Promiscuous Target Interactions in the mariner Transposon Himar1*\[S\]

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We have previously characterized the early intermediates of mariner transposition. Here we characterize the target interactions that occur later in the reaction. We find that, in contrast to the early transposition intermediates, the strand transfer complex is extremely stable and difficult to disassemble. Transposase is tightly bound to the transposon ends constraining rotation of the DNA at the single strand gaps in the target site flanking the element on either side. We also find that although the cleavage step requires Mg\(^{2+}\) or Mn\(^{2+}\) as cofactor, the strand transfer step is also supported by Ca\(^{2+}\), suggesting that the structure of the active site changes between cleavage and insertion. Finally, we show that, in contrast to the bacterial cut and paste transposons, mariner target interactions are promiscuous and can take place either before or after cleavage of the flanking DNA. This is similar to the behavior of the V(D)J system, which is believed to be derived from an ancestral eukaryotic transposon. We discuss the implications of promiscuous target interactions for promoting local transposition and whether this is an adaptation to facilitate the invasion of a genome following horizontal transfer to a new host species.

Himar1 is a synthetic mariner transposon reconstituted by “mixing and matching” DNA sequences from almost identical elements in the horn fly, Hematobia irritans, and the lacewing, Chrysoperla plumatoria (1, 2). mariner is a Class II DNA transposon that belongs to a superfamily of elements that includes Tc1 in eukaryotes and the more distantly related IS630-like\(^1\) elements in bacteria (3, 4). mariner elements are extremely widespread in nature, but the vast majority are inactive due to large numbers of point mutations and deletions. The only active examples identified in insects to date are the MosI elements from Drosophila mauritiana and Drosophila simulans and a newly discovered mariner from an earwig (5).

DNA transposons are well adapted to bacterial hosts and may persist in the genome for an indefinite period of time. In contrast, DNA transposons have a short life span in eukaryotic species and tend to accumulate inactivating mutations during the invasion of a genome (see Ref. 6 and references therein). Therefore, for survival, DNA transposons rely on frequent horizontal transfer between species. As a result of this unusual lifestyle, the presence or absence of mariner does not correlate with the established phylogeny of closely related host organisms. Conversely, almost identical mariner elements are found in more distantly related species (Refs. 1, 6, and 7 and references therein).

mariner elements are very compact and contain a single transposase gene, usually flanked by simple terminal-inverted repeats (for review see Ref. 7). They transpose in the germ line and/or soma via a “cut and paste” DNA intermediate and duplicate a TA dinucleotide upon insertion. All of the classical DNA transposons such as mariner are descended from a common ancestor and have an RNase H-like structural fold in the active site with a characteristic DDE(D) motif. These residues serve to coordinate the catalytic metal ion and are shared by a diverse group of proteins including DNA polymerases, RuvC, the V(D)J recombinase Rag1, and the retroviral integrases. However, there are considerable mechanistic differences, even among the transposases.

The structure of mariner transposons most closely resembles that of the bacterial insertion sequences (IS elements). However, there are important differences in the molecular mechanism of transposition between the prokaryotic and eukaryotic elements. For example, one apparently universal feature of the bacterial IS elements is that the first nick during the excision step generates the 3´-OH at the end of the transposon that is eventually transferred to the target site by a direct transesterification mechanism (8). In mariner and other eukaryotic elements such as Activator and Tam3, the polarity of the reaction chemistry is reversed and the first nick generates the 5´-phosphate at the end of the transposon, for example (9). These and other differences may be attributed to a founder effect in the eukaryotic lineage, but this seems unlikely considering other examples of horizontal transfer. More likely is that the differences between prokaryotic and eukaryotic elements are ancient adaptations favored by the different scale and organization of the respective genomes.

We have already characterized the early intermediates of Himar1 transposition and documented further important mechanistic differences to the bacterial IS elements (6). In contrast to the bacterial elements, our results suggested that Himar1 transposase can multimerize and initiate catalysis at a single isolated transposon end. This shows that the architecture of the mariner synaptic complex has more in common with V(D)J recombination, which is probably derived from an ancestral eukaryotic transposon. Here we have gone on to charac-

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\(^{1}\) The abbreviations used are: IS, insertion sequence; STC, strand transfer complex; TBE, Tris borate-EDTA; PEG, polyethylene glycol; PEC, paired ends complex; ANOVA, analysis of variance.

This paper is available on line at http://www.jbc.org
**Himar1 Target Interactions**

**EXPERIMENTAL PROCEDURES**

**Plasmids and DNA**—Plasmids pKL97 and pKL99 encode 27 bases from the 5' end of Himar1 and are described by Lipkow et al. (6). pKL100 was created by digesting pBluescriptII SK+ with PvuII followed by religation. This procedure removed ~0.5 kb of sequences including the polylinker region. The transposon end fragments were generated by restriction digestion as defined in the figure legends. The DNA fragments were radioactively labeled and purified from polyacrylamide gels as described by Lipkow et al. (6).

**Protein Purification and Transposition Reactions**—Himar1 transposase was purified as described by Akerley and Lampe (13) and modified by Lipkow et al. (6). Transposition reactions described by Lipkow et al. (6) were performed as follows. Transposition reactions (15 μl, unless stated otherwise) were assembled in 25 mM Hepes, pH 7.9, 10% glycerol, 100 mM NaCl, 20 mM NH4Cl, 250 μg/ml bovine serum albumin, 2 mM dithiothreitol, and 2 mM CaCl2. Each reaction contained 500 counts per second of radioactively labeled linear transposon end DNA. The end of the element is indicated by the horizontal line in the figure legends.

**RESULTS**

**The Himar1 Strand Transfer Complex**—Himar1 has a non-replicative mechanism in which the transposon is completely separated from the donor site by double strand breaks at both ends (Fig. 1A). The 3'-end of the transposon is generated by a nick precisely at the end of the element. However, the 5'-end is nicked at several positions, predominantly 2 bp within the element (2, 6). To study Himar1 target interactions, we have used an in vitro insertion assay in which the transposon ends are provided as short radiolabeled DNA fragments (Fig. 1B). The first step of the reaction is the transposase-mediated synthesis of two transposon ends to form a paired ends complex (PEC). The Himar1 PEC has not been observed directly because it appears to be unstable during electrophoresis (6). However, its existence has been inferred from the concerted integration of both transposon ends on either side of a TA dinucleotide (2, 6). PEC assembly is followed by cleavage of the flanking DNA to produce the double-end break complex. In principle, complete separation from the donor site would allow diffusion of the excised transposon and capture of a target site by random collision. Non-covalent target capture would be followed by the strand transfer step that joins the 3'-ends of the transposon to the target site (Fig. 1B). The non-replicative bacterial transposons IS10 and IS50 (Tn5) most closely resemble Himar1 in structure, and these have been shown to transpose by this mechanism (14, 15).

Himar1 transposition reactions were performed with a supercoiled target plasmid and analyzed by TBE-buffered agarose gel electrophoresis (Fig. 2). After electrophoresis, the gel was stained with ethidium bromide, photographed, and dried onto a sheet of HyBond-N+ membrane. Autoradiograms of dried gels were recorded on a Fuji PhosphorImager device.
FIG. 2. Topology of the Himar1 strand transfer complexes. A single large insertion reaction was set up with supercoiled pBluescript as a target and 10 mM MgCl₂ to provide the catalytic metal ion. After incubating for 1.5 h at 30 °C, one-tenth of the volume of a 10× stop mixture was added to give a final concentration of 0.15% SDS, 15 mM EDTA. Aliquots of 17.5 μL were treated as indicated above the gel. The gel was 0.7% agarose buffered with TBE and was run at 65 V for 14 h. The gel was stained with ethidium bromide and photographed to locate the target DNA and molecular weight markers. It was then dried, and an autoradiogram was recorded on a PhosphorImager. Each lane had a 500 counts per second), 15 fmol of transposase (1 nM), and 250 ng of pBluescript as target. The transposon end fragment was generated by digesting pKL97 with SfiI and labeled on the transposon end by end-filling the XhoI site.

has a compact structure that is difficult to perturb. This may seem surprising in view of the instability of the PEC, which does not even survive electrophoresis in a Tris acetate-EDTA-buffered gel (6). However, this is a common feature of transposition reactions where the intermediates generally become more stable as the reaction progresses.

The Target Commitment Assay Conditions—Integration of a transposon into a target site occurs in at least two stages (Fig. 1B). The initial non-covalent interaction between the transpososome and the target site produces a non-covalent target capture complex. This is converted into a STC by the strand transfer step of the reaction. The capacity of a transposon to engage in productive non-covalent target interactions can be assessed in staged reactions in which different target molecules are presented sequentially (11, 12). In preliminary experiments with Himar1 in a simple buffer system, target commitment was detected before and after cleavage of the flanking DNA (see below). However, in similar experiments on V(D)J transposition, reactions were complemented with polyethylene glycol (PEG) (12). The authors did not discuss this point or the effect of PEG on the reaction as a whole. However, PEG is known to help mimic the crowded environment within the cell (see “Discussion”). Preliminary experiments demonstrated that including PEG in Himar1 reaction enhanced target commitment. However, to understand the meaning and potential pitfalls of these results, it was necessary first to determine the different effects of PEG on the Himar1 reaction.

Effects of Molecular Crowding on Himar1 Transposition—Himar1 transposition reactions were set up with the transposon ends encoded on radioactively labeled linear DNA fragments and supercoiled pBluescript as target (e.g. Fig. 1B). Concerted insertion of a pair of transposon ends close to each other on opposite strands of the DNA gives a linear product slightly larger than the target plasmid (6). The reaction was first titrated with transposase at 0 and 10% PEG (Fig. 3A). In the presence of PEG, the optimum transposase concentration is reduced from 8 to 2 nM. The reaction is extremely sensitive to an excess of transposase and is almost completely abolished by transposase concentrations only 4-fold above the optimum. This holds true both in the presence or absence of PEG. Thus, at 10% PEG, the optimum transposase concentration and the amount of transposase required to inhibit the reaction are both reduced to the same extent. This is consistent with the molecular crowding activity of PEG, which excludes large molecules from a significant proportion of the volume of the solution. The transposition reaction was titrated next with 0–10% PEG (Fig. 3B). The transposase concentration in this experiment was limited to 1 nM to preclude the inhibition of the reaction observed at higher concentrations. Under these conditions, 2% PEG has little effect on the reaction. However, at 10% PEG, the reaction is inhibited and only 20% of the insertion activity remains. Finally, to determine whether inhibition of the reaction is a kinetic effect, a time course was performed at 0 and 10% PEG (Fig. 3C). As before, 10% PEG reduced transposition to ~20% but the kinetics of the reactions are similar and both are close to completion after 3 h.

Ca²⁺ Supports the Strand Transfer Step—All of the classical DNA transposases have a DDE(D) motif in the active site, which serves to coordinate the divalent metal ions required for catalysis, for example (16). Divalent metal ions are probably also required to structure the active site, because they promote the assembly, stability, and/or conformational changes in the IS10, phage Mu, and V(D)J transpososomes (11, 12, 17–19). Although the catalytic metal ion in vivo is almost certainly Mg²⁺, Ca²⁺ can serve as a structural non-catalytic analog in some systems. For example, Ca²⁺ increased target commitment in IS10 from 14 to 43% and it was also included in all of the incubation mixtures for V(D)J target commitment assays (11, 12). Therefore, we performed insertion reactions to determine whether Ca²⁺ supported any of the steps of Himar1 transposition. No cleavage or insertion activity was detected with uncleaved transposon ends (data not shown). However, when the transposon ends are pre-cleaved with a restriction enzyme (Fig. 1A), Ca²⁺ supports strand transfer and yields a linear insertion product (Fig. 3D). This contrasts with IS10 where none of the catalytic steps is supported by Ca²⁺ but is identical to phage Mu and V(D)J transposition when the substrates are pre-nicked and pre-cleaved, respectively (19, 20). The ability of Ca²⁺ to support integration suggests that the structure of the active site changes between the excision and strand transfer steps and represents another similarity between mariner and V(D)J recombination.

Target Commitment in Himar1 Transposition—To assess the degree of target commitment with uncleaved and pre-cleaved transposon ends, a staged assay was set up in which two targets of distinguishable size are presented sequentially (Fig. 4, left panel). Transposase was first incubated with transposon ends to allow assembly of the PEC under non-catalytic conditions. Reactions with uncleaved transposon ends contained no Mg²⁺, whereas reactions with pre-cleaved ends were incubated on ice to suppress the strand transfer activity supported by the Ca²⁺ present in the buffer. During Stage 1 of the reaction, Target 1 is presented and incubated for 30 min to allow target interactions to become established. At Stage 2 of the reaction, Target 2 is added together with the catalytic metal ion Mg²⁺. After a further incubation period at 30 °C, the reactions were terminated and analyzed to determine whether insertions are biased toward the target presented during Stage 1 of the assay. This would occur if the transpososome is able to establish a stable non-covalent interaction with the first target that DNA presented and if this is a precursor to strand transfer into this target. If there is indeed a bias of insertions into the target presented during Stage 1, target commitment has occurred. Conversely, if the transposon inserts into both targets equally, no target commitment is observed.

The target plasmids were pBluescript and a derivative with a 448-bp deletion spanning the polylinker. The target plasmids...
were in the supercoiled closed circular form so that insertion of a pair of transposon ends gave a linear insertion product of unique size after deproteination (Fig. 1B) (6). When the targets were presented alone or when both targets were present at Stage 1 of the assay, the short target received slightly more insertions than the long target (Fig. 4, lanes 2–4). We did not investigate this difference extensively, but it appears that Himar1 inserted into the short target more efficiently because it contained a higher ratio of supercoiled to nicked circular DNA. This initial bias was taken into account when calculating the extent of target commitment (see supplementary material).

When the assay is performed in the absence of PEG and the targets are presented together at Stage 1, there is a slight bias toward insertion into the short target as noted above (lane 4). However, when the short target is presented first in a staged reaction, this bias is even more pronounced (lane 6). When the long target is presented first, the bias is reversed and the long target receives slightly more insertions than the short target (lane 5). These results show that, in the absence of PEG, there is a significant commitment to the target presented during Stage 1 of the assay. Commitment is observed for both types of transposon ends, but the effect was noticeably stronger for the pre-cleaved ends.

The assay was performed next with PEG added during Stage 2 of the assay in a mixture with the second target and Mg²⁺ (lanes 7–9). Under these conditions, there is strong commitment to the first target presented (compare lanes 8 and 9). Note that the addition of PEG at Stage 2 is identical to the target commitment assay for V(D)J transposition (12).

Finally, a third set of target commitment assays was performed, but this time PEG was added at Stage 1 of the assay in a mixture with the first target (lanes 10–12). Target commitment for both types of transposon ends is extremely strong, and almost all of the insertions are made into the first target presented. We considered the possibility that the strong target commitment was due to the failure of the targets to mix freely in the presence of PEG. However, this seems unlikely as PEG is widely used in molecular biology and is not known to prevent mixing. Also, if PEG prevented mixing, we would expect the total number of insertions to be much lower when the targets are added at Stage 1 in a mixture with PEG. This is clearly not the case for the reactions with the pre-cleaved ends (Fig. 4, compare lanes 4, 7, and 10 in the bottom panel). We also considered the possibility that the observed target commitment was a consequence of nonspecific binding of DNA to the transposase protein. However, this is also very unlikely as Himar1 transposition in vitro is insensitive to competitor DNA present in the reaction before the addition of transposase (6). If the transposase had a strong nonspecific DNA binding activity, as observed for many bacterial transposition systems, it would be highly likely to perturb the reaction, particularly if it was present in the reaction before transposase. Therefore, we conclude that the strong target commitment when PEG is added at Stage 1 or 2 is a true reflection of Himar1 behavior.
**Himar1 Target Interactions**

**Fig. 4. Himar1 target commitment assay.** Left side, a schematic diagram of the two-stage assay used to measure target commitment. The PEC is first assembled by mixing transposase with uncleaved or pre-cleaved transposon ends and incubating for 30 min under conditions that do not support catalysis. At Stage 1 of the reaction, the first target is presented and incubated for 30 min. During this time non-covalent interactions have an opportunity to become established. At Stage 2 of the reaction, a second target of distinguishable size is presented in a mixture with Mg$^{2+}$ to initiate the catalytic steps of the reactions. After a further incubation period at 30 °C, the reaction is stopped and analyzed to determine the proportion of insertions received by the targets presented during Stage 1 and Stage 2 of the assay. If present, PEG 8000 was added in a mixture with the target at either stage of the reaction. Reactions with the pre-cleaved ends were incubated on ice, because the Ca$^{2+}$ present in the preincubation buffer supports the strand transfer step of the reaction. Although the PEC forms efficiently on ice, the strand transfer activity is almost undetectable. Right side, typical target commitment assays are presented with uncleaved and pre-cleaved transposon ends. The uncleaved transposon end was generated by digesting pKL97 with SfiI, and the pre-cleaved transposon end was generated by digesting pKL105 with BsrDI + XhoI.

**Fig. 5. Quantification of the effect of PEG on Himar1 target commitment.** The data derived from the experiment presented in Fig. 4 were plotted together with duplicate experiments used for statistical analysis (see supplemental material). The percent target commitment was calculated using the formula of Sakai and Kleckner (11) as detailed in supplemental material. It is assumed that each target will receive half of the insertions. The extent of target commitment is calculated from the number of insertions over and above 50% when PEG was added at Stage 2 of the assay (12).

Quantification and Statistical Analysis of Target Commitment—Target commitment assays were repeated several times to allow quantification and statistical analysis of the results. The level of target commitment was calculated using the formula of Sakai and Kleckner (11), taking into account the slight bias of insertions into the short target (see supplementary material). The mean value from multiple experiments was plotted on a bar chart together with mean ± S.E. bars (Fig. 5). In the simple buffer system lacking PEG, target commitment was 6 and 22% for uncleaved and pre-cleaved transposon ends, respectively. This compares with 0.3 and 43% target commitment observed for IS10 transposition under the same conditions (11). When PEG was added at Stage 2 or Stage 1, target commitment was 40 and 70%, respectively, for both types of transposon ends. Target commitment for V(D)J transposition was not explicitly quantified but was close to 100% when PEG was added at Stage 2 of the assay (12).

ANOVA statistical analysis was used to evaluate the significance of the effects of PEG and end cleavage on the target commitment assays (Table I and supplementary material). The ANOVA technique is designed to analyze the variance of an unbalanced proportional data set in a two-factor factorial design (21). All of the data points used to construct the bar chart in Fig. 5 were included in the analysis.

The $p$ value for PEG was extremely low (Table I). This indicates that the molecular crowding activity of PEG caused a significant increase in target commitment when added at Stage 2 or Stage 1 of the assay. The increase in target commitment is particularly strong in the case of the uncleaved transposon ends (Fig. 5). Thus, although pre-cleavage of the transposon ends produces a 4-fold increase in target commitment in the absence of PEG, this effect is reduced to −1.1-fold when PEG is added at either stage of the reaction. This effect is reflected in the ANOVA analysis across the whole data set including all three PEG conditions where the $p$ value of 0.17 was not highly significant. Overall, it therefore appears that there is significant target commitment with both types of transposon ends but that commitment is consistently slightly stronger in the pre-cleaved situation.

Finally, over the whole data set, there was a $p$ value of 0.78 for an interaction between the effects of PEG and whether or not the transposon end was pre-cleaved (Table I). This means that the absence or presence of PEG at any stage of the reaction affected target commitment to the same extent with either type of the transposon end. The lack of interaction between PEG and transposon end cleavage suggests that the forces that deter-
Table 1
Analysis of variance in a factorial design for influences on Himar1 target commitment

<table>
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<th>Source of variation</th>
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<td>390.73</td>
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<td>29</td>
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The data plotted in Fig. 5 were analyzed by the ANOVA method described by Montgomery (21). A definition of the formulas is provided in Supplemental Table S1. The p values were from the HyperStat Online Textbook (davidmlane.com/hyperstatF_table.html).

DISCUSSION

Stability and Topological Constraints on the Himar1 Complexes—The chemical steps of transposition involve no high energy cofactors. Therefore, the reaction intermediates tend to become more stable as the reaction progresses as thermodynamic energy is lost from the system. We have shown previously that the Himar1 PEC is unstable and does not survive electrophoresia in TAE-buffered polyacrylamide gels (6). However, the STC is extremely stable and survives treatment with SDS or proteinase K (Fig. 2). This is similar to other transposition systems. For example, in phage Mu transposition, the STC is extremely stable and a specific protease must be recruited for disassembly of the complex and to allow replication (22).

Target Commitment and the Effects of Molecular Crowding—In the simple buffer mixture lacking PEG, Himar1 target commitment was 6 and 22% for uncleaved and pre-cleaved transposon ends, respectively (Fig. 5). This 4-fold difference is very small compared to similar experiments with IS10 where there is a 143-fold difference between target commitment with uncleaved and pre-cleaved ends (0.32 and 43% target commitment, respectively) (11).

Biochemical reactions in vivo can be influenced by a number of environmental factors absent from in vitro systems. For example, in bacteria and the eukaryotic nucleus, the concentration of the DNA alone is in the region of 10 mg/ml compared with 0.02 mg/ml in our target commitment assays. Furthermore, DNA condensation and aggregation are promoted by multivalent cations, DNA supercoiling, and molecular crowding. In the eukaryotic cytoplasm, macromolecules typically occupy 20–30% of the available volume. In some organelles such as the nucleus, the level of crowding is even higher in the range of 30–45%. All of the intracellular systems have evolved to deal with and to make use of the effects resulting from nonspecific interactions and volume exclusion. Although largely ignored in experimental biochemistry, crowding agents have proven essential for the in vitro reconstitution of DNA replication, transcription, cell division, and many other processes (23). The effect of crowding can be positive or negative. Solubility and diffusion rates are decreased, whereas protein folding and binding are generally increased (24). As an example, the binding of the HU protein to Escherichia coli DNA is increased over 10-fold in the presence of 12% PEG (25). When the Himar1 transposition assays were spiked with PEG at Stage 2 or Stage 1 of the reaction, target commitment with uncleaved and pre-cleaved transposon ends increased to almost 40 and 80%, respectively (Fig. 5). This large increase in target commitment is another example of the way in which molecular crowding preserves interactions between macromolecules.

In IS10 and V(D)J transposition, target commitment assays were accompanied by a physical demonstration that the respective PECs were engaged in a stable non-covalent interaction with the target DNA (11, 12). Himar1 also produced similar non-covalent complexes with target DNA in gel shift experiments (data not shown). However, because the Himar1 PEC is unstable and does not survive electrophoresia (6), the significance of these complexes was unclear.

Local Transposition—Clusters of transposons are present in many bacterial genomes. They are often found inserted within and adjacent to each other in phage sequences and pathogenicity islands, for example (26). The reason is that they may be targeted to their own ends or may tend to insert into distorted or highly bendable DNA sequences, for example (27, 28). In contrast, several different families of eukaryotic transposons have been shown to cluster over much greater distances. This finding suggests that they have a propensity to select target sites physically linked to the donor. For example, 1% of P-element insertions is within 128 kb of the donor site, which is 67-fold more than expected if there was no linkage between the donor and target sites (29). For the Ac/Ds family of elements, ~50% of new insertions are linked to the donor site in maize, Arabidopsis, and tobacco. In Arabidopsis, 35% are within 200 kb with a further 50% within 1,700 kb (see Refs. 30 and 31 and references therein).

Similar clustering is also observed for members of the Tc1 mariner family. For example, of 15 Tc1 insertions isolated from the unc-22 gene in Caenorhabditis elegans, 8 were from a donor site on the same chromosome (32). Local transposition in the Sleeping Beauty element has been even more thoroughly documented, because it is used as a tool for generating mutations in eukaryotic species. In contrast to transposition from a plasmid, which produces a random distribution of insertion sites in HeLa cells, 50% of insertions from a chromosomal donor site are made into the same chromosome (33). In the mouse germ line, 27% Sleeping Beauty insertions were within 200 kb of the donor site and 75% were in the same chromosome (34).

Interaction with a target before excision from the donor site is one mechanism that would account for transposition to linked loci. However, it is possible that other mechanisms contribute as well, e.g., if the transpososome were to remain associated with the DNA flanking the donor site after excision. Indeed, there is evidence for this in V(D)J recombination where mutations in the Rag proteins can influence whether the coding ends (the equivalent of flanking DNA) are rejoined by homologous recombination or by non-homologous end joining (35).

The difference in target selection between prokaryotic and eukaryotic elements raises the issue of whether there is a selective advantage for transposition to linked loci in eukaryotes. One possibility is that the difference is related to the lifestyle of eukaryotic DNA transposons, which rely on a high rate of horizontal transfer (Ref. 6 and references therein). The cut and paste mechanism of transposition does not produce an increase in the number of elements per se. Such elements can only prosper in the germ line if the donor site is restored by homologous recombination from a sister chromosome or from another copy of the element located elsewhere in the genome. This does not present a problem once the element is established. However, the first few transposition events at the start of a genome invasion are likely to be crucial for the survival of the element. A copy of the element close by on the same chromosome may therefore help to ensure restoration of the transposon during repair of the donor site. Indirect support for this model is provided by the exchange of sequences polymorphisms among Tc1 elements (32). The pattern of polymorphisms acquired suggested that, after excision, repair is by the synthesis-

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dependent-strand-annealing pathway using the sister chromosome as template. After synthesis has extended into the transposon sequences, the template is switched to a different copy of the transposon elsewhere in the genome. Because homologous recombination after \( P \)-element excision in \textit{Drosophila} has a strong \textit{cis} bias (36), it may benefit \textit{mariner} transposons in this and other species to transpose to physically linked loci.

**REFERENCES**

DNA: Replication, Repair, and Recombination: 
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