Transferrin receptor (TFRC) is essential for meiotic progression during mouse spermatogenesis

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Summary
Meiosis is a highly conserved process, and is responsible for the production of haploid gametes and generation of genetic diversity. We previously identified the transferrin receptor (TFRC) in the proteome profile of mice neonatal testes, indicating the involvement of the TFRC in meiosis. However, the exact molecular role of the TFRC in meiosis remains unclear. In this study, we aimed to determine the function of the TFRC in neonatal testicular development by TFRC knockdown using the testis culture platform. Our results showed high TFRC expression in 2-week testes, corresponding to the first meiotic division. Targeting TFRC using morpholino oligonucleotides resulted in clear spermatocyte apoptosis. In addition, we used the chromosomal spread technique to show that a deficiency of TFRC caused the accumulation of leptotene and zygotene spermatocytes, and a decrease of pachytene spermatocytes, indicating early meiotic arrest. Moreover, the chromosomes of TFRC-deficient pachytene spermatocytes displayed sustained γH2AX association, as well as SYCP1/SYCP3 dissociation beyond the sex body. Therefore, our results demonstrated that the TFRC is essential for the progression of spermatocyte meiosis, particularly for DNA double-stranded break repair and chromosomal synopsis.

Introduction
Iron is essential for the assembly of functional Fe–S cluster proteins, heme-binding proteins, and ribonucleotide reductases (RNRs) in most eukaryotic cells. These proteins are involved in electron transfer, ribosome maturation, DNA replication and repair, and cell cycle control (Ye and Rouault, 2010; White and Dillingham, 2012; Dlouhy and Outten, 2013). Iron transport and uptake is tightly regulated in all iron-dependent organisms (Sutak et al., 2008; Anderson and Vulpe, 2009; Leichtmann-Bardoogo and colleagues, 2012). Mammalian cells typically obtain most of their iron from the plasma protein transferrin (TF) (Lee et al., 2003; Chua et al., 2007), which binds and delivers iron to the cells. The transferrin receptor (TFRC) is expressed on the cell surface and is responsible for absorbing transferrin-bound iron through receptor-mediated endocytosis (Qian and Tang, 1995; Aisen, 2004). After iron is freed from TF, TF is returned to the cell surface for another cycle of iron transport. The entire cycle lasts a few minutes, and a distinct feature of the TF cycle is the persistence of the TF/TFRC complex (Aisen, 2004; Lamb et al., 1983).

Meiosis consists of meiosis I and meiosis II, however the two processes are very different. Meiosis I includes induction of DNA double-stranded breaks (DSBs), pairing, recombination, and synopsis. Spo11 mediates the occurrence of DSBs, which elicit the DNA damage response and resulting in the activation of ATM kinase and subsequent phosphorylation of H2AX (Baudat and de Massy, 2004; Li and Ma, 2006). The loss of SPO11 function eliminates meiosis recombination and synaptic complex formation (Klapolz et al., 1985; Wastaff et al., 1985). The pairing of homologous chromosomes facilitates the recombination process. DMC1 has DNA-dependent ATPase activity and forms a filamentous structure at the end of single-stranded excised DNA at the DSBs repair site, which is the key to homologous recombination repair in meiosis (Yoshida et al., 1998; Pittman et al., 1998). Synapses are stable connections between chromosomes made by the formation of a specific protein complex. Synchronized with the formation of the synaptic complex, the meiotic DSBs are repaired to facilitate the interaction of homologous chromosomes and finish the synopsis (Carofiglia et al., 2013).

Spermatogenesis is an iron-dependent process in which iron is imported to the seminiferous tubule by transferrin, primarily secreted by Sertoli cells (Morales et al., 1987; Wauben-Pennis et al., 1986). Leichtmann-Bardoogo and colleagues (Leichtmann-Bardoogo et al., 2012) reported details of localization and regulation of many iron transport and storage proteins in the testis.
Male germ cells from early developmental stages to pachytene spermatocytes express high levels of TFRC (Leichtmann-Bardoogo et al., 2012). In a previous study, we constructed a proteomic profile of proteins associated with meiosis onset during mouse testis development and identified 104 differentially expressed proteins (Shao et al., 2015). High levels of TFRC were observed during meiosis initiation, and was consistent with the results of Leichtmann-Bardoogo and colleagues (Leichtmann-Bardoogo et al., 2012). Moreover, we found that the Tfrc gene is retinoic acid (RA) responsive, and that its expression was tightly regulated in RA-treated spermatogonial stem cells (Shao et al., 2015). Several studies have shown the involvement of RA in triggering the onset of meiosis in male and female mammals (Kumar et al., 2011; Li et al., 2011), therefore TFRC is likely to play a role during mouse meiosis. In the present study, we aimed to study the role of TFRC during mouse spermatocyte meiosis using cultured mouse neonatal testes.

**Materials and methods**

**Animals**

ICR mice were maintained in a 12 h/12 h light/dark cycle at 20–22°C and 50–70% humidity with food and water available ad libitum. All animal treatment protocols were approved by the Ethics Committee of Nanjing Medical University (IACUC:16011181).

**Neonatal testis culture**

Testicular tissue from 20 mice on postnatal 5.5-day was cut into uniform pieces of 1–3 mm diameter under the microscope and placed on agarose gel half-soaked in culture medium. The day before sampling, 1.5% agarose gels (10 × 10 × 5 mm placed in six-well plates) were prepared and soaked with culture medium for more than 24 h to replace the water. Three to four agarose gels were placed inside each well of the six-well plates, and 3–5 testis tissue samples were placed on each agarose surface. Plates were maintained in a 5% carbon dioxide in air environment at 34°C. The medium was changed every 2 days. The culture system was based on previous reports (Sato et al., 2011; Shen et al., 2018, 2019; Zheng et al., 2018; Zhao et al., 2019). The medium contained α-minimum essential medium (α-MEM), 10% knockout serum replacement (KSR), 0.1% β-mercaptoethanol, 1% nonessential amino acids solution (NEAA), and 1% penicillin/streptomycin solution. Tissues were cultured for 11 days either with specific morpholinos against TFRC (Mo), or as the negative control (Ctr), at a final concentration of 10 μmol/l. TFRC translation-blocking vivo-Mo (Oligo Sequence: TCTGGCTTGATCCATCA TTCTCAGC) and the control (Oligo Sequence: CCTCTACCTAGTTCAATTATA) were purchased from Gene Tools LLC, Philomath, OR, USA. The experiments were designed with randomized blocks of three replicates and, in total, 12 mice were used.

**Haematoxylin and eosin staining**

Testis tissues were fixed in 4% paraformaldehyde for 48 h, paraffin-embedded, and sectioned into 5-μm sections. Sections were then dewaxed in dimethylbenzene, rehydrated in graded ethanol solutions, and stained with haematoxylin and eosin (H&E). Images were captured by microscopy (Axioskop 2 plus, ZEISS).

**Chromosome spread**

Hypotonic extraction buffer (HEB; 30 mM Tris, 50 mM sucrose, 17 mM trisodium citrate dihydrate, 5 mM EDTA, 0.5 mM DTT, and 0.5 mM phenylmethylsulphonyl fluoride; pH 8.2), and fixative solution [1% paraformaldehyde (PFA), 0.15% Triton X-100 adjusted to pH 9.2 by using 10 mM sodium borate pH 9.2 buffer solution] were prepared. Cultured tissues were harvested, placed in Dulbecco’s modified Eagle’s medium for removing cells from the tubes, and subsequently put in HEB buffer for 40–60 min. Slides were covered with fixative solution. Tubes were cut to pieces at a pH of 8.2 in 100 mM sucrose, and pipetted gently to make a cell suspension, which was painted on the prepared glasses. The slides were incubated in a humidity box for at least 3 h. All samples were washed three times with phosphate-buffered saline (PBS) and air dried for subsequent immunofluorescence staining.

**Immunofluorescence**

Slides were prepared by chromosome spread method followed by recovery at room temperature (RT). Briefly, slides were blocked with 1% bovine serum albumin at RT for 2 h, and incubated with primary antibody at a dilution of 1:500 (Table S1) overnight at 4°C. Slides were then gently washed three times with PBS, incubated with secondary antibody at a dilution of 1:1000 at 37°C for 1 h in the dark with humidity, and washed three times with phosphate-buffered saline (PBS) and Tween. Images were captured using a Zeiss confocal microscope (Ism710, Carl Zeiss).

**Western blot analysis**

Cultured testis tissues were ground with a pestle in protein lysate for complete dissociation. Proteins at 40 μg/lane were transferred to polyvinylidene difluoride membranes and incubated with primary antibodies (Table S1) at a dilution of 1:1000 overnight. Membranes were washed with Tris-buffered saline and 0.1% Tween three times, and incubated with secondary antibodies (1:5000 dilution) at RT for 2 h. Protein signals were visualized using the SuperSignal West Femto Chemiluminescent Substrate (Thermo Scientific, USA).

**Terminal deoxynucleotidyl transferase dUTP nick end labelling (TUNEL) assay**

Paraffin sections were dewaxed with xylene twice at RT for 10 min and then rinsed in a sequence of 100, 90, 80 and 70% alcohol at RT. After soaking in PBS, the sections were incubated with 20 μg/ml proteinase K at RT for 20 min. After equilibration, the sections were incubated in reaction buffer at 37–60 min, followed by 4′,6-diamidino-2-phenylindole (DAPI) staining.

**Results**

**In vitro culture of mouse testis**

We performed in vitro testis culture from neonatal day 5.5 to day 16.5 and observed the morphology of cultured testes by HE staining (Fig. 1). According to the method of identifying cells in testis (Ahmed and de Rooij, 2009), only Sertoli cells and spermatogonia were observed in seminiferous tubules at day 7.5. Preleptotene spermatocytes began to appear at day 9.5. On day 12.5, we observed zygotene spermatocytes in some tubules. On day 14.5, we noticed zygotene and pachytene spermatocytes. By day 16.5, meiosis occurred in most of the seminiferous tubules.

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In our previous study, we found that TFRC protein expression was higher in 10.5-day testis than in 8.5-day testis (Shao et al., 2015), which spans meiosis onset in mouse. Moreover, Leichtmann-Bardoogo and colleagues (Leichtmann-Bardoogo et al., 2012) reported that TFRC was located on leptotene and zygotene spermatocytes in adult mouse testis. In this study, western blot analysis showed that TFRC expression increased between weeks 1 and 2 and decreased between weeks 2 and 3 (Fig. 2A, B). These results indicated that TFRC may play a pivotal role in early meiosis. To elucidate the function of TFRC in meiosis, we knocked down TFRC protein expression using morpholinos specific for TFRC in neonatal testis. Western blot analysis showed a knockdown efficiency of 70% (Fig. 2C, D). HE staining showed zygotene and pachytene spermatocytes in the negative control group. The morpholino-treatment group (Mo) only had zygotene spermatocytes, which were apoptotic (Fig. 2E). The apoptotic signals were further verified by co-staining of SYCP3 with TUNEL (Fig. 2F, G) and cleaved caspase-3 (Fig. 2H, I), respectively. The results revealed a significant increase of apoptosis of spermatocytes in the Mo group. In addition, we also stained somatic cell markers to determine if TFRC knockdown affected somatic cells. We found that there were no differences in somatic cells and no changes in basal membrane of tubules in Mo compared with the control group (Ctr) (Fig. S1).

**TFRC promotes synaptonemal complex (SC) formation**

In order to determine the exact stage of meiotic arrest in Mo testes, we used the chromosomal spread technique. This technique allowed us to observe accurately the chromosomal status of spermatocytes at the single-cell level and therefore determine the stage. We assessed chromosomal synopsis by co-staining SYCP1 (a central element protein of SC) and SYCP3 (a lateral element protein of SC) (Cohen et al., 2006). SC lateral elements are formed as early as the leptotene stage, initiate synopsis through physical juxtaposition at the zygotene stage, and promote complete synopsis on autosomes at the pachytene stage (Kumar et al., 2011). The Ctr group showed complete alignment of SYCP3 and SYCP1 at the pachytene stage, except at apparent sex bodies in which unpaired XY chromosomes lacked the central element. Spermatocytes from Mo remained in a pachytene-like stage, characterized by obvious chromosome pairing and formation of SC lateral elements (SYCP3), but loss of SYCP1 staining at most chromosome sites prevented the autosomes from synchronizing. The expression of gammaH2AX throughout the nucleus and failed to form XY bodies (Fig. 4A), demonstrating the existence of aberrant synopsis in the autosomes (Fig. 3).
Discussion

We used cultured neonatal mouse testes to determine the function of TFRC in neonatal testes, and found that knockdown of TFRC in neonatal testicular culture caused spermatocyte apoptosis. In addition, we observed that disruption of TFRC led to aberrant synapsis and failure of DSB repair. An accumulation of zygotene spermatocytes was also observed after TFRC disruption. Our results demonstrated that TFRC is essential for male meiosis, and defects in TFRC-deficient testes become most evident at the transition from the zygote to pachytene stage.

Iron is essential for the activation of Src kinase, which rapidly phosphorylates and reduces p27, thereby stimulating cyclin-dependent kinase 2 (CDK2 kinase) activity (Hengst and Reed, 1996; Bloom and Pagano, 2003). CDK2 is necessary for chromosome synapsis, and CDK2 knockout mice exhibited abnormal meiosis and extensive spermatocyte apoptosis (Ortega et al.,...
In the absence of CDK2, SC proteins failed to assemble on homologous chromosomes. In this study, we found aberrant distribution of SC in TFRC-deficient spermatocytes. We therefore speculated that knockdown of TFRC in spermatocytes led to decreased intracellular iron and CDK2 activity, and finally caused aberrant synapsis in the autosomes. Alternatively, iron could act as a constraining factor in meiosis (Brault et al., 2016). DNA helicases, such as FancJ, ChlR1, and Dna2, contain a conserved cluster of Fe–S at the N-terminal, which is necessary for DNA helicase activity during DSB (Wu and Brosh, 2012). The DSB formed during recombination can induce phosphorylation of H2AX. In our study, we detected abnormal repair of DSBs in the MO group,
which γH2AX was diffused rather than confinement to the sex chromosomes in the pachytene phase. We therefore obtained that TFRC-mediated iron transport contributed to DSB repair.

In conclusion, in this study, we determined the function of TFRC in mammalian testes by using cultured neonatal testes. Our results demonstrated that TFRC is essential for homologous chromosome synapsis and DSB repair during meiosis.

**Supplementary material.** To view supplementary material for this article, please visit https://doi.org/10.1017/S0967199420000659

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**Conflicts of interest.** None.

**Ethical standards.** All mouse care and use protocols were employed in accordance with the guidelines of the Ethics Committee of Nanjing Medical University, China.

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