HP1γ links histone methylation marks to meiotic synapsis in mice

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SUMMARY
During meiosis, specific histone modifications at pericentric heterochromatin (PCH), especially histone H3 tri- and dimethylation at lysine 9 (H3K9me3 and H3K9me2, respectively), are required for proper chromosome interactions. However, the molecular mechanism by which H3K9 methylation mediates the synapsis is not yet understood. We have generated a Cbx3-deficient mouse line and performed comparative analysis on Suv39h1/h2, G9a- and Cbx3-deficient spermatocytes. This study revealed that H3K9me2 at PCH depended on Suv39h1/h2-mediated H3K9me3 and its recognition by the Cbx3 gene product HP1γ. We further found that centromere clustering and synapsis were commonly affected in G9a- and Cbx3-deficient spermatocytes. These genetic observations suggest that HP1γ/G9a-dependent PCH-mediated centromere clustering is an axis for proper chromosome interactions during meiotic prophase. We propose that the role of the HP1γ/G9a axis is to retain centromeric regions of unpaired homologous chromosomes in close alignment and facilitate progression of their pairing in early meiotic prophase. This study also reveals considerable plasticity in the interplay between different histone modifications and suggests that such stepwise and dynamic epigenetic modifications may play a pivotal role in meiosis.

KEY WORDS: HP1γ, PCH, Synapsis, Centromere clustering, Mouse

INTRODUCTION
Eukaryotes produce viable gametes for sexual reproduction by meiosis, during which the genetic material can be interchanged between paternal and maternal chromosomes and the DNA content of the precursor cell is halved by two successive cell divisions. The meiotic process in most organisms comprises pairing, synapsis, recombination and two successive meiotic divisions. In virtually all organisms, the homologous chromosomes pair along their length, connected along the entire length by the synaptonemal complex and eventually become locked together by recombination. Previous genetic studies mainly in plants, Drosophila, fission and budding yeast shed light on the role of centromeric heterochromatin in homolog pairing and synapsis (Prieto et al., 2004; Dernburg et al., 1996; Ding et al., 2004; Kemp et al., 2004; Tsubouchi and Roeder, 2005). Intriguingly, recent studies in budding yeast suggest that centromere pairing occurs in a sequence-independent manner and involves a non-homologous association and re-sorting processes that couples homologous centromeres (Tsubouchi and Roeder, 2005). Therefore sequence-independent recognition of centromeric regions appears to be a crucial early step in creating meiotic chromosome associations. This model leads to the prediction that this centromere pairing involves chromatin proteins that probably give rise to pericentric heterochromatin (PCH).

Based on previous genetic studies, epigenetic regulation at PCH is suggested to play a crucial role in meiotic prophase. SET-domain proteins, Suv39h1 and Suv39h2, which mediate H3K9me3 at PCH, were shown to be involved in chromosome interactions and subsequent segregation during meiosis (Peters et al., 2001). Another histone methyl transferase (HMTase), G9a, which mediates transient H3K9me2 deposition at PCH during early meiotic prophase, was also shown to be required for synchronous synapsis (Tachibana et al., 2007) (see Fig. S1 in the supplementary material). However, the molecular mechanism by which H3K9 methylation mediates the synapsis is not yet understood.

This study is thus designed to clarify how the functions of two different H3K9 methylation marks are linked and integrated to mediate synapsis during the meiotic prophase. To this end, we focused on heterochromatin protein 1 (HP1) family proteins – evolutionarily conserved chromo-domain proteins that are involved in recognition of H3K9 methylation and localize to heterochromatic regions, including PCH (Metzler-Guillemain et al., 2003; Pidoux and Allshire, 2005). HP1 proteins are also essential for heterochromatin silencing in various organisms and do so by recruiting a vast range of effector molecules (Nakayama et al., 2001; Cheutin et al., 2003; Pidoux and Allshire, 2005). HP1 proteins are also essential for heterochromatin protein 1 (encoded by Cbx3) (Lomberk et al., 2003; Cheutin et al., 2003; Pidoux and Allshire, 2005). HP1 proteins are also essential for heterochromatin protein 1 (encoded by Cbx3) (Lomberk et al., 2003; Cheutin et al., 2003; Pidoux and Allshire, 2005). HP1 proteins are also essential for heterochromatin protein 1 (encoded by Cbx3) (Lomberk et al., 2003; Cheutin et al., 2003; Pidoux and Allshire, 2005). HP1β (encoded by Cbx1 and Cbx3) (Lomberk et al., 2006). It is noteworthy that HP1γ has been shown to form complexes with G9a (Ogawa et al., 2002). Based on genetic studies in Drosophila, mutations in the HP1 protein, which localizes to PCH, eliminate repression of marker genes lying in close proximity to centromeric heterochromatin and cause defective chromosome segregation (Kellum and Alberts, 1995). It has also been reported

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that in the fission yeast, mutations of silencing factors clv4+ and rkl1+ disrupt the localization of the Swi6p (a yeast homolog of HP1) and cause impairment of centromeric functions (Ekwall et al., 1996). Together, these observations suggest that the HP1 family of proteins may have a functional role, for example, to link Suv39h1/h2 and G9a via H3K9me3 recognition at the PCH for the progression of meiotic prophase.

To test this hypothesis, we isolated a mutant Cbx3 allele and performed a comparative genetic approach using mice deficient for Suv39h1/h2, G9a and Cbx3. Our study revealed that H3K9me2 at PCH depended on Suv39h1/h2-mediated H3K9me3 and on its recognition by HP1γ. We further found that centromere clustering and synopsis were commonly affected in G9a- and Cbx3-deficient spermatocytes. These genetic observations suggest that HP1γ/G9a-dependent PCH-mediated centromere clustering is an axis for correct chromosome interactions during meiotic prophase.

MATERIALS AND METHODS

Mice

Cbx3-KO mice were generated by the gene trap method described previously (Naruse et al., 2007). To determine the genotype of mutant mice, genomic PCR was performed using Cbx3 F (5′-GAGTGATT-ACCGACACACCCA-3′) and Cbx3 R (5′-TTTTAATCGGAGACTTG-AAGACG-3′) in intron 1 for the wild-type allele, and Cbx3 F and primer 3 (5′-GTTCCCCCTTCTCGCTTCTGT-3′) in the trap vector for the mutant allele. Briefly, Suv39h1/2 double null mice were maintained on a mixed genetic background of 129/Sv and C57Bl/6J origin (Peters et al., 2001). Double heterozygotes were mated to generate double homozygotes. G9a conditional allele was also maintained on a mixed genetic background of 129/Sv and C57Bl/6J origin (Tachibana et al., 2007). Briefly, germ-line-specific G9a-KO mice were generated by crossing G9afllox/ﬂox females with TNP-Cre, G9aﬂox mice by cross-breeding.

Immunofluorescence of meiotic cell spreads and testes sections

For immunofluorescence analysis, germ cells were isolated from male and female mice of each genotype and prepared using a ‘draining-down’ technique (Peters et al., 1997) with the following modifications. To obtain the germ cells, testes were sliced by needles in phosphate-buffered saline (PBS) supplemented with 10% fetal bovine serum (FBS). Cell suspension was filtered with 100 µm and 50 µm mesh to remove the debris. After centrifugation, cells were placed in 100 µl of hypotonic extraction buffer for 8 minutes. After several washes with PBS, we adjusted the germ cell number to 1×10⁶. Cells were resuspended (10 µl) with 10 µl of sucrose solution and then placed on glass slides that had been dipped in fixation solution. After a cell suspension was slowly dispersed, the slides were dried for 1 hour in a closed box with high humidity and then for 30 minutes in an opened box. After preparation, slides bearing cell spreads were processed using standard procedures. The antibodies used for immunofluorescence analysis in this study were: anti-dimethyl-Histone H3 (Lys9), rabbit, 1:100, Millipore; anti-dimethyl-Histone H3 (Lys9), mouse, 1:300, Abcam; anti-trimethyl-Histone H3 (Lys9), rabbit, 1:100, Millipore; anti-trimethyl-Histone H3 (Lys9), mouse, 1:300, Abcam; anti-HP1γ, rabbit, 1:300, NOVUS; anti-SYCP3, mouse, 1:300, NOVUS; anti-SYCP1, rabbit, 1:250, NOVUS; anti-HP1β, mouse, 1:50, US Biological; anti-HP1β, rat, 1:50, Serotec; anti-HP1α, mouse, 1:50, Euromedex; anti-G9a, mouse, 1:50, PMMX; anti-centromere antibody (ACA), human, 1:50 (Muro et al., 1991); CREST, mouse, 1:50, a gift from Dr Earnshaw (Edinburgh University, UK); Mvh, mouse, 1:100, Upstate; anti-phospho-H2A.X(Ser139), rabbit, 1:300, Millipore; anti-ATR, goat, 1:50, Santa Cruz; anti-trimethyl-Histone H4 (Lys20), rabbit, 1:100, Biolegend; anti-Kit, rat, 1:10, eBioscience; anti-Piz, rabbit, 1:300, Santa Cruz; anti-mouse IgG(H+L) Alexa 488, goat, 1:300, Invitrogen; anti-mouse IgG(H+L) Alexa 568, goat, 1:300, Invitrogen; anti-mouse IgG(H+L) Alexa 647, goat, 1:300, Invitrogen; anti-rabbit IgG(H+L) Alexa 488, goat, 1:300, Invitrogen; anti-rabbit IgG(H+L) Alexa 568, goat, 1:300, Invitrogen; anti-rabbit IgG(H+L) Alexa 647, goat, 1:300, Invitrogen; anti-human IgG(H+) Alexa 488, goat, 1:300, Invitrogen; anti-rat IgG(H+L) Alexa 488, donkey, 1:300, Invitrogen. Tests were fixed overnight in Bouin’s solution, embedded in paraffin and sectioned. After preparation, specimens were processed for immunofluorescence using standard procedures.

TUNEL staining

Testes sections were prepared as described above. Apoptotic cells were visualized by the terminal deoxynucleotidetransferase-mediated dUTP nick end-labeling (TUNEL) assay (In Situ Cell Death Detection Kit, AP; Roche, Germany).

Immunofluorescent in situ hybridization analysis

DNA fluorescent in situ hybridization was carried out after immunofluorescence with anti-SYCP1, anti-SYCP3 and anti-H3K9me3 antibodies. We used digoxigenin, Alexa488 and/or Cy3-labeled probes, prepared using a Nick Translation Kit (Roche), and hybridizations were carried out as previously described (Nakashima et al., 2005) with the following slight modifications. For a digoxigenin-labeled minor satellite specific probe, slides were re-fixed in 2% paraformaldehyde (PFA) for 10 minutes, then rinsed in PBS, dehydrated through an ethanol series (70%, 80%, 90% and 100%) and air dried. After the slides were dipped in 2× SSC buffer, they were denatured at 73°C for 3 minutes and dehydrated through a cold ethanol series (twice for 70%, 80%, 90% and 100%) and air dried. Hybridization reactions were carried out in humid chambers for 2 hours at 37°C. The slides were subjected to stringency washes at 37°C (twice with 2× SSC and 50% formamide, twice with 2× SSC) and then blocked (4× SSC and 5% skim milk) for 1 hour before probe detection. Probe detection was carried out using rhodamine-labeled anti-DIG antibody. Incubations were for 1 hour and slides were washed in 4× SSC and 0.1% TritonX-100. For the Cy3-labeled Chr2-Cen (BAC RP23-60E18) and Alexa488-labeled Chr4-Mid (Cosmid WI1-870P20) probes, slides were re-fixed in 4% PFA for 10 minutes, then rinsed in PBS and incubated in PBS supplemented with 20% glycerol. After four cycles of freeze-thawing in liquid nitrogen, we incubated the slides in 0.1 N HCl for 10 minutes. After the slides were dipped in 2× SSC buffer at room temperature and 2× SSC and 50% formamide at 4°C, they were denatured at 73°C for 5 minutes, dehydrated through a cold ethanol series (twice for 70%, 80%, 90% and 100%) and air dried. Hybridization reactions were carried out in humid chambers overnight at 37°C. We then subjected the slides to stringency washes at 42°C (twice with 2× SSC and 50% formamide, twice with 2× SSC and 0.1% Tween20) and PBS at room temperature.

Quantitative RT-PCR and bisulfite DNA sequencing analyses

Total RNA for quantitative RT-PCR analysis and genomic DNA for bisulfite DNA sequencing analysis were isolated from the testicular germ cells of 2-week-old Cbx3 heterozygous and homozygous mutant mice. We performed these analyses as described previously (Sharif et al., 2007).

Whole-mount immunofluorescence

The whole-mount immunohistochemical analysis was performed as reported previously (Ohmura et al., 2004). The antibodies used for whole-mount immunostaining are listed above.

RESULTS

H3K9me2 at PCH depends on Suv39h1/h2 during meiotic prophase

To examine the link between Suv39h1/h2 and G9a during meiotic prophase, we compared subnuclear localization of H3K9me3 and H3K9me2 and spermatogenetic defects in respective mutants. We found that H3K9me2 colocalized with H3K9me3 at the PCH intensely at the leptotene, but only weakly at the pachytene and diplotene stages (see Fig. S2 in the supplementary material) (Peters et al., 2001; Tachibana et al., 2007). Although H3K9me2 signals in the pachytene spermatocytes were much weaker than leptotene and zygotene, these were specific as we did not observe any signals in G9a-KO spermatocytes (Y.T., unpublished) (Khalil et al., 2004).
By using immunofluorescent in situ hybridization analysis for SYCP3 and SYCP1 proteins (Lammers et al., 1994; Meuwissen et al., 1992) and centromeric repeats, we observed that the meiotic defects in G9α-KO mice resembled those observed previously in Suv39h dominant-negative (dn) mice and most probably represent defects in the pairing of homologous chromosomes at early meiotic prophase (Peters et al., 2001) (Table 1; see Fig. S1 in the supplementary material). These results suggest that G9α may functionally be linked to Suv39h1/h2 to mediate the synopsis.

We went on to determine how the activities of G9α and Suv39h1/h2 are linked. Previous studies showed that inactivation of G9α did not perturb H3K9me3 in meiotic cells in male mice (Tachibana et al., 2007). We, therefore, asked whether disruption of H3K9me3 impairs H3K9me2 deposition. We analyzed the H3K9me2 pattern in meiotic spermatocytes from Suv39h dn (dn) mice and found the expected H3K9me2 defect in Suv39h dn spermatocytes as previously reported (Peters et al., 2001). This was accompanied by severe impairment of H3K9me2 deposition, spermatocytes as previously reported (Peters et al., 2001). These findings therefore suggest that among HP1 family members, HP1γ participates in the recognition of H3K9me3 at PCH and, therefore, suggest that HP1γ is a strong candidate as a molecular linker for H3K9me3 and H3K9me2 to mediate proper meiotic synopsis.

### HP1γ localization at PCH depends on H3K9me3 catalyzed by Suv39h1/h2

We went on to address the molecular mechanisms that link Suv39h to G9α. The HP1 family includes the key proteins that recognize methylated H3K9 at heterochromatic regions via their evolutionarily conserved chromodomain and, therefore, are attractive candidates for this role. Indeed, in mammalian cells H3K9me3 catalyzed by the Suv39h1/h2 enzymes has been shown to create a binding platform for HP1 at PCH (Lachner et al., 2001). Another study reported delocalization of HP1γ from PCH in Suv39h dn B-spermatogonia (Peters et al., 2001). These findings support our hypothesis that HP1γ is linked to epigenetic modifications of H3K9 at PCH.

HP1 proteins in mammals have three isotypes, HP1α, HP1β and HP1γ. In order to identify the most likely candidate(s), we performed immunofluorescent analysis to detect colocalization of HP1γ, HP1β and HP1γ with SYCP3 during meiotic prophase, consistent with previous findings in human testis (Metzler-Guillemin et al., 2003). HP1γ was present within broad domains of the PCH, in which different numbers of centromeres were clustered, from leptotene until just before the first meiotic division (see Fig. S3A in the supplementary material). By contrast, HP1β at the PCH was only weakly detected at leptotene, becoming more clearly visible beginning with the zygote stage (see Fig. S3B in the supplementary material). Bright focal distributions of HP1α were not detected at the leptotene stage but appeared at pachytene (see Fig. S3C in the supplementary material). These findings suggest that among HP1 family members, HP1γ is involved in the recognition of pericentric H3K9me3 at early meiotic prophase.

To further analyze the role of HP1γ in linking Suv39h1/h2 and G9α, we next performed a comparative analysis of the pericentric deposition of HP1γ in Suv39h dn and G9α-KO spermatocytes at early meiotic prophase. Quantitative immunofluorescence analysis revealed approximately 60% reduction of pericentric HP1γ deposition in Suv39h dn spermatocytes (n=60) (Fig. 1C). By contrast, obvious reduction of HP1γ deposition was not seen in G9α-KO spermatocytes (n=50) (Fig. 1D). These findings suggest that HP1γ participates in the recognition of H3K9me3 at PCH and, therefore, suggest that HP1γ is a strong candidate as a molecular linker for H3K9me3 and H3K9me2 to mediate proper meiotic synopsis.

### Meiotic catastrophe in Cbx3-deficient spermatocytes

We went on to analyze the role of HP1γ during meiosis by taking advantage of a gene-trap mutation where there has been a single insertion of a trap vector into the first intron of the Cbx3 gene (see Fig. S4 in the supplementary material). This insertion impairs the expression of Cbx3 in homozygous mutant mice (Cbx3-KO). As the Cbx3 genomic locus includes the divergently transcribed Hnrnpa2b1 gene, it is possible that transcription of this gene is concurrently affected by this insertion (Sato et al., 2001; Williams et al., 2005). We thus checked the expression of Hnrnpa2b1 and found that it was unaffected in Cbx3-KO (C.N., unpublished observations). With this compound background, homozygous mutants appeared in a similar ratio as previously reported and displayed growth retardation (Brown et al., 2010) (Y.T., unpublished).

We found that all Cbx3-KO males and most females were infertile with a single exception among more than 50 Cbx3-KO females, which gave birth to a single offspring after natural mating. Brown and colleagues also reported a similar result that the one adult Cbx3<sup>gfp<sub>hop/hop</sub></sup> female analyzed in their study had normal ovaries, although that female was sterile (Brown et al., 2010). Consistent with these reproductive defects, testes and ovaries from Cbx3-KO mice were reduced in size (Fig. 2A; Y.T., unpublished). In male mutants, we observed severe depletion of spermatocytes and post-meiotic cells (Fig. 2B). Accumulation of zygotene and pachytene spermatocytes was particularly affected in the Cbx3-KO mice (Fig. 2C). Careful histological analysis further revealed reduction of late leptotene spermatocytes (C.N., unpublished). These defects were associated with extensive apoptotic outbursts of germ cells in the seminiferous tubules (Fig. 2D). Taken together, we suggest that considerable numbers of Cbx3-KO spermatocytes are progressively deleted during early meiotic prophase.

To better understand the impaired meiotic phenotypes of the Cbx3-KO male mice, we checked meiotic synopsis by immunofluorescent in situ hybridization analysis (Fig. 2E). All

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**Table 1. Morphological alterations seen in pachytene spermatocytes in Cbx3- and G9α-KO mice at 15 dpp**

<table>
<thead>
<tr>
<th>Phenotypes</th>
<th>Frequency of chromosomes with respective phenotypes (%)</th>
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<td></td>
<td>Wild type</td>
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<td>Asynapsis of entire chromosomes</td>
<td>0.1</td>
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<td>Asynapsis at the telocentric regions</td>
<td>0.3</td>
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<td>Asynapsis at the middle regions</td>
<td>0.3</td>
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<tr>
<td>Asynapsis at the telomeric regions</td>
<td>0.3</td>
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<tr>
<td>Normal</td>
<td>99</td>
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Based on five categories of synaptic defects, we scored the frequency of chromosomes at pachytene stage spermatocytes in wild type (wt), Cbx3-KO and G9α-KO. The numbers of spermatocytes analyzed were as follows: wild type, n=154 from seven mice; Cbx3-KO, n=57 from three mice; G9α-KO, n=29 from two mice at 15 dpp.
Cbx3-KO cells (100%; n=97) showed some degree of asynapsis, affecting the autosomes or sex chromosomes, or both (Table 1). Synaptic failures in Cbx3-KO mice were further confirmed by dual staining with antibodies to SYCP3 and phosphorylated H2A.X (γH2AX) or ATR. Cbx3-KO spermatocytes with extensive asynapsis showed diffuse γH2AX and discontinuous ATR staining of unsynapsed chromosomes (see Fig. S5 in the supplementary material). A similar effect of Cbx3 loss on germ cell development and chromosome synapsis was seen in females (see Fig. S6A in the supplementary material). Cbx3-KO females exhibited severe and progressive depletion of oocytes during meiotic prophase and synaptic failures as revealed by immunostaining for γH2AX (see Fig. S6B,C in the supplementary material). Asynapsis to various extents was observed in 25% of chromosomes in Cbx3-KO pachytene spermatocytes whereas 75% of chromosomes normally synapsed (Table 1). These observations imply that HP1γ is dispensable for the synapsis but facilitates this process.

Interestingly, the asynaptic phenotype in Cbx3-KO pachytene spermatocytes occurred preferentially at the centromeric ends of the chromosome pairs (Fig. 2E; Table 1). Close examination of bivalents in the mutants that had undergone apparently normal synapsis revealed a centromeric abnormality, with a proportion of the homologous centromeric signals being staggered rather than showing complete colocalization, indicating a defect in the condensation of PCH (Fig. 2E,F). Consistent with these structural alterations involving centromeres, we observed various chromosomal aberrations that potentially emanated from defects in the pairing of homologous chromosomes, such as heterophilic interactions of chromosomal ends and univalency of homologous and sex chromosomes (Y.T. and Y.C., unpublished). These findings suggested that Cbx3-deficiency impaired the functions of PCH in the early meiotic prophase. These defects in Cbx3-KO meiotic germ cells were similar to those seen in Suv39h dn and G9a-KO mice (Peters et al., 2001; Tachibana et al., 2007), suggesting that the role of HP1γ is to link H3K9me3 with H3K9me2 at PCH.

**Recruitment of G9a to PCH depends on HP1γ**

We went on to test whether HP1γ is involved in the H3K9me2 modification at PCH by using immunofluorescence analysis. We indeed observed significant reduction of H3K9me2 levels at the
PCH in Cbx3-KO cells during meiotic prophase, suggesting that acquisition of this mark at the PCH depends on HP1γ (Fig. 3A,B; see Fig. S7 in the supplementary material). By contrast, obvious differences in H3K9me2 levels were not seen outside the PCH between the wild type and Cbx3-KO. Consistent with this, we found several G9a target genes still repressed in Cbx3-KO spermatocytes (Y.T., unpublished). These observations suggest that HP1γ mediates H3K9me2 at PCH by recognizing H3K9me3. Consistently, loss of HP1γ did not affect pericentric deposition of H3K9me3 in Cbx3-KO spermatocytes (Fig. 3C).

Fig. 2. Defects in spermatogenesis in Cbx3 mutants occur at early meiotic prophase. (A) Testis hypoplasia seen in 8-week-old Cbx3-KO mouse. Scale bar: 1 cm. (B) Reduction of spermatocytes in Cbx3-KO mice. Cross-sections of testes from 4-week-old wild type and Cbx3-KO are shown. Sections were stained with Hematoxylin and Eosin. The Cbx3-KO section reveals many seminiferous tubules that lack germ cells, accompanied by the appearance of morphologically abnormal spermatocytes indicated by arrowheads. Scale bars: 100 μm. (C) Spermatogenic defects in the Cbx3-KO at early meiotic prophase. Developmental profiles of meiotic spermatocytes in wild type and Cbx3-KO at 16 dpp are graphically depicted. Frequency of leptotene (L), zygotene (Z) and pachytene (P) spermatocytes were shown by blue, red and green bars, respectively. The significance of the difference between wild-type and Cbx3-KO at leptotene and pachytene spermatocyte was evaluated using Student’s t-test (leptotene; P=0.005, pachytene; P=0.008). The numbers of spermatocytes analyzed were as follows: wild type, n=382 from four mice; Cbx3-KO, n=234 from three mice. Data are mean±s.e.m. (D) Increased apoptotic spermatocytes in Cbx3-KO testes. Incidence of apoptosis was examined in wild-type and Cbx3-KO testes at day 19 dpp by TUNEL labeling. In Cbx3-KO testes, a significant number of TUNEL-labeled cells were observed in the thinned layers of seminiferous tubules. Scale bars: 100 μm. (E) Meiotic catastrophe in Cbx3-KO spermatocytes. Immunofluorescent in situ hybridization results for SYCP3 (green) and SYCP1 (red) proteins and satellite repeats (minor; white) in wild type and Cbx3-KO are shown. Higher magnification views (indicated by boxes in the left panels) are shown in the right panels for each genotype. Red double-headed arrows show the ranges of minor satellite signals; red arrows show the asynapsis at the telocentric region. Scale bars: 5 μm. (F) Quantitative analysis of minor satellite repeats length between wild-type and Cbx3-KO spermatocytes. Minor satellite repeats were significantly elongated in Cbx3-KO compared with wild type. The numbers of spermatocytes analyzed were as follows: wild type, n=360 from two mice; Cbx3-KO, n=330 from two mice at 15 dpp. Each dot represents an observed length of minor satellite and horizontal line represents median of the distribution. The significance of the difference was evaluated using Student’s t-test (P=5.15E–80).
It is, however, known that Dnmt3b and Suv4-20h1/h2, an HMTase for H4K20, are potentially linked to H3K9me3 by HP1 proteins and thus could also contribute to progression of meiotic prophase (Lehnertz et al., 2003; Schotta et al., 2004). We, therefore, determined whether the Cbx3 deficiency might influence DNA methylation status at the centromeric repeats and the silencing of their transcripts. We performed bisulfite DNA sequencing analysis and found that inactivation of Cbx3 had no effect on overall DNA methylation in the minor satellite repeats and the silencing of their transcripts. We performed bisulfite DNA sequencing analysis and found that inactivation of Cbx3 had no effect on overall DNA methylation in the minor satellite repeats and LINE1 (see Fig. S8A in the supplementary material; Y.T. and J.S., unpublished). Consistently, real-time PCR analysis for the silencing of their transcripts. We performed bisulfite DNA sequencing analysis and found that inactivation of Cbx3 had no effect on overall DNA methylation in the minor satellite repeats and LINE1 (see Fig. S8A in the supplementary material; Y.T. and J.S., unpublished). Consistently, real-time PCR analysis for the silencing of their transcripts. We performed bisulfite DNA sequencing analysis and found that inactivation of Cbx3 had no effect on overall DNA methylation in the minor satellite repeats and LINE1 (see Fig. S8A in the supplementary material; Y.T. and J.S., unpublished). Consistently, real-time PCR analysis for the silencing of their transcripts.

**HP1γG9a axis is involved in maintaining centromere clustering in early meiotic prophase**

We went on to address how HP1γ regulates PCH functions. Centromeres are known to cluster in early meiotic prophase in a wide range of organisms, including mice (Stewart and Dawson, 2008). Although this process may play a role in the search for homologs that is required for subsequent chromosome synapsis, this role is poorly understood (Stewart and Dawson, 2008). In wild-type mice, centromere clustering was shown to occur as a punctate distribution at the nuclear periphery and has been observed as early as in intermediate and Type B spermatogonia, concurrent with loss of Plzf expression (Payne and Braun, 2006). It is noteworthy that this process was accompanied by induction of H3K9me2 and loss of H3K9me2 deposition at PCH in Cbx3-KO spermatocytes (see Fig. S8B,C in the supplementary material). By notable contrast, we observed a complete loss of trimethylated H4K20 at PCH in all meiotic substages in the Cbx3-KO (see Fig. S9 in the supplementary material), suggesting that regulation of H4K20me3 during meiotic prophase is an additional role for HP1γ. It is, however, unlikely that H4K20me3 solely regulates the synapsis, which was shown to be impaired in G9a-KO cells despite normal H4K20me3 deposition at PCH (see Fig. S10 in the supplementary material). This implies that the HP1γG9a cascade is the dominant pathway by which H3K9me3 promotes proper synapsis.
spermatogonia but was hardly seen in the undifferentiated spermatogonia in adult Cbx3-hetero mice (Fig. 4A,B). We found that Plzf-/c-Kit+ spermatogonia were more frequent and densely populated in Cbx3-KO than in Cbx3-hetero mice due to the reduction of post-mitotic spermatocytes. The H3K9me2 signal in Plzf+/c-kit+ undifferentiated spermatogonia and Plzf-/c-kit+ differentiated spermatogonia are indicated by white and yellow lines, respectively. Broken yellow circles indicate Sertoli cells. Scale bars: 50 μm. (B) The number of H3K9me2-positive Plzf-/c-Kit+ differentiated spermatogonia was significantly reduced in Cbx3-KO compared with Cbx3-hetero. The numbers of spermatocytes analyzed were as follows: Cbx3-hetero, n=1092 from two mice; Cbx3-KO, n=595 from two mice at 21 dpp. The significance of the difference was evaluated using Student’s t-test (P=1.34E−05). Data are mean±s.e.m. (C) Punctate distribution of the PCH in the absence of H3K9me2 in differentiated spermatogonia of the Cbx3-KO. Immunofluorescence analysis was performed on testis sections for H3K9me2 (K9me2; green), c-kit (white) and Plzf (magenta) with DAPI counterstaining (red) in 3-week-old Cbx3-hetero (upper panels) and Cbx3-KO mice (lower panels). Plzf-/c-kit+ differentiated spermatogonia are indicated by broken lines in the lower panel. Scale bars: 10 μm.

Fig. 4. Defects in H3K9me2 deposition in Cbx3-KO spermatogonia. (A) Defects in H3K9me2 deposition in c-kit positive spermatogonia in Cbx3-KO mice. Whole-mount immunostaining was performed on seminiferous tubules for H3K9me2 (K9me2; green), c-kit (white) and Plzf (magenta) with DAPI counterstaining (red) in 3-week-old Cbx3-hetero (upper panels) and Cbx3-KO mice (lower panels). Higher magnification views for the region indicated by boxes in the left panels are shown in the right panels. Clusters of Plzf+/c-kit– undifferentiated spermatogonia and Plzf-/c-kit+ differentiated spermatogonia are indicated by white and yellow lines, respectively. Broken yellow circles indicate Sertoli cells. Scale bars: 50 μm. (B) The number of H3K9me2-positive Plzf-/c-Kit+ differentiated spermatogonia was significantly reduced in Cbx3-KO compared with Cbx3-hetero. The numbers of spermatocytes analyzed were as follows: Cbx3-hetero, n=1092 from two mice; Cbx3-KO, n=595 from two mice at 21 dpp. The significance of the difference was evaluated using Student’s t-test (P=1.34E−05). Data are mean±s.e.m. (C) Punctate distribution of the PCH in the absence of H3K9me2 in differentiated spermatogonia of the Cbx3-KO. Immunofluorescence analysis was performed on testis sections for H3K9me2 (K9me2; green), c-kit (white) and Plzf (magenta) with DAPI counterstaining (red) in 3-week-old Cbx3-hetero (upper panels) and Cbx3-KO mice (lower panels). Plzf-/c-kit+ differentiated spermatogonia are indicated by broken lines in the lower panel. Scale bars: 10 μm.

spermatogonia but was hardly seen in the undifferentiated spermatogonia in adult Cbx3-hetero testis (Fig. 4A,B). We found that Plzf-/c-Kit+ spermatogonia were more frequent and densely populated in Cbx3-KO than in Cbx3-hetero mice due to the reduction of post-mitotic spermatocytes. The H3K9me2 signal in Plzf-/c-Kit+ differentiated spermatogonia in the Cbx3-KO was barely detectable, although the signal in Sertoli cells was similar to that in the Cbx3-hetero (Fig. 4A, broken yellow circles). We went on to test whether the punctate distribution of PCH was affected in Cbx3-KO and found no remarkable changes (Fig. 4C). Therefore, HP1γ is shown to mediate H3K9me2 at PCH as early as the differentiated spermatogonia stage, but is not required for punctate distribution of PCH at these stages.

We went on to investigate whether the Cbx3 deficiency affects centromere clustering in early meiotic prophase, as an intense PCH distribution of H3K9me2 was continuously observed after entry into meiotic prophase. We performed immunofluorescence analysis for H3K9me3, anti-centromere antibody (ACA or CREST) and DAPI and counted the number of clusters. We chose areas in which H3K9me3, DAPI and CREST/ACA dots were all included as the centromeric clusters (indicated by broken lines in Fig. 5A). Labeling of leptotene cells with H3K9me3 and CREST or ACA revealed that centromere clustering was indeed disturbed; wild-type cells contained on average three to five clusters of heterochromatin, whereas in the Cbx3-KO the majority of cells contained six clusters or more (Fig. 5A,B). Consistent with the epistatic link of HP1γ with G9a, we found very similar defects in centromere clustering in G9a-KO spermatocytes (Fig. 5A,B). Based on these results, we suggest that the HP1γ/G9a axis is required to maintain the clustering of PCH and/or re-cluster the PCH at early in prophase, which may facilitate the synopsis.
HP1γ facilitates homologous chromosome pairing

As homologous synapsis is initiated by chromosome pairing, we went on to examine whether HP1γ/G9a-dependent PCH clustering is involved in mediating the pairing. We used immunofluorescent in situ hybridization analysis to detect genomic regions close to the centromeric region of chromosome 2 (Chr2-Cen), together with SYCP3 and H3K9me3 to analyze the correlation between the pairing and PCH clustering (Fig. 6A). We also tested a non-centromeric genomic region in the middle part of chromosome 4 (Chr4-Mid) as a reference (see Fig. S11 in the supplementary material).

We first investigated wild-type pachytene spermatocytes, in which pairing is mostly completed, to determine the quantitative parameters that distinguish paired and unpaired homologous chromosomes (Fig. 6B; see Fig. S11 in the supplementary material). We found Chr2-Cen probes detected four or more speckles that associated with a single cluster of PCH. This may be due to the ~250 kb probe length, as 40 kb Chr4-Mid probes always detected four speckles. In both cases, four or more speckles were located in close proximity. Average distances between the most separated speckles were 4.6±1.8 µm for Chr2-Cen probe and 3.3±1.3 µm for Chr4-Mid probe at this stage. By contrast, at the leptotene and zygotene stages, we frequently found two clusters of paired speckles, which may represent cohesion of sister chromatids, at each genomic region. These two clusters were separated more than 10 µm on average at the leptotene stage and became slightly closer at zygotene. Based on these observations, we arbitrarily identified paired chromosomal regions as clusters of four or more speckles in which all speckles were located within a distance of no more than 6.4 or 4.6 µm (mean+1 s.d.) for Chr2-Cen and Chr4-mid, respectively (Fig. 6B; see Fig. S11 in the supplementary material).

We then investigated how homologous chromosome pairing progressed in meiotic spermatocytes by using these criteria. The Chr2-Cen region was shown to pair in 23% and 44% of meiotic spermatocytes paired at the leptotene and zygotene stages, respectively, and almost 100% at the pachytene stage. We also observed that the pairing at Chr4-Mid region progressed in a similar fashion (see Fig. S11 in the supplementary material). These results are reminiscent of previous observations on proximal X chromosomes in early female mouse meiosis (O’Keeffe et al., 1997). We went on to examine the pairing progression in Cbx3-KO mice.
Fig. 6. PCH-mediated early meiotic prophase centromere clustering of unpaired homologous chromosomes is impaired in the Cbx3-KO. (A) Genomic position and properties of the probe to detect a genomic region close to centromeric region of chromosome 2 (Chr2-Cen). BAC clone, RP23-60E18, was used to generate the fluorescent in situ hybridization probe. This probe detects 2qA1 region on chromosome 2 (shown by the red bar). (B) Progression of pairing at the Chr2-Cen region. Representative results of immunofluorescent in situ hybridization analysis for Chr2-Cen probe (red), SYCP3 (green) and H3K9me3 (K9me3; white) on meiotic cell spreads from wild type at the leptotene (a,b), zygotene (c,d) and pachytene (e) stages are shown (left panels). Higher magnification views for the PCH indicated by broken white boxes in a to e are shown in a to e, respectively, with fluorescent in situ hybridization signals. The most separated Chr2-Cen signals in each spermatocyte are indicated by yellow double-headed arrows in each panel and their distances are also shown. Average distances of the most separated Chr2-Cen signals at each stage were determined and are graphically depicted (right panel). The broken line in each box represents the average distance (leptotene, 13.9 μm; zygotene, 9.7 μm; pachytene, 4.6 μm) and s.d., respectively. The numbers of spermatocytes analyzed were as follows: leptotene, n=110; zygotene, n=66; pachytene, n=56 (from two wild-type mice at 15 dpp). Scale bars: 5 μm. Error bars indicate the range of measurement data. (C) Defects in association of unpaired Chr2-Cen regions with a single PCH in Cbx3-KO. We examined pairing of Chr2-Cen regions and their association with a single or two PCH in each spermatocyte of wild type (wt) and Cbx3-KO (KO). We identified pairing of the Chr2-Cen region when four or more signals are not separated more than 6.4 μm (mean + 1 s.d.). Based on these parameters, spermatocytes are classified into four categories, as shown in the right-hand panel. We determined the frequency of cells included in each category at each stage and show the results graphically (left). The following color codes are used: blue, Chr2-Cen regions were paired and associated with a single PCH; green, Chr2-Cen regions were paired and associated with two PCH; red, Chr2-Cen regions were not paired and associated with a single PCH; purple, Chr2-Cen regions were not paired associated with two PCH. The numbers (n) of spermatocytes analyzed at each stage are indicated. (D) Schematic summary for this study. Sequential epigenetic modifications at PCH that occur in early meiotic prophase are shown on the left. HP1γ is identified as a link between H3K9me3 and H3K9me2. The HP1γ/G9a cascade at PCH is required to maintain centromere clustering early in prophase, which may facilitate homologous chromosome pairing and synopsis.
and, to our surprise, did not find obvious difference at either genomic region in comparison with the wild type. This indicates that HP1γ is dispensable for the homology search at both centromeric and middle regions of the chromosome and is indeed consistent with a previous report showing initiation of synopsis at multiple points along the mouse chromosome (Liebe et al., 2004). Although the pairing in Cbx3-KO spermatocytes seemingly progressed in a manner similar to the wild type, this is likely to represent the consequence of considerable depletion of mutant spermatocytes during early meiotic prophase. We therefore assume that meiotic spermatocytes that failed to undergo a certain extent of pairing at each stage might be preferentially deleted during early prophase, presumably by quality control mechanisms. Consistent with this model, synaptic defects in Cbx3-KO spermatocytes that survived up to the pachytene stage were only seen in limited chromosomal regions (Table 1). We thus suggest a role for HP1γ to facilitate the pairing.

We then examined whether HP1γ-dependent PCH clustering was involved to facilitate the homology search. To this end, we tested the correlation between PCH-clustering and the pairing by scoring the number of cells, in which Chr2-Cen regions were paired and/or associated with a single PCH, at each stage (Fig. 6C). Analyses of wild-type spermatocytes revealed that pairing of the Chr2-Cen region was not always accompanied by association with a single PCH or vice versa at leptotene or zygotene stages, whereas they mostly coincided at pachytene (see panels a to d in Fig. 6B and summary in 6C). This may reflect the plastic and dynamic nature of PCH clustering during the homology search. Consistent with defects in PCH clustering in Cbx3-KO mice, association of four or more Chr2-Cen speckles with a single PCH was seen in only 11% of leptotene spermatocytes compared with 24% in the wild type. We further observed considerable differences between the wild type and Cbx3-KO at leptotene and zygotene stages in the frequency of spermatocytes in which the Chr2-Cen regions were associated with a single PCH but did not pair (a category represented by panel a in Fig. 6B). This fraction represented 8% at leptotene and 20% at zygotene in the wild type, but was reduced to 2.1% and 3.6%, respectively, in the Cbx3-KO. This suggests that HP1γ contributes to retain centromeric regions of unpaired homologous chromosomes in a single PCH, probably by maintaining their clustering and keeping them in close alignment before they pair.

**DISCUSSION**

Our data support the model that Suv39h1/h2-catalyzes the trimethylation of histone H3K9 at PCH, which then acts as a platform for HP1γ localization. HP1γ in turn recruits G9a, which mediates transient acquisition of the H3K9me2 mark at PCH in differentiated spermatogonia and spermatocytes. HP1γ is thus identified as a functional link for sequential H3K9 epigenetic modifications at PCH that are required for proper progression of meiosis (Fig. 6D). Consistently, centromere clustering at early meiotic prophase and subsequent homologous synopsis are commonly affected in Cbx3 and G9a mutant spermatocytes. Finally, we show that HP1γ/G9a-dependent PCH clustering is not essential for the pairing but crucially facilitates homologous chromosome interactions by keeping their centromeric regions in close proximity irrespective of their pairing status in early meiotic prophase. The HP1γ/G9a cascade is also dispensable for centromere clustering in differentiated spermatogonia (Fig. 4). This differential requirement implies that potential mechanisms that unsettle the centromere clustering begin operating once germ cells enter meiosis and are balanced by HP1γ/G9a-dependent mechanisms to cluster centromeres at PCH. Intriguingly, such bipartite functions of meiotic centromeres have been previously shown in budding yeast. Here, centromeres serve as sites of homology-independent initial chromosomal association and as sites for the later synopsis initiation that occurs upon their homologous coupling. They are also the site of a destructive disjunction that occurs upon failure of chromosomal cross over (Tsubouchi and Roeder, 2005; Tsubouchi et al., 2008). The HP1γ/G9a cascade is therefore likely to be involved in mediating evolutionarily conserved functions of meiotic centromeres for correct homologous partner choice to initiate synopsis.

Based on genome-wide analysis of its distribution, dimethylated H3K9 has recently been suggested to play a role in regulation of chromosome dynamics because of the existence of large blocks of heterochromatin in differentiated cells that are dimethylated at H3K9 (Wen et al., 2009). These regions overlap significantly with previously described large nuclear lamina-associated domains (Guelen et al., 2008). Based on these observations, Wen and colleagues proposed that H3K9me2 marks would bring these large genomic regions close to the nuclear lamina (Wen et al., 2009). Similarly, HP1γ-dependent H3K9me2 at the PCH probably links meiotic centromeres to each other to facilitate synopsis. Our study thus provides the first functional evidence for the role of PCH with H3K9me2 marks for stage-specific regulation of chromosome dynamics, although the mechanisms for recognition of H3K9me2 still await discovery.

This study also provides insight into functional correlations of two different H3K9 methylation marks. Previous studies, in which ES cells and embryonic fibroblasts were used, demonstrated that H3K9me2 and H3K9me3 are localized to distinct silent domains: H3K9me2 was enriched within silent euchromatic regions whereas H3K9me3 was enriched at PCH (Lehnertz et al., 2003; Tachibana et al., 2002; Tachibana et al., 2005). Our study clearly indicates that this distinction is conditional. In particular, acquisition of H3K9me2 marks seems to be flexible, in contrast to the constitutive deposition of H3K9me3 at PCH, and thus may not solely rely on genomic signatures. Concordant with this interpretation, G9a is reported to form complexes with not only HP1γ but also with other proteins such as Wiz and Np95 (Estèvre et al., 2006; Ueda et al., 2006). These interactions may aid in the recognition of various epigenetic configurations by G9a and enable local and conditional deposition of H3K9me2. Our study thus reveals considerable plasticity in the interplay between different histone modifications, and suggests that such stepwise and dynamic epigenetic modifications may play a pivotal role during differentiation and/or cell cycle progression.

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**Competing interests statement**

The authors declare no competing financial interests.

**Supplementary material**

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