An essential role for a mammalian SWI/SNF chromatin-remodeling complex during male meiosis

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SUMMARY
Germ cell development and gametogenesis require genome-wide transitions in epigenetic modifications and chromatin structure. These changes include covalent modifications to the DNA and histones as well as remodeling activities. Here, we explore the role of the mammalian SWI/SNF chromatin-remodeling complex during spermatogenesis using a conditional allele of the ATPase subunit, brahma-related gene 1 (Brg1, or Smarca4). Not only do BRG1 levels peak during the early stages of meiosis, genetic ablation of Brg1 in murine embryonic gonocytes results in arrest during prophase of meiosis I. Coincident with the timing of meiotic arrest, mutant spermatocytes accumulate unrepaired DNA and fail to complete synopsis. Furthermore, mutant spermatocytes show global alterations to histone modifications and chromatin structure indicative of a more heterochromatic genome. Together, these data demonstrate a requirement for BRG1 activity in spermatogenesis, and suggest a role for the mammalian SWI/SNF complex in programmed recombination and repair events that take place during meiosis.

KEY WORDS: Chromatin remodeling, SWI/SNF, Mouse spermatogenesis, Meiosis, Mouse

INTRODUCTION
Mammalian gametogenesis requires numerous epigenetic changes to accompany the transition from somatic, diploid precursors to mature, haploid gametes (reviewed by Sasaki and Matsui, 2008). Embryonic epigenetic states are first erased and reprogrammed during the development of primordial germ cells (PGCs). Later, as germ cells differentiate and proceed through meiosis, their genomes undergo large-scale changes to histone and DNA modifications as well as chromatin structure. This transition is important for the progression through meiosis, which itself requires the action of macromolecular complexes to manage the series of events entailing meiotic recombination between homologous chromosomes. It is therefore not surprising that faithful execution of the meiotic program requires the action of a large number of epigenetic pathways. Recent work has identified DNA methyltransferases, histone-modifying enzymes, and RNA-binding proteins, which when inactivated by mutations, result in failure of spermatogenesis (Kota and Feil, 2010).

In both male and female germ cells, homologous recombination occurs during the first meiotic prophase. During this time DNA double-stranded breaks (DSBs) are induced, and repair at the DSBs generates DNA recombination between homologous chromosomes. Many of the factors required for repair of stress-induced DNA damage in somatic cells function during meiosis. In addition to their well-characterized roles in transcriptional regulation, chromatin-remodeling complexes have roles in DNA repair (Bao and Shen, 2007; Clapier and Cairns, 2009). Among them, members of the SWI/SNF ATP-dependent chromatin remodelers appear to have a conserved function in the DSB repair process in yeast (Chai et al., 2005) and human somatic cells (Park et al., 2006; Zhao et al., 2009). Upon induction of DNA damage by ionizing radiation, the SWI/SNF catalytic subunit BRG1 (SMARCA4 – Mouse Genome Informatics) is required for the phosphorylation of the histone variant γH2AX (H2AFX – Mouse Genome Informatics), which in turn promotes the recruitment of downstream repair proteins. These observations suggest a role for mammalian SWI/SNF remodeling complexes in the repair of stress-induced DNA damage; however, whether they also play a role in programmed DNA repair events, such as those during meiosis, is not yet known.

In this report, we show that a germline-specific ablation of Brg1 results in a critical defect in spermatogenesis in the mouse. We demonstrate that BRG1 protein levels normally peak during the early phases of meiosis I. Consistent with this pattern, germ cells lacking BRG1 fail to complete prophase I. Although γH2AX appears normally induced in mutant spermatocytes, it persists into later stages of prophase I along with aberrant foci of repair proteins. BRG1-depleted spermatocytes showed significant deviation in the expected global patterns of epigenetic modifications, including those that are associated with DNA damage and heterochromatin. Together, these results demonstrate an essential role for BRG1 in spermatogenesis, and suggest a function for BRG1-containing complexes in homologous recombination during meiosis.

MATERIALS AND METHODS
Brg1 conditional deletion and genotyping
Mice carrying a floxed allele of Brg1 (Sumi-Ichinose et al., 1997) and Mvh-Cre (Gallardo et al., 2007) were maintained on a mixed background. Mutant and normal littermates were obtained from crosses between female homozygous Brg1floxF1 mice with male Mvh-Cre/+; Brg1floxF1 mice. PCR genotyping primers for wild-type and floxed alleles of Brg1 included: forward 5'-GCTGTTGTCACGGATGGG and reverse 5'-GCTGATTAGCGGGTGGTG; for the excised allele of Brg1, forward 5'-GATGATTAGCGGGTGGTG and the same reverse sequence; for Cre, forward 5'-CAGTGACCGCGATTAAGCCTGGG and reverse 5'-TTCCTGCTTAAACACCCGTTAA. All animal work was carried out in accordance with IACUC protocols at UNC.
Histological analysis
After dissection, testes were fixed in Bouin’s fixative overnight at 4°C, dehydrated in an ethanol series, and embedded in paraffin wax. Sections were made at 3 μm thickness using a microtome. Following standard protocols, sections were deparaffinized, rehydrated, and then stained with Hematoxylin and Eosin for histology.

Immunofluorescence staining and antibodies
Preparation of testis cryosections and nuclear surface spreads of meiocytes were performed as described previously (Peters et al., 1997; Kim et al., 2007) with the following modifications. For the preparation of cryosections, tissues were washed in PBS at pH 7.4, permeabilized in PBST (PBS with 0.1% Triton X-100), and fixed in 4% paraformaldehyde in PBS overnight at 4°C. Fixed tissues were saturated through a sucrose series and embedded in OCT. Slides were cut at 8 μm thickness using a microtome. Following standard protocols, sections were deparaffinized, rehydrated, and then stained with Hematoxylin and Eosin for histology.

For the preparation of nuclear spreads, seminiferous tubules were dissected and incubated for 20 minutes in a hypotonic extraction buffer (30 mM Tris pH 8.2; 50 mM sucrose; 17 mM citrate; 5 mM EDTA, 0.5 mM Triton X-100), and fixed in 4% paraformaldehyde in PBST overnight at 4°C. Fixed tissue sections were cut at 8 μm thickness. Slides were dried for 2 hours on a 37°C warming plate or overnight at room temperature (RT). An antigen retrieval step was required for several antibodies: slides were washed in 0.4% solution to release hypotonized nuclei by pipetting repeatedly or mincing

Antibodies
The following antibodies were used for immunofluorescence staining: rabbit anti-BRG1 (1:100, Santa Cruz, sc-10768), monoclonal mouse anti-BRG1 (1:1000, Santa Cruz, sc-17796), rabbit anti-IRF1 (1:250, Abcam ab15597), rabbit anti-beta-galactosidase (1:500, Cappel, #55976), rabbit anti-CRE (1:200, Covance, MMS-106R), mouse anti-BRCA1 (1:500, Vector), mouse anti-BRD3 (1:200, Millipore, M8204), mouse anti-MLH1 (1:500, BD Bioscience, #51-1327), rabbit anti-histone H3 acetylated lysine 9 (1:500, H3K9ac, Abcam, ab1220), rabbit anti-histone H3 acetylated lysine 9 (1:500, H3K9Ac, Millipore, #06-942), rabbit anti-histone H4 pan-acetylated (1:200, Millipore, #06-866), rat anti-HP1β (1:500, Abcam, ab10811), rabbit anti-HP1γ (1:500, Abcam, ab66617), mouse anti-MLH1 (1:500 BD BioScience, #51-1327), rabbit anti-MVMH (1:500, Abcam, #13840), mouse anti-PLZF (1:100, Calbiochem #OP128), rabbit anti-RAD51 (1:250, Calbiochem PC130T; 1:100, Santa Cruz sc-8349), rabbit anti-RPA (1:100, Bethyl Lab HIC-00409), rabbit anti-SCP1 (1:1000, Abcam, ab15090), rabbit anti-SCP3 (1:500, Abcam, ab15093), mouse anti-TRA98 (1:500, Abcam, #OP128), rabbit anti-RAD51 (1:250, Calbiochem PC130T; 1:100, Santa Cruz sc-8349), rabbit anti-RPA (1:100, Bethyl Lab HIC-00409), rabbit anti-SCP1 (1:1000, Abcam, ab15090), rabbit anti-SCP3 (1:500, Abcam, ab15093), mouse anti-TRAF9 (1:500, Cosmo Bio 73-003-EX), Secondary antibodies used were goat or donkey IgG conjugated with one of Alexa Fluor 488, 568 and 594 (Invitrogen). When applicable, we used secondary antibody matched for the isotypes.

Cell proliferation and apoptosis assay
Proliferating cells were detected by immunostaining with a mitotic marker. Histone H3 phosphorylated at serine 10 (pHH3) specifically labels cells in metaphase. For cell apoptosis analysis, fluorescent TUNEL assay was conducted by using the In Situ Cell Death Detection Kit (Roche, #11 684 795 001).
Statistical analyses
Chi-squared analysis was carried out to test differences in meiotic stage distribution in mutant and wild-type spermatocytes. A two-sided Fisher’s exact test was used to determine significance of SYCP3, RAD51, RPA (RPA1 – Mouse Genome Informatics), MLH1 distribution patterns. At least two mice per genotype were used for each experiment.

RESULTS
BRG1 expression in male germ cells
To determine whether BRG1 plays a role in gametogenesis, we analyzed BRG1 expression during spermatogenesis by immunofluorescence staining. BRG1 was detected as early as 3 days post partum (dpp), when the prospermatogonia, the quiescent precursors to the spermatogonial stem cells, re-enter the cell cycle (Fig. 1A). BRG1 expression continued at 7 dpp (Fig. 1B) as prospermatogonia differentiate into spermatogonia marked by the spermatogonial stem cell marker PLZF (ZBTB16 – Mouse Genome Informatics) (Buaas et al., 2004; Costoya et al., 2004) (inset, Fig. 1B). BRG1 expression remained at 12 dpp as spermatocytes proceeded with meiosis (Fig. 1C). However, in adult testes, where all stages of spermatogenesis are present, BRG1 was detected predominantly in SYCP3-expressing meiocytes (Fig. 1D). BRG1 levels increased from zygonema to pachynema (Fig. 1E), during which DNA repair and recombination take place. We further analyzed the expression of the BRM ATPase subunit expression during spermatogenesis. In contrast to BRG1, it is expressed in somatic cells and differentiating spermatids, but not in wild-type spermatocytes (supplementary material Fig. S1). Thus, BRG1 and BRM may have complimentary, non-redundant roles during male meiosis. Together, these observations demonstrate that BRG1 is dynamically regulated during spermatogenesis, and its increased levels in spermatocytes suggest a role for BRG1 in the progression of meiosis.

Brg1 deficiency results in meiotic arrest
To determine whether BRG1 is required for spermatogenesis, we used a germ-cell-specific Cre recombinase to delete a Brg1 floxed allele (Sumi-Ichinose et al., 1997) during embryonic germ cell
increase cell death in mutant testes compared with wild-type littermates (Fig. 2J,K). Some of the TUNEL-positive cells also stained positively for the spermatocyte marker SYCP3 (Fig. 2L). Therefore, deletion of Brg1 impedes progression of spermatogenesis during meiotic stages, resulting in increased apoptosis.

**Synopsis is impaired in Brg1\(^{CKO}\) spermatocytes**

To determine whether mutant spermatocytes progress properly through prophase I, we analyzed the expression and localization patterns of meiotic markers. γH2AX levels are known to increase during leptotene, correlating with DSB formation, then diminish as breaks are repaired during zygonema, eventually becoming confined to the XY bivalent by the pachytene stage (Mahadevaiah et al., 2001; Celeste et al., 2002; Fernandez-Capetillo et al., 2003). We observed a pattern of γH2AX staining in Brg1\(^{CKO}\) tubules consistent with the leptotene stage of the first meiotic prophase. However, in contrast to wild-type tubules, where the normal pattern of the diffusely staining γH2AX in leptotene or zygotene spermatocytes is a single layer, we observed these cells accumulating in multiple layers in Brg1\(^{CKO}\) tests (Fig. 3A,B). We next assayed SYCP3, which is highly expressed in zygotene spermatocytes, becoming confined to the axes of paired chromosomes during pachynema. Similar to γH2AX staining, intensely staining SYCP3 spermatocytes accumulated abnormally in Brg1\(^{CKO}\) tubules (Fig. 3C,D).

To examine the defect more closely, we monitored meiotic progression by using spermatocyte spreads immunostained with markers for axial and transverse elements of the synaptonemal complex, SYCP3 and SYCP1, respectively. In wild-type spermatocytes, SYCP3 localization to chromosomal axes begins in the leptotene stage, continues along the aligning axes in the zygotene stage, and forms a condensed synaptonemal complex by the pachytene stage (Fig. 4A). Although SYCP3 patterns reflecting zygonema and pachynema could be detected in Brg1\(^{CKO}\) spermatocytes, localization of SYCP3 to the synaptonemal complex was abnormal (arrows in Fig. 4B). A significant increase in pachytene nuclei displaying asynapsis (70/80 nuclei) was observed in mutants compared with wild type (29/127 nuclei) (P<0.001, two-sided Fisher’s exact test). Examination of SYCP1 localization, which becomes enriched at the transverse element bridging the two homologs together, confirmed that Brg1\(^{CKO}\) pachytene spermatocytes fail to produce a complete synaptonemal complex (compare Fig. 4C, wild type, with 4D, mutant, incomplete synaptonemal complex highlighted with arrows). Furthermore, after quantifying the stages of meiosis I from nuclear spreads, we did not observe any diplote stage spermatocytes at 20 dpp in Brg1\(^{CKO}\) tubules (supplementary material Fig. S4). Together these observations demonstrate that synopsis is impaired in the absence of Brg1.

**DNA repair is compromised in Brg1\(^{CKO}\) spermatocytes**

A defect in processing of DSBs is often associated with abnormal synopsis (Baker et al., 1995; Burgoyne et al., 2009). Brg1-depleted zygotene spermatocytes consistently displayed prolonged γH2AX expression (Fig. 4B,D), implying that unrepaired DSBs are persistent and that deficiency in DNA repair might be linked to incomplete synopsis. Therefore, we used immunofluorescence to analyze levels and distribution of RAD51 (Shinohara et al., 1993) and replication protein A (RPA) (Plug et al., 1997), both of which are critical components of the DNA repair complex. RPA binds single-stranded DNA, and it is replaced by RAD51, which...
facilitates DNA strand exchange. Both factors showed irregular distribution and kinetics in mutant spermatocytes (Fig. 5A-D). Each formed enlarged and persistent foci between zygonema and pachynema, suggesting abnormal repair of DSBs (Petrini and Stracker, 2003). Notably, the exacerbated foci were associated with increasing synaptic defects (arrows in Fig. 5B,D). The majority of pachytene spermatocytes (58/79, 73%) contained multiple, enlarged RPA-foci accumulating to locally asynaptic axes. These patterns were never observed in wild-type spermatocytes.

In mouse, ~300 DSBs per leptonema nucleus are generated by SPO11 (Keeney, 2001). DNA repair generates two alternative recombination products, crossover (CO, <10% of all the DSBs) or non-crossover (NCO) (Moens et al., 2002). To compare wild-type and Brg1CKO recombination patterns, distribution of the recombination protein MLH1 was examined. MLH1 specifically marks CO-designated sites in mid to late pachytene spermatocytes (Moens et al., 2007). Although CO formation in Brg1CKO spermatocytes was readily observed, the average number of MLH1 foci in each nucleus was significantly reduced in mutant pachytene spermatocytes compared with controls (Fig. 5E-G, 17.3 versus 21.1 MLH1 foci/spermatocyte, \( P = 2.3 \times 10^{-6} \)). Mutant nuclei with fewer than 20 MLH1 foci displayed extensive asynapsis, suggesting that the decrease in MLH1 foci among mutant spermatocytes is likely to be a consequence of delayed synaptic progression, possibly linked to deficiency in DNA repair.

Brg1CKO spermatocytes show abnormal chromatin modifications

SWI/SNF chromatin remodelers such as BRG1 are thought to produce a more open chromatin structure (Bultman et al., 2006). To determine whether the failure in meiotic progression correlated with changes in chromatin structure in the absence of BRG1, we
examined global patterns of histone modifications and chromatin-binding proteins. We first investigated acetylation of lysine 14 of histone H3 (H3K14Ac), a modification thought to facilitate the recruitment of DNA damage response proteins (Lee et al., 2010; Buard et al., 2009). We found that, although H3K14Ac was induced in mutant spermatocytes, it persisted abnormally into the pachytene stage (Fig. 6A,B). Similarly, dimethylation at histone H3K9 (H3K9me2), a heterochromatin-associated modification, was also abnormally increased in mutant tubules (Fig. 6C,D). Staging nuclear spreads with SYCP3 revealed that this upregulation occurred during the zygotene stage, preceding the period of ectopically increased H3K14Ac (Fig. 6E,F).

Heterochromatin protein 1 (HP1; CBX5 – Mouse Genome Informatics) is a non-histone protein that regulates the assembly of heterochromatin (Zhao et al., 2000). We examined expression of all three members of mammalian HP1 proteins: HP1α, HP1β and HP1γ. HP1α expression was negligible in both wild-type and mutant spermatocytes (data not shown). In wild-type tubules, HP1β and HP1γ strongly stained cells at the base of the lamina with levels decreasing as cells entered meiosis and moved towards the lumen. Only HP1β was reactivated in pachytenic spermatocytes (Fig. 6G). In Brg1 CKO tubules, broad staining of both HP1β and HP1γ persisted into spermatocytes (arrows in Fig. 6H), which contained abnormally high levels of γH2AX (Fig. 6J). Taken together, these results show differences in the patterns of histone modifications in the absence of BRG1 during meiosis and suggest a more closed, heterochromatic state.

**DISCUSSION**

Chromatin-remodeling proteins have significant roles in facilitating DSB repair and maintaining genome stability (Downs et al., 2007). Here, we demonstrate an essential role for a catalytic subunit of the mammalian SWI/SNF complex, BRG1, during the programmed DNA damage events of meiosis in the male germline. Although DSB repair appears to begin normally in Brg1 CKO spermatocytes, DNA damage persists into later stages of prophase I, as indicated by persistent γH2AX, unresolved repair foci and damage-associated H3K14Ac, suggesting that DSB repair is unable to proceed to completion. Subsequently, progression through the first meiotic prophase of Brg1 CKO spermatocytes is blocked, resulting in the elimination of the spermatocytes presumably by meiotic checkpoint-triggered cell death. Recombination and synopsis are mutually interdependent, such that the resolution of recombination intermediates requires assembly of intact synaptonemal complexes (Plug et al., 1998). Unrepaired DSBs in the Brg1 CKO mutants might result from incomplete synopsis, deficiency in DNA repair, or some defect upstream of synopsis/repair. Intriguingly, we observed the presence of crossover sites, as measured by MLH1 foci, in Brg1 CKO mutant spermatocytes despite measurable asynapsis. It is possible, therefore, that BRG1 is specifically required for synopsis in condensed, heterochromatic domains.

Previously, Park et al demonstrated that upon induction of DSBs by ionizing radiation, BRG1 is required to promote high levels of γH2AX for efficient repair (Park et al., 2006). In contrast, we observe that γH2AX appears normally in Brg1 CKO spermatocytes during the
leptotene stage of meiosis. However, γH2AX distribution was abnormal. Instead of being normally displaced from autosomes and confined to the XY body, γH2AX remained broadly dispersed in mutant zygotene spermatocytes and into the pachytene stage. Therefore, during meiosis, BRG1 appears to function downstream of γH2AX accumulation. This discrepancy may reflect mechanistic differences in DNA repair that occur in response to stress and those that occur during meiosis (Andersen and Sekelsky, 2010). The timing of BRG1 requirement during meiotic DSB repair is reminiscent of that observed in yeast. In this organism, the SWI/SNF remodeling complex appears to be involved later in the DSB repair process, perhaps during or after the invasion of single-stranded DNA to donor DNA (Chai et al., 2005).

We have previously observed differences in the histone modifications of BRG1-depleted embryos (Bultman et al., 2006). Here, we show that Brg1CKO spermatocytes undergo changes in heterochromatin-associated histone modification patterns. These observations suggest a more condensed chromatin state relative to wild-type spermatocytes. Heterochromatic regions require SWI/SNF complexes to complete recombination in yeast (Sinha et al., 2009). Thus, the defect in DNA repair coupled with the increased heterochromatic nature of Brg1CKO spermatocytes suggest that mammalian SWI/SNF complexes perhaps facilitate DSB repair and recombination in more condensed genomic contexts. Together, our results suggest an essential role for the BRG1 ATPase in mammalian male meiosis.

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