Targeted induction of meiotic double-strand breaks reveals chromosomal domain-dependent regulation of Spo11 and interactions among potential sites of meiotic recombination

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ABSTRACT

Meiotic recombination is initiated by programmed DNA double-strand break (DSB) formation mediated by Spo11. DSBs occur with frequency in chromosomal regions called hot domains but are seldom seen in cold domains. To obtain insights into the determinants of the distribution of meiotic DSBs, we examined the effects of inducing targeted DSBs during yeast meiosis using a UAS-directed form of Spo11 (Gal4BD-Spo11) and a meiosis-specific endonuclease, VDE (PI-SceI). Gal4BD-Spo11 cleaved its target sequence (UAS) integrated in hot domains but rarely in cold domains. However, Gal4BD-Spo11 did bind to UAS and VDE efficiently cleaved its recognition sequence in either context, suggesting that a cold domain is not a region of inaccessible or uncleavable chromosome structure. Importantly, self-association of Spo11 occurred at UAS in a hot domain but not in a cold domain. However, Gal4BD-Spo11 did bind to UAS and VDE efficiently cleaved its recognition sequence in either context, suggesting that a cold domain is not a region of inaccessible or uncleavable chromosome structure. Importantly, self-association of Spo11 occurred at UAS in a hot domain but not in a cold domain, raising the possibility that Spo11 remains in an inactive intermediate state in cold domains. Integration of UAS adjacent to known DSB hotspots allowed us to detect competitive interactions among hotspots for activation. Moreover, the presence of VDE-introduced DSB repressed proximal hotspot activity, implicating DSBs themselves in interactions among hotspots. Thus, potential sites for Spo11-mediated DSB are subject to domain-specific and local competitive regulations during and after DSB formation.

INTRODUCTION

Meiosis is a specialized cell cycle that occurs during the formation of gametes. During meiosis, recombination is a key event, not only in that it acts as a source of genetic variation, but also in that it forms physical connections between homologous chromosomes known as chiasmata, which permit proper segregation of homologous chromosomes (1). Meiotic recombination is initiated by programmed DNA double-strand break (DSB) formation catalyzed by a type II topoisomerase-like protein, Spo11 (2). In addition to Spo11, several conserved and non-conserved gene products have also been revealed to be involved in meiotic DSB formation (2–5); however the precise roles of these additional factors remain unclear. Meiotic DSBs are repaired using the unbroken homologous chromatid as a template to produce alternative recombinants, non-crossovers and crossovers, the latter of which result in chiasma formation (1).

In a variety of organisms, meiotic recombination occurs non-randomly along chromosomes (6). Mainly based on studies of the yeast *Saccharomyces cerevisiae*, formation of DSB during meiosis is thought to be controlled by several factors that influence the number and position of DSBs. First, meiotic recombination are preferentially initiated at defined sites called recombination hotspots. In hotspots, DSBs occur within a region of 50–250 bp, in which no obvious consensus sequences have been found (2,7). Most hotspots are in intergenic regions, which often harbor binding sites for transcription factors. DSB activity at some hotspots is dependent on the binding of transcriptional machinery but does not directly correlate with transcriptional activity (8,9). Hotspots are also
frequently found at ectopic insertions of external sequence (10–12). A common feature of hotspots is that they are located in accessible regions of chromatin that are hypersensitive to DNaseI and micrococcal nuclease (MNase) (13–15). Additionally, neighboring hotspots appear to interact: insertion of a hotspot near a pre-existing hotspot reduces the activity of both hotspots, and deletion of a hotspot can stimulate a new site of DSB (11,12,16).

Chromosome- or genome-wide analyses of meiotic DSBs have also revealed that DSBs are likely to occur preferentially in chromatin loops, away from DNA-axis associations mediated by cohesins and axial-element (AE) proteins (17,18). In addition, at least in rad50S or sac2A mutant, a large fraction of hotspots cluster in 50–100 kb domains (hot domains) and few DSBs occur in domains near telomeric or centromeric regions (cold domains) (19,20). The locations of many hotspots correlate with regions with high GC content (6,18). These features of higher-order chromosome structure appears to be more important to DSB formation than local structure of open chromatin, as open chromatin sites can be found in cold domains (21). Moreover, the frequency of DSB formation in an integrated hotspot sequence depends on the broader context, i.e. insertion in a hot or cold domain, even when the hotspot sequence has a constitutively open chromatin configuration (21,22). It is to be noted that some of the features of the chromosomal distribution of DSBs are likely to be exaggerated since those have been revealed using rad50S or sac2A mutants, which accumulate unprocessed DSBs but have reductions in DSBs at particular regions (23).

Studies with Spo11 fused to the DNA-binding domain of Gal4 (Gal4BD-Spo11) have provided important insights into the control of DSBs. Gal4BD-Spo11 can stimulate novel DSBs at Gal4-binding sequences in normally cold regions, raising the possibility that DNA binding by Spo11 is a primary determinant of DSB sites (24). However, genome-wide mapping analysis recently revealed that the distribution of DSB sites formed by Gal4BD-Spo11 does not necessarily correspond to that of the binding sites of Gal4BD-Spo11, indicating that binding of Spo11 per se is not sufficient for a DSB (25).

In spite of the accumulating knowledge on the topic, the molecular mechanisms governing the distribution of DSBs remain to be elucidated. Control of the amount and positions of DSBs appears to be important, because reduction of in vivo activity of Spo11 decreases spore viability in yeast and because occurrence of crossovers around centromeric or telomeric regions is deleterious to accurate chromosome transmission (26–28). In this study, to obtain insights into the molecular basis of meiotic DSB distribution, we induced formation of site-specific DSBs using Gal4BD-Spo11 and an intein-encoded nuclease, VDE (also called PI-Scel). VDE is a member of the homing endonuclease protein family and in a Spo11-independent manner, can generate a DSB at the VDE-recognition sequence (VRS) during meiosis of S. cerevisiae (29,30). Integration of the Gal4-binding sequence and VRS enables tethering the endonuclease to a chromosomal site of interest. Using this system, we uncovered multiple pathways for spatial control of meiotic DSB formation, by means of which a limited number of DSBs are formed in distinct chromosomal domains.

**MATERIALS AND METHODS**

**Strains and culture conditions**

Yeast strains used in this study are of the SK1 background (31) and are listed in Table S1 in the Supplementary Data. Strains were constructed via standard genetic crosses, transformation and other genetic procedures (32). The VMA1-105 allele is a complete deletion of the VMA1 intein [VMA1(−)] and the VMA1 allele contains the VMA1 intein [VMA1(+) ] (33). The plasmids pTF101 (34) or pTF100 (see below) were used for integration of sequences containing VRS or the promoter region of the GAL2 gene (UAS), respectively. Sequences of primers used for integration of VRS or UAS are listed in Table S2 in the Supplementary Data. Gal4BD-Spo11, Gal4BD-Spo11-Flag and Spo11-Flag were expressed under the ADH1 promoter at the TRP1 gene locus using strains with a complete deletion of the authentic SPO11 gene. Wild-type Spo11 was expressed from the authentic gene. The alleles expressing Gal4BD-Spo11 and Gal4BD-Spo11-Flag were derived from ORDS806 (24) and YHS900 (35), respectively. For expression of Spo11-Flag, integration plasmid harboring ADH1-promoter fused GAL4BD-SPO11-FLAG was replaced by the ADH1-promoter fused SPO11-FLAG fragment from pAUS (35). The resultant plasmid was integrated into the TRP1 gene locus. To examine genetic rearrangement of genes around HIS3, the neighboring genes MCA1 and FMP38 were replaced with the CgLEU2 and CgURA3 gene, respectively (36), with primers described previously (34). All integrations and gene disruptions were confirmed by PCR or Southern blot analysis.

Synchronous meiosis was performed essentially as described previously (37). Strains were grown in presporulation medium, SPS (0.5% yeast extract, 1% peptone, 0.17% yeast nitrogen base without ammonium sulfate and amino acids, 0.05 M potassium phthalate, 1% potassium acetate and 0.5% ammonium sulfate, pH 5.0), and then shifted into sporulation medium (SPM, 1% potassium acetate). Cells were cultured with vigorous aeration at 30°C.

**Plasmids**

The plasmid pTF100 was created such that the promoter region of the GAL2 gene was placed on both sides of the URA3 gene in the pBluescript SK vector (Stratagene). The primer pairs TFO1 (5’-CTA TAG ATG GTA CTA CAT GTA TTC CAG ATT CCG AAA GCT TTC TTC CCG AAT G-3’), TFO2 (5’-CTA GCC CGG GTG TCG GAG TGA TTC GCC CCG ATG AT-3’), TFO3 (5’-CTA GCC CGG GTG TCG GAG TGA TTC GCC CCG ATG AT-3’) and TFO4 (5’-CTA CTA CCC TTA ATT GTG GTT CCG AGT CCG CCC CGA TAC T-3’) were used for amplification of the upstream region of GAL2 using genomic DNA.
as a template. The PCR fragments were cloned into XhoI–XbaI interval of pBluescript SK, followed by the insertion of the URA3 gene at the Smal site. The resultant plasmid, pTF100, was used as a template for amplification of the UAS–URA3–UAS cassette using a primer pair containing 5′-TGG TAG GAC ATG TAT TCC AG-3′ and 5′-TAG TAC GCT TCA TAA TTG GT-3′ at each 3′-terminal, which can also be used to amplify the VRS–URA3–VRS cassette using pTF101 as a template (34).

Chromatin preparation and Southern bloting

Preparation of crude chromatin fractions from meiotic yeast cells and treatment of chromatin with MNase were performed as described (38). For Southern blot analysis, genomic DNA isolated from each sample was digested with the appropriate restriction enzymes, separated by agarose gel electrophoresis and transferred to a positively charged membrane (GE Healthcare). Restriction enzymes used for detections of DSB signals were as follows: HpaI for HIS3; BglII for YCL056C, HIS4, the YCR048W hotspot and YCR099C; XhoI for YCP4; PstI for the GAT1 hotspot; and Asel for the CY3S hotspot. Probes were prepared by random priming of DNA fragments of appropriate PCR-amplified products. The sequences of the PCR primers used for generating probes are listed in Table S2 in the Supplementary Data. The membranes were hybridized according to Church and Gilbert (39). Pulsed-field gels were run, blotted and hybridized as described (21).

Chromatin immunoprecipitation (ChIP) assay

ChIP was performed essentially as described (35). Aliquots of premeiotic (0 h) or meiotic (3 h) cells were fixed in 1% formaldehyde for 15 min at room temperature, quenched for 5 min with glycine and lysed with zirconia beads using a Multibeads-Shocker (Yasui Kikai). Samples were sonicated to shear chromatin, and then immunoprecipitations were carried out with anti-Flag antibody (Sigma) bound to protein G or protein A-coated Dynabeads (Invitrogen). Recovered DNA was subjected to quantitative PCR analysis in real-time using an ABI 7300 (Applied Biosystems) with SYBR Premix ExTaq and ROX-dye (Takara) following the manufacturer’s protocol. The primer pairs used in the assay were as follows: for TEL, 5′-GGG TAA CAA AGC ATG CAT AAT GCC TCC-3′ and 5′-CTC GTT AGG ATC ACG TTC GAA TCC-3′; for UAS, 5′-GGG AAA GCT TCC TTC CGG AAT GGC-3′ and 5′-TG CTC CAG GGA CAT GGA CCC CTG-3′; for HIS4, 5′-GGA AAG GTG ATG CTA AGC CAA AG-3′ and 5′-TCT GC ATG ATC GGA TTG ACT AAA TGC-3′; and for CWH43, 5′-TAC CAT GGG GAA CAG GGA TCT AAC-3′ and 5′-CTG GAG AGG GCA ATA AAT GAT GGC-3′. Sequences for GAL2 primer pairs were as described (35). The amounts of immunoprecipitated DNA (IP) and whole-cell extract DNA (WCE) were measured and compared to a standard sample of yeast genomic DNA.

Tetrad analysis

For tetrad analysis, parental haploid cells were mated on YPD plates for 8 h, then transferred to sporulation plates (1% potassium acetate). After 2–3 days at 30°C, spores were dissected and incubated on YPD for 2–3 days at 30°C, followed by replica plating to the plates containing the appropriate combination of amino acids. To assess the frequency of VDE-initiated recombination, we prepared VRS-integrated haploid strain and URA3-integrated haploid strain for each gene locus using pTF101 and pTF102, respectively, as previously described (34). Unidirectional recombination rates were measured based on the segregation pattern of URA3. For the 4:0 and 3:1 tetrads, the frequency of recombination was calculated on the basis of two and one events per two possible recombination events, respectively.

RESULTS

Gal4BD-Spo11-initiated DSB and recombination at sites of UAS integration

To study the regulation governing the distribution of meiotic DSBs, we utilized DSB targeting using Gal4BD-Spo11 or VDE during yeast meiosis. We recently developed a PCR-based integration method that can be used to introduce the 200-bp sequence containing the VRS into the yeast genome repeatedly (34). This method enables us to induce VDE-initiated meiotic DSB and recombination at any chromosomal position of interest. We have now extended this approach to the targeting of Gal4BD-Spo11. The strategy, as outlined in Figure S1 in the Supplementary Data, is the same as that used for the integration of the VRS (34). Using this method, 260 bp of promoter region of the GAL2 gene harboring four upstream activation sequences (UASs), which are target sites of Gal4 (24), can be introduced into yeast chromosomes. Hereafter, we refer these 200-bp and 260-bp sequences as VRS and UAS, respectively.

We first introduced UAS into the HIS3 gene locus and examined induction of meiotic DSBs in sae2Δ strains, which enabled us to detect DSBs formed by Spo11, as the DSBs cannot be repaired in the background (40,41). Southern blot analysis revealed that Gal4BD-Spo11 caused meiotic DSBs (7.4% at 9 h) at sites of integration of UAS (Figure 1A). The formation of DSB depends on the UAS integration and on expression of Gal4BD-Spo11 (Figure 1A). Subsequently, recombination was also examined by measuring the genetic distance between flanking marker genes (Figure 1B). In the GAL4BD-Spo11 strain, an increase in the genetic distance between markers indicated that UAS integration led to a higher frequency of crossovers (Figure 1B). Thus, introduction of UAS can induce meiotic DSB and recombination accompanied by frequent crossovers, a phenomenon common to endogenous hotspots.

Ectopic insertion of external sequences into chromosomes sometimes creates an open chromatin site, which is suitable for meiotic DSB formation (10–12,42). We next explored chromatin structure around the integrated UAS
or VRS by indirect end-labeling analysis of MNase-digested chromatin. Figure 1C shows positions of individual nucleosomes and nuclelease-sensitive sites around HIS3 in the presence and absence of an integrated element. Relatively strong and discrete sites of MNase sensitivity were specifically observed at the inserted UAS but little sensitivity was observed at the VRS (Figure 1C). It is likely that cis-acting element(s) in UAS function(s) to form an open chromatin configuration, because the authentic GAL2 promoter also displays an open chromatin configuration (24). Although DSBs were not observed on the UAS integrated at HIS3 in the SPO11 strain (Figure 1A), it should be noted that the UAS insertion provides an open chromatin structure, a potential site for meiotic DSB (See below).

Gal4BD-Spo11 induces DSBs at UASs integrated in hot domains but rarely in cold domains

Robine et al. (25) recently reported that binding of Gal4BD-Spo11 per se does not necessarily produce DSBs and that the frequency of occurrence of DSBs at a Gal4-binding site is influenced by the surrounding chromosomal context. As described above, DSB hotspots are concentrated in hot domains and rarely observed in cold domains. To explore a domain effect on targeted DSB formation by Gal4BD-Spo11, we chose six gene loci in chromosome III, two of which are in a hot domain and four of which are in a cold domain (Figure 2A). UAS was integrated in the open reading frame region of each gene with the exception of YCR099C, where UAS was inserted 1.2-kb downstream of the stop codon. In cells harboring UAS at HIS4 or YCR048W, which are within a hot domain, DSBs were frequently observed at the UAS integration site (Figure 2B). In contrast, little or no DSB signal was detected at the UAS integrated in CWH43, YCP4 or YCR099C, each of which is located in a cold domain (Figure 2B). Significant levels of DSBs were detected at the UAS inserted at YCL056C in a cold domain, but the frequency was smaller than what was observed for UAS insertions in hot domains (Figure 2B and C). Thus, it appears that Gal4BD-Spo11 can form DSBs at UASs integrated in hot domains but less effectively at those in cold domains.

Since UAS integration results in an open chromatin structure (Figure 1C), creating a potential site for DSB formation, we next asked if wild-type Spo11 could introduce meiotic DSBs at sites of UAS integration. As expected, in cells expressing Spo11, DSBs were formed at UASs inserted in a hot domain, but the effect was less robust than what was observed in strains expressing calculated using the following formula: cM = 100 (TT + 6NPD)/2 (PD + TT + NP). The HIS or his3::UAS strain was obtained by mating TFY179 and TFY181, or TFY180 and TFY182, respectively. (C) Meiotic chromatin (4h) was purified from SPO11 cells without (none, strain MJL1720), or with integration of VRS (his3::VRS, strain TFY236) or UAS (his3::UAS, strain TFY237) at the HIS3 gene. Each chromatin sample was treated with 0, 5, 10 or 20 U/ml of MNase. MNase-sensitive sites were detected by indirect end labeling using a probe for the sequence adjacent to the SphI site. The vertical gray arrows indicate the positions of the coding region of HIS3.
Gal4BD-Spo11 (HIS4, Figure 2D; YCR048W, Figure 4A; CYS3, Figure S2 in the Supplementary Data). In contrast, Spo11-mediated DSBs were not observed when UAS was inserted in a cold domain (YCL056C, Figure 2D). Thus, we can conclude that UAS-derived open chromatin sites are sufficient to induce meiotic DSBs in a hot domain. Moreover, forcible recruitment of Spo11 to a UAS via fusion with Gal4BD further increases the frequency of DSBs in hot domains but can overcome the cold nature of a domain only to a very limited extent.

Meiotically induced self-association of Spo11 occurs in a hot domain but not in a cold domain

To explore possible causes of the domain effect on DSB formation, we assessed chromosome accessibility and cleavability at each of the loci we tested. First, ChIP assays revealed that Gal4BD-Spo11 bound the UAS to a similar extent at each integration site (Figure 3A). Thus, the data show that the domain effect cannot simply be attributed to accessibility to Gal4BD-Spo11, consistent with the results of Robine et al. (25). Second, we examined the frequency of VDE-produced DSBs at VRSs inserted in the same loci. Diploid strains heterozygous for the VRS-inserted allele and a URA3-inserted allele at each gene locus were prepared and the frequency of DSB formation in each was measured by determining the unidirectional gene conversion rate of the VRS-inserted allele to the URA3-inserted allele. As shown in Figure 3B, VDE efficiently induced recombination regardless of location, indicating that cold domains are also accessible to VDE...
and that cold domains are not regions of uncleavable chromosome structure. Next, we tested whether chromosome core components have a role in the domain effect as the distribution of meiotic DSBs appears to be influenced by that of chromosome axis and chromatin loops (17,18,20). DSB formation by Gal4BD-Spo11 at the CWH43 locus, which is located in a cold domain, was analyzed in the absence of the meiotic cohesin component, Rec8, or the AE protein, Red1, both of which are main components of the chromosome axis during meiosis (18,43,44). We found that DSB formation was not restored at the UAS integrated at CWH43 in either mutant strain (Figure 3C), suggesting that the domain effect cannot be attributed to differences in chromosome structure mediated by these proteins.

Figure 3. Exploring the causes of the domain effect of meiotic DSB. (A) Chromatin binding of Gal4BD-Spo11 at UAS inserted in each gene locus. In the UAS-inserted cells (∆P_{GAL2}), authentic UAS at the upstream region of GAL2 is deleted so that they should contain a single copy of UAS only at the insertion site, whereas non-inserted cells (wild-type) have UAS only at the GAL2 site. Gal4BD-Spo11-Flag and Spo11-Flag were expressed during both mitosis and meiosis, as they are under the control of the ADH1 promoter. For premeiotic cells (0 h), ChIPs were performed as described in Materials and Methods section. DNA purified from the immunoprecipitations was subjected to quantitative real-time PCR using primers specific to UAS or the telomere region of chromosome VI (TEL). Error bars denote the standard deviation among three independent experiments. The cells used were GAL4BD-SP011-FLAG strains harboring UAS at YCL056C (strain TFY277), HIS4 (strain TFY278), YCP4 (strain TFY279), CWH43 (strain TFY280), YCR048W (strain TFY281), or YCR099C (strain TFY282), GAL4BD-SP011-FLAG strain without UAS-integration (strain TFY262) and SP011-FLAG strain without UAS-integration (strain TFY325). (B) Frequency of VDE-induced recombination at the indicated sites. For each gene locus, strains heterozygous for the VRS-integrated allele (derivatives of strain TFY286) and the URA3-integrated allele (derivatives of strain YOC3685) were constructed. Recombination frequency was calculated based on the segregation pattern of URAS for at least 44 four-spore-viable tetrads per one experiment. Error bars denote the standard deviation among three independent experiments. (C) A deletion of a gene encoding a chromosome core protein was introduced into the GAL4BD-SPO11 strain that contains UAS integration at the CWH43 gene locus indicated by the arrow. Southern blot analysis was performed as in Figure 2B. Lanes 1–4, strain TFY081; lanes 5–8, strain TFY082; lanes 9–12, strain TFY083. (D) Meiotic association of Spo11-Flag with UAS mediated by Gal4BD-Spo11. ChIP was performed on premeiotic (0 h) and meiotic (3 h) cells. All forms of Spo11 were expressed during both mitosis and meiosis, as they are under the control of the ADH1 promoter. The strains have three copies of the GAL2 promoter, two of which are integrated at HIS4 and CWH43 and the other of which is at the authentic site (GAL2). Binding of Spo11-Flag to each UAS in the absence (strain TFY091) or presence (strain TFY092) of Gal4BD-Spo11 was examined with primers specific to sequences adjacent to each UAS.
with Gal4BD-Spo11 (35). Using this system, we examined whether Spo11 self-interaction occurs at UASs located in the CWH43, HIS4 and GAL2 loci. As expected, in a strain co-expressing Spo11-Flag and Gal4BD-Spo11, Spo11-Flag was recruited onto the UASs of co-expressing Spo11-Flag and Gal4BD-Spo11, Spo11—shown (lower panel). A longer exposure of the blot is also detected by Southern blot analysis with a probe specific to the end of HIS4, YCR048W or VRS at the left arm. However, Spo11-Flag was not detected on the UAS during meiosis as observed by ChIP (Figure 3D).

Effects of UAS insertion near meiotic DSB hotspots

Hotspots that are present in close proximity to one another have been observed to compete for meiotic DSB formation in some chromosome contexts but not in others (11,12,16,45). To systematically study interactions among hotspots, we constructed strains harboring UAS or VRS proximal to well-known hotspots and then assessed DSB formation around the hotspots. Experiments were performed using the VMA1(−) strain, which does not express VDE. Around the YCR048W locus, two major hotspots (Figure 4A, sites I and II) exist and an additional hotspot (Figure 4A, site G) appears when Gal4BD-Spo11 is expressed (24). We constructed strains in which UAS or VRS was integrated in the YCR048W gene about 1.3 kb away from the site I hotspot, and examined DSBs in the strains by Southern blot analysis (Figure 4A). In the SPO11 strain, meiotic DSBs were observed at the UAS integration site (Figure 4A, lanes 9–12), probably due to the open chromatin structure created by UAS integration. We also noted a concomitant reduction in DSB signals at natural YCR048W hotspots (Figure 4A and B). By contrast, integration of VRS did not form DSBs at the integration site, nor did it reduce the frequency of formation of DSBs at neighboring hotspots (Figure 4A, lanes 5–9). Therefore, the lower level of hotspot activity near the UAS integration site is not a simple consequence of an artificial sequence interruption. Instead, it is more likely that competitive interactions among DSB sites occur around the UAS insertion. This notion is consistent with the observation that the total amount of DSBs in the 11-kb region around YCR048W appears to be nearly constant (Figure 4B), implying competition for DSB capacity in the region. Furthermore, in the GAL4BD-SPO11 strain, the integration of UAS resulted in more frequent DSB formation at the UAS, with DSBs at native hotspots much less frequent (Figure 4A, lanes 13–16). In contrast to what was observed for the SPO11 strain, in the UAS-integrated GAL4BD-SPO11 strain, the total DSBs within the 11-kb interval was much higher than in the strain without integration (Figure 4B). This suggests that Gal4BD-Spo11 allows recruitment of the DSB formation machinery to the integrated UAS more efficiently than wild-type Spo11, increasing the capacity for DSBs in this interval. This explanation is supported by chromosome-wide detection of DSBs, wherein DSBs were frequently induced at the UAS by Gal4BD-Spo11 and caused long-range repression within a >30-kb interval, such that the total number of DSBs was kept constant (Figure 4C).

We also introduced UAS or VRS into the CYS3 hotspot, where two major break sites can be detected. As shown in Figure S2, the results were similar to what was found for insertions at YCR048W. UAS insertion caused meiotic DSBs at the site and reduced nearby hotspot activity, whereas introduction of VRS at the same site had no effect. Although the UAS insertion in the SPO11 strain caused little alteration in the total amount

Figure 4. Repression of hotspot activity by UAS integration. (A) Southern blot analysis was performed on strains expressing Spo11 or Gal4BD-Spo11 without (none) or with integration of UAS or VRS at the YCR048W gene locus. All strains are sae2Δ background. The insertion site, two prominent natural hotspots (site I and II), and a Gal4BD-Spo11-dependent hotspot (site G) are indicated. Lanes 1–4, strain TFY372; lanes 5–8, strain TFY505; lanes 9–12, strain TFY504; lanes 13–16, strain TFY259; lanes 17–20, strain TFYO11. (B) Quantification of results obtained in (A). The amounts of DSB signal at 6 h are represented as a histogram. (C) Pulsed-field gels of undigested DNA from meiotic cells. DSBs along chromosome III were detected by Southern blot analysis with a probe specific to the end of the left arm. GAL4BD-SPO11 sae2Δ strains without (none, strain TFYO11) or with the UAS insertion at YCR048W (strain TFY259) or HIS4 (strain TFY256) are shown. A longer exposure of the blot is also shown (lower panel).
of DSBs around CYS3, Gal4BD-Spo11 stimulated DSBs at the inserted UAS at levels higher than the innate permissible level for the interval.

In contrast to YCR048W and CYS3, a different feature was observed around an UAS integration at the GAT1 hotspot on chromosome VI. When UAS was introduced 0.3 kb away from the GAT1 hotspot in the SPO11 strain, hotspot activity was severely repressed and DSBs were not detected at the inserted UAS (Figure 5B, lanes 1–8). Hotspot activity gradually increased as the UAS was inserted further from the hotspot, whereas DSB formation at the inserted UAS remained at lower than detectable levels (Figure 5B and C). Insertion of VRS at the same sites neither repressed DSB formation at the GAT1 hotspot nor caused DSBs at the insertion site (Figure 5B, lanes 17–32), indicating that inactivation of the GAT1 hotspot by the UAS insertion was not simply due to an interruption of the DNA sequence around GAT1. Thus, in this region, local UAS integration per se prevents nearby meiotic DSB formation. We further examined the effect of UAS integration around GAT1 in a strain expressing Gal4BD-Spo11. In the strain, DSBs were observed at the integrated UAS (Figure 5B, lanes 33–48) and GAT1 hotspot activity was slightly higher in comparison with the strain harboring UAS at the same site (Figure 5C). Thus, forced recruitment of the DSB formation machinery to the UAS may enhance the capacity to form DSBs at this region and thus overcome the inhibitory effects of the UAS insertion.

Next, we investigated possible causes of the inhibitory effect of UAS at GAT1. Binding of the transcription machinery affects some meiotic DSBs (8,9). To examine whether the binding of authentic Gal4 to UAS prevents GAT1 hotspot activity, we deleted the GAL4 gene and then assessed DSB formation around GAT1. As shown in Figure 5D, a gal4Δ mutation did not restore GAT1 hotspot activity in the UAS-inserted strains, indicating that prevention of DSB formation is not due to binding of Gal4 to the UAS.

We then examined the chromatin configuration around the GAT1 gene. As observed at the HIS3 gene locus, UAS insertions were associated with open chromatin (Figure 5E, arrowheads) whereas insertions of VRS were not. However, the chromatin configuration near the DSB site was independent of insertion, implying that prevention of hotspot activity by UAS integration is not attributed to the alteration in chromatin configuration at the GAT1 hotspot. These data raise the possibility that two neighboring open chromatin sites (i.e. potential sites of meiotic DSB formation) compete for the DSB formation machinery, leading to reduced activation at both sites (See Discussion section).

**VDE-mediated DSB formation reduces proximal hotspot activity**

As shown above, an UAS insertion near GAT1 hotspot repressed hotspot activity without inducing DSB formation at the UAS, implying that interactions among hotspots may occur before or during DSB formation. To examine whether a DSB itself can affect nearby DSB formation, we next tested the effects of VDE-mediated DSBs on hotspot activity. We integrated VRS around the GAT1 hotspot in a VMA1(+) strain that expresses VDE. As shown in Figure 6A, VDE-mediated DSBs were induced at the inserted VRS site during meiosis. Parental bands and VDE-produced DSB fragments gradually disappeared at later time points probably because VDE efficiently cleaved all chromatids and eliminated intact templates for recombinational repair, resulting in continuous DSB end resection. DSB formation at the GAT1 hotspot was severely impaired when VDE-mediated DSBs occurred at sites located 0.3, 1.3 or 2.3 kb away from the hotspot (Figure 6A). The reduction of GAT1 hotspot activity was also seen in strains in which VRS was integrated more than 10 kb away from the hotspot, and DSB formation was partially restored when VRS was inserted 19 kb away from the hotspot (Figure 6A and B). Quantification results indicate that DSBs at the hotspot are reduced more profoundly than parental signals, suggesting that the DSB reductions were not simply due to the loss of chromosome by resection (Figure 6B).

Similarly, reduction in hotspot activity was also observed at the YCR048W hotspot when VDE-mediated DSBs were introduced proximally (Figure 6C and D). Figures 4A and 5B show that the VRS insertion itself does not affect hotspot activities, indicating that the observed reductions are due to VDE-mediated DSBs. Moreover, VMA1(+) strains harboring VRS around GAT1 displayed normal DSB formation at the YCR048W hotspot and vice versa (data not shown), indicating that the influence of VDE-mediated DSB is local or regional. Thus, DSB formation at one site appears to prevent nearby DSB formation by Spo11 over regions of ~20 kb in length.

To study inhibition caused by VDE-mediated DSBs at the GAT1 hotspot in more detail, we prepared a diploid strain in which part of the BUD27 gene, which is upstream of GAT1, was replaced by a marker gene on one chromosome (Figure 7A, bud27::L) but not the other. This replacement enables us to detect each chromosome separately by Southern blot analysis with probes that recognize the BUD27 region that is present only on one chromosome (Figure 7A, M probe) or recognize the marker gene (Figure 7A, P probe). We introduced VRS 2.3 kb away from the GAT1 hotspot on one homolog but not on the other. These strains are useful to examine the effect of VDE-mediated DSB on the cleaved chromosome (cis effect) and on the other intact homologous chromosome (trans effect). Southern blot analysis revealed that replacement of a part of BUD27 does not affect hotspot activity on either chromosome (Figure 7B, lanes 1–6 and 19–24). As expected, Spo11-mediated DSBs at the GAT1 hotspot were severely reduced on the VDE-cleaved chromosome (Figure 7B, lanes 7–12 and 31–36). Interestingly, a significant reduction in DSB formation at the hotspot was observed on the non-cleaved homologous chromosome (Figure 7B lanes 13–18 and 25–30; Figure 7C), implying a trans effect. Thus, the number of meiotic DSBs in each hot region may be regulated by at least two repression mechanisms, competition for
Figure 5. Repression of DSBs at the \textit{GAT1} hotspot by UAS integration. (A) Schematic representation of the \textit{GAT1} hotspot region. The gray arrows indicate the position and orientation of the coding region for each gene. The positions of \textit{PstI} sites and a probe for detection of DSBs and UAS or VRS integration sites are indicated. (B) Detection of \textit{GAT1} hotspot activity by Southern blot analysis. UAS (left and right panel) or VRS (middle panel) was integrated 0.3, 1.3 or 2.3 kb away from the hotspot in strains expressing Spo11 (left and middle panel) or Gal4BD-Spo11 (right panel). DNA was purified from synchronous meiotic cells at the indicated times after incubation in SPM, digested with \textit{PstI}, and analyzed using the probe as shown in (A). Strains without integration are designated ‘none’. All strains are \textit{sae2}Δ background without VDE-expression. Strains are derivatives of TFY372 (lanes 1–16), TFY311 (lanes 17–32) or TFY011 (lanes 33–48). (C) The intensities of signals corresponding to DSBs at the \textit{GAT1} hotspot were quantified and expressed as a mean of at least three independent experiments. (D) Southern blot analysis was performed as in (B) on strains without (none, strain TFY431) or with integration of UAS 0.3 kb (strain TFY432) or 1.3 kb (strain TFY433) away from the \textit{GAT1} hotspot. Strains have \textit{sae2}Δ and \textit{gal4}Δ mutations. (E) Meiotic chromatin (4 h) was purified from the \textit{SPO11} strain without integration (none, strain TFY371) or its derivatives with integration of VRS or UAS 0.3 or 1.3 kb away from the \textit{GAT1} hotspot. Each chromatin sample was treated with 0, 5 or 10 U/ml of MNase. MNase-sensitive sites were detected by indirect end labeling using a probe for the sequence adjacent to the SalI site. The arrowheads show MNase-sensitive sites at the UAS insertion.
activation of DSB among candidate sites and inhibitory
effect to candidate sites by a neighboring DSB. Moreover,
the latter regulation appears to contain a fully inhibitory
cis effect and a partial trans effect.

**DISCUSSION**

In this report, we studied the effects of targeted meiotic
DSB formation induced by Gal4BD-Spo11 and VDE in
order to obtain insights into regulation of the distribution
of meiotic DSBs. The PCR-based method enables us to
easily introduce single or multiple integrations of a sequence containing the VDE-cutting site (VRS) or containing four Gal4-binding sites (UAS) into the yeast genome using a fixed set of oligonucleotide primers. Introduction of UAS leads to an open chromatin structure
at the insertion site (Figures 1C and 5E), creating
a potential site for meiotic DSB formation. Indeed, DSBs

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**Figure 6.** Repression of hotspot activity by VDE-produced DSBs. (A) VRS was integrated 0.3, 1.3, 2.3, 11 or 19-kb downstream or 16-kb upstream of the GAT1 hotspot into the sae2Δ strain expressing VDE (none, strain TFY312). GAT1 hotspot activity was examined by Southern blot analysis as in Figure 5. The asterisks indicate sites of the bands detected especially in the +11-kb insertion strain, which might stem from products formed during the repair process of VDE-introduced DSBs since the bands were detected in spo11Δ cells (data not shown). (B) As in (A), using VDE-expressing sae2Δ cells without (none) or with VRS integration 19-kb downstream of the GAT1 hotspot (strain TFY407), the intensities of signals corresponding to parental bands (left) and DSBs at the GAT1 hotspot (right) were determined by normalizing to an internal standard in each lane using an appropriate probe (HIS4). Values are expressed as a mean of three or four independent experiments with standard deviation. (C) VRS was integrated 1.3, 15 or 16 kb away from the YCR048W hotspot into the sae2Δ strain expressing VDE (none, strain TFY312). Southern blot analysis was performed as described for Figure 4. (D) As in (C), using VDE-expressing sae2Δ cells without (none) or with VRS integration 15 kb away from the YCR048W hotspot (strain TFY408), the intensities of signals corresponding to parental bands (left) and DSBs at the YCR048W hotspot (site I, right) were determined as described in (B). Values are expressed as a mean of four independent experiments with standard deviation.
Figure 7. Cis and trans effects of VDE-mediated DSBs on hotspot activity. (A) Schematic representation of the \textit{GATI} hotspot region in the \textit{BUD27/bud27::L} heterozygous diploid strain. Part of the \textit{BUD27} gene is replaced by the \textit{CgLEU2} gene on one homologous chromosome (P) of the diploid strain but not on the other (M). A probe specific to \textit{CgLEU2} (P probe) and a part of \textit{BUD27} corresponding to the deletion in P (M probe) can be used to detect the homologous chromosomes P and M, respectively. (B) VRS was introduced 2.3 kb away from \textit{GATI} hotspot on either the P chromosome (\textit{bud27::L VRS}) or the M chromosome (\textit{BUD27 VRS}). Systematic integrations of UAS along chromosome III revealed that DSBs tend to be introduced at UAS when it is inserted in a hot domain but rarely occur when it is inserted in a cold domain. This kind of domain effect has been reported by others using chromosome-wide insertion of sequence from the \textit{ARG4} hotspot (11,21) or genome-wide comparison of binding sites and cleavage sites of \textit{Gal4BD-Spo11} (25). Furthermore, it has been revealed that insertion of \textit{Gal4}-binding site near centromere III allows binding of \textit{Gal4BD-Spo11} but prevents DSB formation at the site due to an inhibitory effect by the centromere (25). Here, we also demonstrated that a cold domain is not a region of inaccessible or uncleavable chromosome structure (Figure 3). This is consistent with the previous result that cold and hot domains are similarly accessible to DNase I and topo-isomerase II (21). Moreover, self-association of Spo11 does not occur at UAS in a cold domain (Figure 3D). The data suggest that not all Spo11 localized to a chromosome self-assembles and furthermore that self-interaction of Spo11 is likely to be regulated in a chromosome-domain-dependent manner. Thus, we propose that the domain effect of meiotic DSBs is regulated through activation of Spo11 in hot domains or through inhibition of Spo11 in cold domains. In addition to Spo11, at least nine other proteins have been implicated in meiotic DSB formation in \textit{S. cerevisiae}. These proteins are thought to form a large complex consisting of multiple sub-complexes that localize to chromatin (46,47). Among them, Rec102 and Rec104 are required for self-interaction of Spo11 (35). Rec114 is dispensable for Spo11 self-interaction, but is required for meiotic loading of Spo11 to DSB sites (4,35). Therefore, it may be that the local distribution or activation of one or more of these proteins along chromosomes determines sites of DSB via promotion of Spo11 self-assembly on the chromatin.

In addition to studying the domain effect along a chromosome, we also analyzed competitive interactions among hotspots. Introductions of UAS in the vicinity of well-known hotspots revealed two types of effects. One was observed at \textit{YCR048W} (Figure 4) and \textit{CY3} (Figure S2 in the Supplementary Data) and the other was observed at \textit{GATI} (Figure 5). The former case is consistent with the model of competition for DSB chromosome (\textit{BUD27 VRS}) of the \textit{BUD27/bud27::L} heterozygous diploid strain. Southern blot analysis was done using the P or M probe to detect each homologous chromosome (upper panel, P chromosome; lower panel, M chromosome). The asterisk indicates a site of cross-hybridization with the P probe, which might be attributable to the authentic \textit{LEU2} gene locus. All strains are \textit{sae2} background expressing VDE. Lanes 1–6 and 19–24, strain TFY062; lanes 7–12 and 25–30, strain TFY063; lanes 13–18 and 31–36, strain TFY064.

(C) Quantification of results obtained in (B). The intensities of signals corresponding to DSBs at the \textit{GATI} hotspot were quantified and expressed as a mean of four independent experiments with standard deviation.
among hotspots, in that the production of a new hotspot reduces DSB activity at nearby pre-existing hotspots, keeping the overall level of DSBs constant. Previously, mutual inhibition among hotspots has been revealed to occur both over a short range (11,12,16,24) and a long range (11,25,48). Here, we revealed that the extent of repression is higher when DSB activity is stronger at a given site. In the case of GAT1, an UAS insertion at GAT1 in the SPO11 strain reduces hotspot activity despite the fact that DSBs are not formed at the inserted UAS. This case can also be explained by competition. That is, insertion of UAS provides a potential site for meiotic DSB and then competition between the authentic hotspot and the UAS takes places, resulting in a lack of sufficient activation of DSB at either site. A similar type of repression has been reported previously: insertion of 12 tandem repeats of a nucleosome-excluding sequence generates a strong DSB hotspot, whereas insertion of 48 copies does not (49).

It is conceivable that competitive interaction among hotspots can be attributed to competition for limiting factor(s) involved in DSB formation. Spo11 is not likely to be the sole candidate for such a limiting factor, since Spo11 is abundant during meiosis and only a small fraction of the available Spo11 forms intermediate products during the formation of DSBs (50). Moreover, a mutant allele of SPO11 defective in DSB formation does not lead to a strong dominant negative phenotype in combination with a wild-type allele, as might be expected if Spo11 were the limiting factor (26). Therefore, other component(s) of the DSB formation complex may be titrated out in a certain chromosomal regions, such that competition among DSB hotspots takes place. Alternatively, it might be that the DSB formation complex is very large or forms a specialized DNA or chromosome structure, for example, a highly bended or distorted configuration, such that the presence of a complex at one site makes it difficult or impossible for another complex to be formed nearby. If the complex generates such a specialized chromosome structure, it would be possible that meiotic chromatin transition observed at active DSB sites reflects such a specialized structure (14,37).

Intriguingly, DNA cleavage by VDE represses DSB formation over a region of ~20 kb in length (Figure 6), implicating formed DSB itself in interactions among hotspots. DSB formation by VDE apparently occurs via a pathway parallel to that mediated by Spo11, since VDE can cleave its target in the absence of the Spo11 DSB formation complex (30) and without regard to the chromosomal context of its target (Figure 3B). Hence, in addition to competition for factors involved in DSB formation, it is likely that there is also a mechanism for restricting the number of DSBs that recognizes a DSB at one site and transmits the signal to prevent DSB formation at neighboring other potential sites. Several studies on mitotic cells suffering a DSB have revealed that after cleavage, DSB ends are subjected to multiple interdependent or independent processes, including DNA end resection, chromatin remodeling, histone modification and recruitment of repair proteins or cohesin complex (51). It is currently not known if these are relevant to meiotic cells, however, it seems reasonable that one or more of these processes might affect the DSB formation machinery and inhibit Spo11-mediated DSBs near an existing cleavage site. For example, it is conceivable that resection of DSB ends removes the DSB formation complex from DNA. Alternatively, DSB-induced nucleosome remodeling or histone modification may alter the chromatin configuration or histone code required for DSB formation (9,52–54). A further possibility is that loading of the cohesin complex onto DSB sites may help to recruit the DNA region into the chromosome axis, where DSBs rarely occur. Indeed, phosphorylation of histone H2A (55) or loading of cohesin (56,57) has been observed to occur over a large region (~50 kb) surrounding a DSB, a region sufficient in size to explain DSB repression by VDE observed in our study. It is also possible that DSB repair proteins loaded around the DSB site inactivate or replace the DSB formation complex.

Some repair proteins can invade or capture a homologous chromosome as well as a broken chromatid, explaining the trans inhibition of DSBs observed at an intact homologous chromosome (Figure 7). In addition to these factors, which act upon DSB ends directly, we should consider the possibility of mechanical or physical aspects of DNA caused by DSB as discussed in crossover controls (58,59). For example, it might be that DSB formation at a site alters the mechanical forces on DNA that are a prerequisite for DSB formation by Spo11, such as alteration in regional DNA topology, an increase or decrease in mechanical stress or release of a tension. Theses mechanical or physical factors may help to explain the rapidly and locus-specific suppression of DSBs in a region already containing a break.

The domain effect restricts the positioning of DSBs within particular hot domains and the interaction among hotspots limits the number of DSBs. During meiotic recombination, crossover interference and crossover homeostasis tightly regulate the distribution of crossovers (59,60). To ensure that DSBs are sufficiently abundant also seems important, since mutant strains that produce fewer DSBs also have reduced viability during meiosis (26). On the other hand, excess production of DSBs should also be avoided, since DSBs are deleterious lesions that can cause genomic instability and dose-dependent cell death. Therefore, ensuring and limiting the number of DSB seems an essential point of regulation for cell integrity. Furthermore, the location of DSBs also seems important, since formation of a chiasma at an inappropriate site can lead to chromosome missegregation (27).

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SUPPLEMENTARY DATA
Supplementary Data are available at NAR Online.

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