Translational repression by MSY4 inhibits spermatid differentiation in mice

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SUMMARY

In developing male germ cells, newly synthesized protamine mRNAs are stored for up to 7 days before translational activation. Translational repression of protamine 1 (Prm1) mRNA requires sequences present in its 3′ untranslated region (UTR) and substantial evidence suggests a role for the murine Y-box protein MSY4 in this process. To determine if MSY4 can mediate translational repression in vivo, we generated transgenic mice in which translation of the transition protein MSY4 disrupted the normal completion of spermatogenesis and caused dominant sterile. Immunocytochemical analysis of several seminal markers, including the protamines, indicated that MSY4 prevented normal activation of translation. mRNAs whose translation was inhibited contained at least one MSY4 RNA recognition site, suggesting sequence-dependent translational repression. Altered translational activation resulted in defective processing of protamine 2 and severe defects in sperm morphogenesis. These results suggest that MSY4 plays an active role in translational repression of several mRNAs in differentiating spermatids.

Key words: Translational control, mRNPs, Protamine, Spermatogenesis, RNA-binding, Mouse

INTRODUCTION

Post-transcriptional control is a major form of gene regulation during mammalian gametogenesis. In haploid spermatids, proteins required for sperm morphogenesis are synthesized from stores of polyadenylated mRNAs packaged as cytoplasmic ribonucleoprotein particles (RNPs). Unknown signaling events promote unmasking, translational activation, deadenylation and the eventual degradation of translationally repressed mRNAs. Several proteins have been proposed to function as translational regulators in spermatids; however, little is known about the mechanism of repression and activation.

Chromosome condensation in mammalian spermatids involves an initial displacement of the somatic histones with the testis-specific transition proteins TP1 and TP2, and their subsequent replacement by the protamines (Bellve, 1979). The protamine genes Prm1 and Prm2 encode small basic proteins first transcribed in haploid round spermatids (Mali et al., 1989). The protamine mRNAs are stored in translationally inert mRNP particles for up to 10 days, until translational activation in elongated spermatids (Balhorn et al., 1984; Mali et al., 1984; Kleene and Flynn, 1987). Translational regulation of the protamine mRNAs is mediated by sequences in their 3′ untranslated region (3′ UTR) (Braun et al., 1989; Fajardo et al., 1997; Zhong et al., 2001). Mutation of the protamine 1 (Prm1) 3′ UTR causes premature nuclear condensation and dominant male sterility (Lee et al., 1995). Translation of the transition protein mRNAs, as well as that of other mRNAs required for spermatid differentiation, is also repressed during spermiogenesis (Balhorn et al., 1984; Mali et al., 1989). Translational repression occurs at a time when other mRNAs are actively being translated, indicating that repression is message specific (Braun, 1998).

Y-box proteins were first isolated based upon their ability to bind the DNA Y-box element present in many eukaryotic promoters (Wolffe and Merc, 1996). Y-box proteins have since been shown to bind dsDNA, ssDNA and RNA, both specifically and non-specifically (Matsumoto and Wolffe, 1998). The murine Y-box protein MSY4 is expressed in the testis and specifically (Braun, 1998).

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period of protamine translation. Expression of MSY4 in late-stage spermatids just prior to and during the process of translationally repressed protamine mRNA (Davies et al., 2000). MSY4 could have a direct role in translational repression we expressed a construct, with a region of the RSV leader containing this site, is specifically repressed by chk-YB-1b and 2 in a rabbit reticulocyte extract system.

Substantial evidence suggests an involvement of MSY4 in the translational regulation of the protamine mRNAs. MSY4, along with the murine Y box protein MSY2, is a component of the translational regulation of the protamine mRNAs. MSY4, along with the murine Y box protein MSY2, is a component of the translational regulation of the protamine mRNAs. MSY4 could have a direct role in translational repression as previously described (Cathala et al., 1983). RNA samples were electrophoresed in 1.5% agarose-formaldehyde gels, transferred to nylon (hybond-N; Pharmacia BioTeck, Peapack, NJ) and hybridized for 15-20 hours with radioactive (α-32P) DNA probes prepared by random oligonucleotide-primed synthesis. The nylon membrane was washed at a final stringency of 0.1xSSC and 0.5% SDS at 60°C and exposed to X-ray film.

Sperm counts and analysis
Sperm counts were made on epididymal sperm. The epididymis was isolated from mouse by dissection and placed in 1 ml of 1xphosphate buffer saline solution (PBS). The tissue was diced to release sperm and incubated at room temperature for 2 hours before counting. Samples were counted with a hemocytometer either undiluted or diluted 10-fold. All counts were made in duplicate and averaged.

Sperm morphology was analyzed using phase contrast microscopy. Samples were analyzed in PBS with a hemocytometer. Acridine Orange staining was as previously described (Kosower et al., 1992). Fluorescence microscopy was carried out using a Zeiss Axioscop microscope with Filterset 10.

Antibodies
The MSY4 antibody used is as previously described (Davies et al., 2000). Polyclonal antibody to the HA tag was purchased from Clontech (Palo Alto, CA). Mouse monoclonal antibodies to PRM1 and PRM2 are HUB1N and HUP2B, respectively (Stanker et al., 1993). TP1 and TP2 antibodies were kindly provided by Steven Kistler. Debbie O’Brien provided the GAPD-S antibody and Frans van der Hoorn provided the OD2F2 antibody.

Immunocytochemical and histological analysis
Immunocytochemistry was performed as previously described (Braun et al., 1989). Testis were dissected from adult mice and fixed in Bouin’s fixative overnight and embedded in paraffin wax. Sections were deparaffinized with xylene and rehydrated using standard procedures. Tissue sections were treated with primary antibody overnight at 4°C or 2-3 hours at room temperature. Either biotinylated goat anti-rabbit IgG or biotinylated goat anti-mouse IgG was used in conjunction with streptavidin conjugated to horseradish peroxidase as recommended by the manufacturer (Zymed Laboratories, San Francisco, CA). Peroxidase activity was visualized with the chromagen aminoethyl carbozole. Tissue sections were counterstained with Hematoxylin. Primary antibodies were used in the following dilutions: MSY4 (1:3000), HA (1:500), OD2F2 (1:400), HUP1N (1:1500), HUP2B (1:2000), TP1 (1:1500), TP2 (1:1500) and GAPD-S (1:2000). The following antigen retrieval protocol was used with the TP1, TP2, HUP1N and HUP2B antibodies: testis sections were boiled in 100 mM sodium citrate for 10 minutes. Sections were counterstained with Hematoxylin and Periodic Acid/Schiff reagent.

Basic nuclear protein preparation
Isolation and analysis of spermatid nuclear basic proteins was performed as previously described (Lee et al., 1995; Platz et al., 1977), with the following modifications. The protease inhibitors used were leupeptin (0.5 μg/ml), phenylmethylsulfonyl fluoride (PMSF) (0.5 mM) and pepstatin A (1 μg/ml). One testis was homogenized in 0.8 ml of 20 mM Tris-HCl (pH 7.7), 40 mM KCl and 17 mM MgCl2. Homogenates were not filtered through cheese cloth, unlike the method that has previously been described (Lee et al., 1995). Basic proteins were dissolved in 8 M urea/0.9 M acetic acid/0.1 M 2-mercaptoethanol/1% Methyl Green and separated in polyacrylamide slab gels containing 15% acrylamide, 0.1% bisacrylamide, 6.2 M urea and 0.9 M acetic acid. Gels were run and stained as previously described (Lee et al., 1995).
RNA probe synthesis, protein extracts and EMSA analysis

RNA probes were prepared as previously described (Giorgini et al., 2001). The wild-type YRS RNA contains two copies of the YRS (Davies et al., 2000). The C26A RNA contains a point mutation of the YRS that disrupts binding of MSY4 (Giorgini et al., 2001).

Testes were dissected from adult mice and placed in 1 mg/ml Buffer A [10 mM Hepes (pH 7.6), 1.5 mM MgCl2, 10 mM KCl, 0.5 mM DTT] containing the following protease inhibitors: leupeptin, pepstatin A and PMSF. The nuclei and mitochondria were collected by centrifugation for 2 minutes at 14,000 g for 15 minutes at 4°C in a fixed angle rotor. 0.11 volumes of Buffer B [0.3 M Hepes (pH 7.6), 1.4 M KCl, 30 mM MgCl2] was added to the supernatant, followed by addition of glycerol to 20% v/v final. Extracts were stored at -70°C following quick freezing in liquid nitrogen.

EMSA analysis was performed as previously described (Giorgini et al., 2001).

Polysome analysis

Each testis was dissected from an adult mouse and homogenized in 1 ml homogenization buffer [100 mM NaCl, 1.5 mM MgCl2, 20 mM POPSO (pH 7.5) and 1 mM PMSF]. The nuclei and mitochondria were collected by centrifugation for 2 minutes at 12,000 g; and the supernatant was layered over a 1 ml linear 15-50% (w/w) sucrose gradient in lysis buffer and centrifuged in a Beckman SW40 rotor for 110 minutes at 205,000 g. The gradients were fractionated into 12x1 ml fractions using an Isco Density Gradient Fractionator (Model 185), while monitoring ultraviolet absorbance at 254 nm. As a control to verify mRNA association with polysomes, equivalent supernatants were prepared and centrifuged in sucrose gradients in buffer in which the MgCl2 was replaced by 20 mM EDTA. The presence of EDTA causes mRNA and ribosomes to disassociate. Northern and western analysis was performed on each fraction. For western analysis, 200 µl of each fraction was concentrated and analyzed as described in the section Immunoblotting. For northern analysis, 500 µl of each fraction was treated with proteinase K at 0.2 µg/ml for 90 minutes at 55°C, and 100 µl was analyzed as described in the section RNA isolation and analysis.

Immunoblotting

Protein extracts were mixed with Laemmli buffer, boiled and electrophoresed in 8% SDS-polyacrylamide gels. The proteins were transferred to nitrocellulose (Gibco-BRL Life Technologies). After transfer, the membrane was blocked for 30 minutes to several hours at room temperature in 5% nonfat dry milk and phosphate buffered saline (BPBS) and then incubated overnight at 4°C with primary antibody at a 1:10,000 dilution. The membrane was washed once in BPBS with 0.05% Tween 20 and twice in BPBS, then incubated with secondary antibody conjugated to horseradish peroxidase (HRP) for several hours at room temperature. After washing again as above, the HRP activity was detected using enhanced chemiluminescence (ECL) as described (Schnepenheim and Rautenberg, 1987). ECL reagent was prepared immediately prior to use by dissolving 40 mg of luminol (5-amino-2,3-dihydro-1,4-phthalazinedione) and 10 mg of 4-iodophenol in 1 ml of DMSO. Following the addition of 10 ml of 0.1 M Tris (pH 8.5), 5 ml of 5 M NaCl, 17 ml H2O and 125 µl of H2O2, the membrane was incubated for 2 minutes and exposed to X-ray film.

RESULTS

Expanded expression of MSY4 causes sterility

To determine if the temporal expression pattern of MSY4 is important for the translational repression and activation of developmentally regulated mRNAs, we extended its normal expression pattern in spermatogenesis. Endogenous MSY4 is detected in pachytene spermatocytes and round spermatids (Davies et al., 2000). By expressing MSY4 in later stage spermatids, and observing its effect on translational repression and activation of developmentally regulated messenger RNAs, we hoped to gain insight into the normal function of MSY4 in vivo. In order to express MSY4 in elongating and elongated...
spermatids, we constructed two gain-of-function transgenes (Fig. 1A). Both transgenes contain the Prm1 promoter, Prm1 5’ untranslated region (UTR) and Msy4 cDNA. The PMP transgene contains the Prm1 3’ UTR while the PMH transgene contains the hGH 3’ UTR. These control sequences have been previously used to drive expression of heterologous transgenes specifically in haploid spermatids (Braun et al., 1989). The presence of the Prm1 3’ UTR should confer Prm1-like translational control on the PMP transgene, and thus delay translation of MSY4 until the elongated spermatid stage (Fig. 1B). The presence of the hGH 3’ UTR in the PMH transgene is expected to relieve this repression and allow translation in round spermatids.

Our analysis of the PMH and PMP transgenic lines is summarized in Table 1. For the PMH transgene, we analyzed five transgenic founder males and the F1 male offspring from two founder females. Two of the five PMH founder males were infertile and had either no sperm or very low sperm numbers by epididymal sperm counts. The remaining PMH founder males were fertile and had a range of sperm counts, from approximately 8% of wild-type levels (founder 7531) to wild-type amounts (founder 6293). However, although the founder males were fertile, transmission ratio distortion was observed: out of a combined 44 offspring, none carried the PMH transgene. Male progeny from the PMH 8861 line were sterile, with no detectable normal sperm by epididymal sperm counts. Male offspring of the PMH 9501 founder line were also sterile. Although sperm counts were 30% of wild-type, a high

<table>
<thead>
<tr>
<th>Founders</th>
<th>Fertility</th>
<th>Transmission ratio (number of positives/number of progeny)</th>
<th>Sperm count (number of sperm/ml)</th>
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<tr>
<td>Wild-type</td>
<td>Fertile</td>
<td>n/a</td>
<td>1.8×10^7 (n=4)</td>
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<tr>
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<td>0/27</td>
<td>1.7×10^7</td>
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<td>0/7</td>
<td>0.95×10^7</td>
</tr>
<tr>
<td>PMH 7531</td>
<td>Fertile</td>
<td>0/10</td>
<td>0.14×10^7</td>
</tr>
<tr>
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<td>n/a</td>
<td>0.009×10^7</td>
</tr>
<tr>
<td>PMH 7666</td>
<td>Sterile (plugs n=2)</td>
<td>n/a</td>
<td>No sperm</td>
</tr>
<tr>
<td>PMH 8861*</td>
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<td>n/a</td>
<td>No sperm (n=6)</td>
</tr>
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<tr>
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<tr>
<td>PMP 3791*</td>
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<td>n/a</td>
<td>1.2×10^7 (n=5)</td>
</tr>
<tr>
<td>PMP 3464*</td>
<td>Sterile (plugs n=2)</td>
<td>n/a</td>
<td>0.062×10^7 (n=3)</td>
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n/a, no offspring born or offspring were not analyzed.
*Female founders; male progeny from these founders were analyzed.

Fig. 2. Immunocytochemical detection of MSY4 and MSY4-HA. (A,C,E) Testis sections from PMP transgenic mice. (B,D,F) Testis sections from PMH transgenic mice. (A,C) Serial sections of a stage VI tubule from a PMP animal. (B,D) Serial sections of a stage VI tubule from a PMH animal. (A,B) Endogenous MSY4 detected with MSY4 antibody in pachytene spermatocytes (ps) and round spermatids (rs). The transgenic MSY4-HA proteins lack the N-terminal epitope recognized by the MSY4 antibody. (C,D) MSY4-HA detected with HA antibody in elongated spermatids (eds) of PMP and PMH animals, respectively. (E) Detection of MSY4-HA expression in elongated spermatids in a stage VII tubule of a PMP transgenic testis. Notice the absence of MSY4-HA in round spermatids. (F) Expression of MSY4-HA in round and elongated spermatids of a stage VII tubule from a PMH testis. Sections were counterstained with Hematoxylin.
proportion of the sperm had abnormal morphology (described below).

The 3578 PMP founder male was sterile with sperm counts 1% of wild-type levels (Table 1). The male progeny from one of the two PMP founder females were sterile, with sperm counts less than 4% of wild-type levels. The male progeny from the second PMP founder female were fertile with epididymal sperm numbers at about 67% of wild-type levels.

To determine whether epididymal sperm counts and fertility correlated with transgene expression levels, we performed Northern blot analysis on RNA isolated from testes of transgenic mice (Fig. 1C). The PMH transgenic founder male with the lowest levels of transgenic mRNA (7520) correlated to near wild-type levels of sperm and fertility, while the highest expresser of the transgene among the PMH male founders (7666) had no visible sperm by epididymal sperm counts and was sterile. Male progeny of the PMH 9501 line expressed low levels of the transgenic mRNA, were fertile and had high sperms counts, while males of the 3464 line were infertile and oligospermic. It is clear that in both PMH and PMP transgenic males, increasing levels of transgene expression, and consequently increasing levels of MSY4, correlates with decreased sperm count and decreased fertility.

Expression of MSY4-HA

The MSY4 transgenic protein encoded by both PMH and PMP transgenes was tagged with the small hemaglutinin (HA) epitope tag on its C terminus for immunodetection. Additionally, 76 of the codons encoding the N terminus of MSY4 are deleted in this transgene. A MSY4 antibody was raised to a peptide present in the MSY4 N-terminal region, and thus specifically recognizes endogenous MSY4 and not MSY4-HA (Davies et al., 2000). Previous studies have shown that the N terminus is not necessary for the specific RNA-binding of MSY4 (Davies et al., 2000; Giorgini et al., 2001).

We performed immunocytochemistry on serial testis sections from PMH and PMP transgenic mice with antibodies to MSY4 and HA. In the PMP mice, normal expression of endogenous MSY4 was seen in the cytoplasm of pachytene spermatocytes and round spermatids (Fig. 2A). However, MSY4-HA was only detected in the cytoplasm of elongated spermatids, and was absent in pachytene spermatocytes and round spermatids (Fig. 2C,E). Thus, the PMP transgenic mRNA in under the same translational control as endogenous Prm1 mRNA and expresses MSY4-HA in elongated spermatids. In stage VI tubules of PMH transgenic males, expression of endogenous MSY4 was again seen in the cytoplasm of round spermatids (Fig. 2B), while MSY4-HA was detected in the cytoplasm of elongated spermatids (Fig. 2D). However, MSY4-HA was also detected in round spermatids of stage VII tubules (Fig. 2F) demonstrating that the presence of the hGH 3’ UTR relieves Prm1-like translation control of the PMH transgenic mRNA. From this analysis we conclude that the two gain-of-function transgenes extend the normal temporal window of MSY4 expression as designed.
MSY4-HA disrupts spermatid differentiation

To investigate the consequences of expressing MSY4-HA in later stage spermatids, we analyzed testes from wild-type and transgenic mice using histological methods. In wild-type adult male mice, stage IX seminiferous tubules contain leptotene spermatocytes, pachytene spermatocytes, and step 9 elongating spermatids (egs) (Fig. 3A,D). Like the control, stage IX tubules from both PMP and PMH transgenic adult males contained leptotene spermatocytes, pachytene spermatocytes, and step 9 elongating spermatids; however, they also contained elongated spermatids (Fig. 3B,C,E,F). Mature spermatids are normally released into the lumen in stage VIII tubules. As expected from the retained elongated spermatids in the tubules, very few spermatozoa were seen in the PMP cauda epididymis (Fig. 3H) or PMH cauda epididymis (Fig. 3I) when compared with a wild-type epididymis (Fig. 3G). The retention of elongated spermatids in transgenic tubules probably accounts for the low sperm counts seen in the PMP 3464, PMH 8861 and PMH 9501 lines.

Despite the presence of retained spermatids in stage IX tubules, some transgenic males contained sperm in their epididymis. To ascertain the morphology of the epididymal spermatozoa, we released sperm from the epididymis into phosphate-buffered saline and viewed them by phase contrast microscopy. The majority of epididymal sperm from wild-type mice had normal morphology, with less than 12% abnormal (Table 2). The normal sperm displayed the characteristic hook at the apex of their heads (Fig. 4A, Fig. 5A) and intact flagella with normal middle pieces (Fig. 4A). Epididymal sperm from PMH transgenic mice exhibited a high percentage of abnormal sperm. Line 8861 produced no normal looking sperm. Those that were produced had abnormal head morphology (Fig. 4C, Fig. 5A) and flagellum that were short and thin (Fig. 4C). Line 9501 had only 4% normal sperm, and nearly 71% of the sperm were found to have a bent head, a 14-fold increase over wild-type levels (Fig. 4D and Table 2). A fourfold increase in the number of kinked sperm was seen in these mice when compared with wild-type mice (Table 2, Fig. 4E). Additionally, a 10-fold increase in two-headed sperm was seen in PMH mice over wild type (Table 2, Fig. 4F). Despite sterility in the PMP mice, their epididymal sperm were very similar to wild type (Table 2, Fig. 5A).

To analyze chromatin compaction in wild-type and transgenic sperms heads, we performed Acridine Orange staining of sperm samples. Acridine Orange staining fluoresces from yellow to orange when chromatin is partially compacted and fluoresces green when chromatin is fully compacted (Kosower et al., 1992). When the integrity of the chromatin is highly compromised, absence of fluorescence occurs (Cho et al., 2001). Green fluorescence was observed from wild-type sperm heads (Fig. 5B, part i) as well as from morphologically normal heads from PMP and PMH samples (Fig. 5B, part iii and Fig. 5B, part iv, respectively). In our studies, morphologically abnormal heads did not fluoresce, indicating that chromatin integrity was severely disrupted. As a control, wild-type sperm were first treated with dithiothreitol to reduce disulfide bonds between cysteines in the protamines and then with 4-vinylpyridine to alkylate these cysteine residues. This treatment compromised the integrity of chromatin compaction in wild-type sperm, and produced yellow and orange fluorescence upon Acridine Orange staining (Fig. 5B, part ii).

We analyzed the nuclear basic proteins from normal wild-type testis and epididymis, as well from these tissues in PMH and PMP transgenic mice (Fig. 6). Total basic proteins from both sonication sensitive nuclei and sonication resistant spermatid nuclei were fractionated by acid-urea polyacrylamide gel electrophoresis and detected by napthol
blue-black staining. As expected, the protamines (PRM1 and PRM2) were not seen in sonication sensitive fractions (Fig. 6, lanes 1-3 and 7-9). PRM2 is synthesized as a precursor of 106 amino acids, and through a series of proteolytic cleavages is processed to a mature size of 63 amino acids (Chauviere et al., 1991). In the sonication resistant nuclei preparations from the testes of PMH and PMP mice, processing of PRM2 to the mature 63 amino acid form did not occur (Fig. 6, lanes 4 and 5). In the epididymis, sperm nuclei from PMH mice lacked PRM2, but contained low levels of PRM1 (Fig. 6, lane 10). PMP sperm nuclei contained both PRM1 and correctly sized mature PRM2, albeit at much lower levels and at different ratios from wild type (Fig. 6, lanes 11 and 12). Thus, in both lines of mice MSY4-HA expression disrupted the normal displacement of the histones with the protamines, resulting in altered processing of PRM2 and incomplete nuclear condensation.

MSY4-HA retains sequence-specific binding in vivo

We have previously characterized a 48/50 kDa RNA-binding activity in testis extracts that contains MSY4 (Davies et al., 2000). This activity has been shown to specifically bind the YRS consensus sequence (Giorgini et al., 2001). In order to show that transgenic MSY4-HA protein retained its binding specificity, electrophoretic mobility shift assays (EMSAs) were performed (Fig. 7). Testis extracts from wild-type, PMH, and PMP mice were incubated with either a radiolabeled portion of the wild-type Prm1 3' UTR (wt YRS) or a radiolabeled mutant version of this RNA (C26A). We have previously shown that the C26A point mutation disrupts binding by MSY4 (Giorgini et al., 2001). These binding complexes were resolved by non-denaturing polyacrylamide gel electrophoresis (PAGE). Extracts from the testis of all three strains produced an EMSA complex with wt YRS RNA (indicated by the lowest arrow in Fig. 7). Formation of this complex was completely disrupted by C26A RNA in both PMH and PMP testis extracts (Fig. 7, lanes 9 and 15). HA antibody supershifted a region of the complexes formed by wt YRS and either PMH or PMP testis extracts (Fig. 7, lanes 7 and 13, middle arrow), while failing to supershift the complex containing wt YRS in wild-type extracts (Fig. 7, lane 3). These results indicate that MSY4-HA can specifically bind the YRS. MSY4 antibody, which specifically recognizes endogenous MSY4, also supershifted a portion of the EMSA complex in PMH and PMP extracts (Fig. 7, lanes 6 and 12, upper arrow). Double-supershift experiments using both MSY4 and HA antibody (Fig. 7, lanes 8 and 14) did not produce double-supershift complexes, indicating either that endogenous MSY4 and transgenic MSY4-HA do not bind the same RNA molecule or that protein binding by one antibody excludes protein binding by the other antibody.

Altered translational regulation in PMH mice

If MSY4-HA plays a role in translational repression one would
expect to find MSY4-HA associated with translationally inert messenger ribonucleoprotein particles (mRNPs). Sucrose gradient sedimentation coupled with western analysis was used to evaluate the polysome distribution of MSY4 and MSY4-HA in transgenic testis extracts (Fig. 8). Testis extract was fractionated on a sucrose gradient while monitoring the optical density of the eluant. The optical density profile (top panel) shows noticeable peaks of ribosomal subunits, monosomes, disomes, trisomes and higher molecular weight polysomes. Transgenic MSY4-HA and endogenous MSY4 sedimented in the mRNP fraction suggesting that both proteins are complexed with repressed mRNAs.

Translationally regulated proteins expressed late in spermatogenesis were analyzed by immunocytochemistry of adult testis sections from wild-type and PMH animals to determine if expression of these proteins is perturbed by MSY4-HA expression in round and elongated spermatids (Fig. 9). In addition to the basic nuclear proteins TP1, TP2, PRM1 and PRM2, we analyzed expression of testis-specific glyceraldehyde 3-phosphate dehydrogenase (GAPD-S) and outer dense fiber protein 2 (ODF2). GAPD-S probably plays a role in regulation of glycolysis during spermatogenesis and regulation of energy production for sperm motility (Cooper, 1984; Fraser and Quinn, 1981; Jones, 1978; Mohri et al., 1975). ODF2 is one of three outer dense fiber proteins that assemble as nine fibers surrounding the axoneme of the sperm tail (reviewed by Kierszenbaum, 2002). All six of these proteins have been shown to be under translational control during murine spermatogenesis (Balhorn et al., 1984; Bunch et al., 1998; Kleene et al., 1984; Kleene and Flynn, 1987; Yelick et al., 1989). Translation of five of the six markers was dramatically reduced in PMH transgenic mice when compared with wild-type mice (Fig. 9). Only the expression of TP1 seemed unaffected in PMH mice (Fig. 8I,J). To determine if this specificity of MSY4-HA dependent repression was due to the presence of YRS consensus sites in the repressed messages, we searched the published full-length mRNA sequences for these MSY4 binding sites (Table 3). In addition to scanning the...
sequences for the canonical YRS site found in the Prm1 3'UTR, we searched for all single and double variations of the defined consensus nucleotides (Table 3). Interestingly, the Tnp1 mRNA is the only one of the six sequences analyzed lacking a YRS consensus site. Thus, a strong correlation can be drawn between presence of a YRS site in an mRNA and MSY4-dependent repression of that message in vivo.

DISCUSSION

In this study, we have analyzed two gain-of-function transgenes. Using the Prm1 promoter and different 3' UTRs, we extended the temporal window in which MSY4 protein is normally expressed. Both transgenes severely disrupted late-stage spermatid differentiation and caused dominant sterility. Biochemical and immunocytochemical analyses suggest the primary cause of sterility was a failure to execute the normal developmental program of translational activation. These studies provide strong support for MSY4 as a translational regulator in spermatids.

PMH and PMP transgenic mice exhibit severe oligospermia. The most striking of the abnormalities seen in these mice is the large number of two-headed sperm. Approximately 7% of epididymal sperm from PMH 9501 mice were double-headed, compared with 0.5% in wild-type mice. Sperm from the PMP 3464 line exhibited approximately 4% two-headed sperm. High incidence of double-headed sperm have been previously characterized in heterozygous In(5)9Rk mice (Hugenholtz and Bruce, 1979). These mice carry one copy of a long paracentric inversion in chromosome 5, and were found to produce between 6.0 and 8.8% double-sized sperm (double-headed or with a double-sized head) dependent on genetic background. It is thought that the dicentric anaphase bridge of paracentric inversion heterozygotes impedes cytokinesis and causes double-sized sperm. It is possible that the increase in two-headed sperm in PMH and PMP mice is due to reduced synthesis of flagellar components and the failure to complete the process of sperm individualization that occurs during spermatid differentiation.

Mice lacking the casein kinase II α2 catalytic subunit, the Csnk2a2 gene product, exhibit round-headed sperm (globozoospermia) similar to that in both the PMP 3464 and PMP8861 lines of mice (Xu et al., 1999). In addition, the epididymal sperm occasionally have bent and kinked flagella. Similar head abnormalities have been seen in human familial globozoospermia, making Csnk2a2 a candidate gene for the syndrome. As Csnk2a2 is translated during spermiogenesis, it is possible that the globozoospermia seen in PMP and PMH mice is due to repression of this message by MSY4-HA. Haploinsufficiency of either protamine 1 or protamine 2 in mice causes infertility due to disruption of spermatid nuclear formation (Cho et al., 2001). Sperm from these mice exhibit various abnormalities in head structure, including heads with a rounded appearance. Additionally, an infertile individual with 76-99% round-headed sperm in his ejaculate also expresses reduced amounts of protamine 1 and 2 (Carrell et al., 1999), suggesting that the repression of protamine translation in elongating and elongated spermatids of the PMP and PMH transgenic mice could contribute to the observed head defects.

Analysis of the spermatid nuclear basic proteins in the PMH and PMP transgenic mice demonstrated that these animals are defective in processing PRM2. Defects in PRM2 processing have been seen in mice deficient for either TP1 or TP2 (Yu et al., 2000; Zhao et al., 2001), in mice haploinsufficient for Prm1 or Prm2 (Cho et al., 2001), and mice that pre-maturely express PRM1 in round spermatids (Lee et al., 1995). Perturbation in the levels of these basic proteins in the spermatid nucleus could lead to an alteration in chromatin packaging required for normal PRM2 processing. This model would explain the processing defects seen in PMH and PMP mice, as three of these proteins exhibit reduced levels in these mice.

Expression of MSY4-HA in round spermatids produced a more severe phenotype than its expression in elongated spermatids. When comparing high expression lines, PMH mice had lower epididymal sperm counts, and the few sperm found had severely abnormal head and tail morphologies. In addition, the nuclear basic protein preparations described herein show that PMP epididymal sperm contain both mature PRM2 and PRM1, whereas PMH preparations contain only PRM1. Finally, PMH mice exhibit stronger repression of marker protein translation during spermiogenesis when compared with PMP mice (data not shown). The increased severity of the PMH phenotype is presumably due to its early expression in round spermatids and more severe effects on protein synthesis.

Transgenic experiments indicate that the YRS probably plays a role in Prm1 translational control. Deletion mapping of the Prm1 3' UTR has shown that the first 37 nucleotides of the
3’ UTR are sufficient to confer Prm1-like translational control on a reporter gene (Fajardo et al., 1997). A consensus YRS site maps to this region and mutation of this site relieves translational repression (Giorgini et al., 2001). Our data strongly suggest that the function of the YRS is mediated by the binding of MSY4 and probably the other major Y box protein MSY2. A second site within the Prm1 3’ UTR also appears to be involved in this translational control. This site, known as the translational control element (TCE), is found in the 3’ end of the Prm1 3’ UTR and is both necessary and sufficient for protamine-like translational control of a transgene (Zhong et al., 2001). A trans factor for the TCE has not yet been identified.

The YRS consensus sequences are likely to appear very frequently in the genome. One of the consensus sites appears randomly approximately once every 455 nucleotides. Thus, almost every mRNA would be predicted to contain a YRS consensus site. Does MSY4 actually bind all mRNAs containing one of these sites in vivo? Perhaps, but it is more likely that additional factors are involved in selection of mRNA targets by MSY4. It is possible that proteins which bind other regulatory sequences, such as the TCE in the Prm1 3’ UTR (Zhong et al., 2001), or the other murine Y-box proteins expressed in spermatids, MSY1 and MSY2, aid in target specificity. It is also possible that the number or position of YRS sites within the targeted mRNA is important for MSY4-dependent repression. We have seen that the presence of two adjacent copies of the YRS in an RNA dramatically increases EMSA binding by MSY2 and MSY4 (F. G. and R. E. B., unpublished). Proximity of nascent transcripts to Y-box DNA elements in the nucleus could also aid in selection of mRNA targets. Both the Prm1 and Prm2 promoters contain Y-box DNA elements, and MSY2 has been shown to interact with the Prm2 promoter (Johnson et al., 1988; Nikolajczyk et al., 1995). Thus, it is possible that MSY4 first binds a Y-box DNA element in the Prm1 promoter and then binds the YRS site in the 3’ UTR of the message, and that this complex is exported from the nucleus to the cytoplasm.

Our analysis of six different mRNAs showed that translation of five of these mRNAs was suppressed in PMP and PMH mice. Provocatively, the mRNAs that were affected all contained at least one YRS-binding site. The one transcript that was not affected, Tnp1, did not contain a YRS site. These data, as well as extensive three-hybrid and EMSA analysis of all possible single nucleotide sequence variants of the YRS (Davies et al., 2000; Giorgini et al., 2001), support our in vivo transgenic data that MSY4 binds specific RNAs via the YRS. In previously published studies (Davies et al., 2000), we found that several mRNAs co-precipitated with MSY4. A retrospective analysis of these mRNAs indicated that all contained at least one YRS, suggesting that these results may describe physiological interactions. However, one of these mRNAs, actin, is not known to be under translational control during spermatogenesis. This suggests that there are likely to be other factors that work together with MSY4 and MSY2 to mediate selective translational repression during spermatogenesis.

The mechanism by which MSY4 contributes to translational repression remains unknown. MSY4 could inhibit an early step in translational initiation by masking the entire mRNA, or alternatively, MSY4 (or proteins that interact with MSY4) could directly interfere with translation initiation through a
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nonlinear mechanism that involves an interaction between the two ends of the message. Further identification of the proteins contained in the ribonucleoprotein particle should help distinguish between these two possibilities.

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