski A, Ji D, Hayama T, Ahmed R, et al (2017) Correction of a pathogenic gene mutation in human embryos. Nature 548: 413–419. doi:10.1038/nature23305

61. Grell EH (1961) The tetrasomic for chromosome 4 in Drosophila melanogaster. Genetics 46: 1177–1183.

62. Kosicki M, Tomberg K, Bradley A (2018) Repair of double-strand breaks induced by CRISPR-Cas9 leads to large deletions and complex rearrangements. Nat Biotechnol 36: 765–771. doi:10.1038/nbt.4192

63. Yagi R, Mayer F, Basler K (2010) Refined LexA transactivators and their use in combination with the Drosophila Gal4 system. Proc Natl Acad Sci USA 107: 16166–16171. doi:10.1073/pnas.1005957107

64. Markstein M, Pitsouli C, Villalta C, Celniker SE, Perrimon N (2008) Exploiting position effects and the gypsy retrovirus insulator to engineer precisely expressed transgenes. Nat Genet 40: 476–483. doi:10.1038/ng.101

65. Holtzman S, Kaufman T (2013) Large-scale imaging of Drosophila melanogaster mutations. FlyBase Reference Report (Last updated 2013). Accessed on 2013.

66. Bridges CB (1916) Non-disjunction as proof of the chromosome theory of heredity (concluded). Genetics 1: 107–163.

License: This article is available under a Creative Commons License (Attribution 4.0 International, as described at https://creativecommons.org/licenses/by/4.0/).