Sperm plasma membrane breakdown during Drosophila fertilization requires Sneaky, an acrosomal membrane protein

Kathleen L. Wilson¹, Karen R. Fitch², Blaine T. Bafus¹ and Barbara T. Wakimoto¹,²,³,*

Fertilization typically involves membrane fusion between sperm and eggs. In Drosophila, however, sperm enter eggs with membranes intact. Consequently, sperm plasma membrane breakdown (PMBD) and subsequent events of sperm activation occur in the egg cytoplasm. We previously proposed that mutations in the sneaky (snky) gene result in male sterility due to failure in PMBD. Here we support this proposal by demonstrating persistence of a plasma membrane protein around the head of snky sperm after entry into the egg. We further show that snky is expressed in testes and encodes a predicted integral membrane protein with multiple transmembrane domains, a DC-STAMP-like domain, and a variant RING finger. Using a transgene that expresses an active Snky-Green fluorescent protein fusion (Snky-GFP), we show that the protein is localized to the acrosome, a membrane-bound vesicle located at the apical tip of sperm. Snky-GFP also allowed us to follow the fate of the protein and the acrosome during fertilization. In many animals, the acrosome is a secretory vesicle with exocytosis essential for sperm penetration through the egg coats. Surprisingly, we find that the Drosophila acrosome is a paternally inherited structure. We provide evidence that the acrosome induces changes in sperm plasma membrane, exclusive of exocytosis and through the action of the acrosomal membrane protein Snky. Existence of testis-expressed Snky-like genes in many animals, including humans, suggests conserved protein function. We relate the characteristics of Drosophila Snky, acrosome function and sperm PMBD to membrane fusion events that occur in other systems.

KEY WORDS: Fertilization, Male fertility, Acrosome, Paternal effect mutations, Drosophila

INTRODUCTION

Studies of fertilization have revealed the universal importance of membrane events to prepare and coordinate the gametes and ensure their successful union. These events have been most extensively studied in sperm of selected marine invertebrate and mammalian species and include dynamic changes in membrane proteins and lipids during sperm capacitation, acrosome exocytosis, binding, adhesion and membrane fusion with the egg (reviewed by Flesch and Gadella, 2000; Evans, 2002). The majority of molecules with confirmed roles in these processes are cell adhesion molecules, ion channels or signal transduction components with molecular mechanisms of action that have been studied in multiple cell types (reviewed by Talbot et al., 2003; Neill and Vacquier, 2004; Rubinstein et al., 2006). There is considerable interest in discovering proteins that act specifically during fertilization. The characterization of these molecules will contribute to a better understanding of the specialized properties of gametes and to the practical goal of identifying new targets for contraceptives.

To identify novel sperm molecules required for fertilization, we have pursued a genetic approach using Drosophila melanogaster. Previous studies of male sterile mutants indicated that those affecting fertilization might be relatively rare. Therefore, we isolated and categorized a large number of male-sterile mutations to find a subset that disrupt sperm-egg interactions or induce paternal effect defects (Fitch et al., 1998; Wakimoto et al., 2004). We previously described mutations in a gene called sneaky (snky), which met our genetic criteria of specifically affecting fertilization (Fitch and Wakimoto, 1998). Mutations of snky showed detectable effects only on male fertility. Sperm produced by mutant males were competent to enter the egg but arrested before sperm nuclear decondensation and aster formation. We proposed that this sperm activation defect was due to a failure in breakdown of the sperm plasma membrane, a step that normally occurs immediately after sperm entry into the egg in Drosophila.

In this study, we provide phenotypic evidence of a role for Snky in affecting the integrity of the sperm plasma membrane during fertilization. We molecularly identify the snky gene and characterize its transcript and predicted protein to investigate how the protein might function. The results indicate that Snky is an acrosomal membrane protein that is contributed to the early embryo. In addition to suggesting a possible molecular role for Snky, these studies have implications for the function and the fate of the acrosome during Drosophila fertilization.

MATERIALS AND METHODS

Drosophila strains

Mutations are described in Fitch and Wakimoto (Fitch and Wakimoto, 1998) or FlyBase (http://flybase.bio.indiana.edu), except as noted below. The snky⁰⁰⁵⁶ and snky²⁴⁶⁰ alleles were recovered as ethylmethane sulfonate (EMS)-induced male sterile mutations from the Zuker collection (Koudakjian et al., 2004; Wakimoto et al., 2004). The strain P[PZ] Syx1°⁶⁴⁷⁰ rv⁰⁰⁵⁰/TM3 (Bloomington Drosophila Stock Center) was used to generate deletions near the P-element by transposase-induced male recombination (Preston et al., 1996) and one snky⁺ chromosome, denoted Df(3L) Syx1°⁶⁴⁷⁰ rv⁰⁰⁵⁰/TM3, was recovered. This chromosome is homozgyous viable but poorly so due to deletion of genes other than snky⁺ (Fitch and Wakimoto, 1998). A transgenic line that expressed the secreted Green fluorescent protein (GFPsecr) of Pfeiffer et al. (Pfeiffer et al., 2000; Pfeiffer et al., 2002) under the control of the β2 testis-specific promoter from the tv3 vector (Wong et al., 2005) was generously provided by J. Brill.

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Molecular characterization of the snky gene, mutations and transcript

Molecular studies were carried out essentially as described by Sambrook and Russell (Sambrook and Russell, 2001). Genomic fragments flanking P-element insertions in the P[P2] Syx1G470a and Df(3L) Syx1G470aS5 chromosomes were isolated and sequenced to identify the P-element insertion site and locate the deficiency breakpoints (Preston et al., 1996). These fragments were used as probes to select hybridizing genomic clones from a phage library (Tamkun et al., 1992). Overlapping clones that spanned the deleted region were used to probe genomic Southern blots containing DNA from snky+ and its parental mnh red e line to identify restriction site polymorphisms. The snkym2066 and snkym2402 mutations were identified using PCR to amplify and sequence selected regions from mutant and parental b c chromosomes.

For northern blots (Fig. 2), the lanes contained ~0.25 μg polyA+ RNA from testes (350 pairs of testes) or ~7.4 μg polyA+ RNA isolated from 40 males after removal of the testes. The probes were a 32P-labeled 3.3 kb AvaI genomic fragment isolated from the clone BAC05N10 (UK-HGMP Resource Center) and a clone containing the ribosomal protein gene rp49.

We sequenced snky cDNA clones, which we generated from polyA+ RNA isolated from testes of b c males. Standard protocols were used for reverse transcription (Gibco Superscript II RNase H-Transcriptase Kit), S5 RACE (Ambion Choice RLM-RACE Kit), and cDNA cloning into the TOPO- TA vector (Invitrogen). Primers (Gibco) for cDNA amplification were: S1 (CCTCTCTACTGGACTCGTGT), S2 (GTGGTGAAGGCCGAAAGA), S3 (CGAAGCTTACGGTATTAGA), S4 (GTGGATCCCTGGCCACAAAT), S5 (TGTTAAGCTTGGCCATCAATT), S6 (GGCGAAAGCCCACCTCGATA).

Construction of transgenic lines and assays for male fertility

The rat CD2 coding region was isolated as a 1.1 kb ClaI/XhoI fragment from a plasmid kindly provided by N. H. Brown (Dumin-Borkowski and Brown, 1995) and cloned downstream of the testis-specific β2-tubulin promoter in P-element transformation vector of Hoyte et al. (Hoyte et al., 1995). The construct also contained the white+ snky gene and was introduced into y w 4872 flies using standard germline transformation techniques. A line carrying a transposon on chromosome 2 was used to construct the y w 118B; P[w+wsnky B2;:CD2] 2a; snky1 eye/mes, y+ Ser e strain.

The genomic region containing the CG11281 gene was isolated as a 7.3 kb SalI fragment from BACNOH10 and cloned into pcCasPer4, which carries the white+ gene (Thummel and Pirrotta, 1992). Three independent insertions, denoted P[w+wsnky snky-t7A, B and C were obtained. Two were on chromosome 3 and were introduced into a snky+ background by recombination onto Df(3L) Syx1G470aS5.

A transgene expressing Snky-GFP fusion protein, denoted P[w+wsnky snky-GFP] was created by inserting the Enhanced green fluorescent protein (EGFP) coding region from pEGFP-N3 (Clonetec) into the pcCasPer4-7.3 S construct described above. The fusion protein retained the snky+ gene promoter and flanking regions. It extended the snky+ open reading frame (ORF) just before the stop codon to include: a 30 bp linker from pEGFP-N3, the EGFP coding sequences (amino acid 1 to 237) and, as a consequence of the cloning scheme, an in-frame duplication of the last seven codons of the snky ORF. The transgene was used to generate the y w; P[w+wsnky snky-GFP]; snky1 eye/Mes, y+ Ser e lines.

Fertility assays were performed for males carrying P[w+wsnky snky-t7A] or P[w+wsnky snky-GFP] in a snky+ background to test for activity of the transgenics. Fertility was monitored in crosses of single males mated to three females. Percentage of fertile crosses and progeny sex were recorded. Male fertility was monitored in crosses of single males mated to three females for 10 days. Percentages of fertile crosses and progeny sex were determined.

RESULTS

Sperm produced by snky males retain a plasma membrane marker after entry into the egg

Males mutant for the snky gene are sterile despite normal spermatogenesis, successful transfer of normal quantities of sperm to females and efficient sperm entry into eggs (Fitch and Wakimoto, 1998). We previously reported that the snky defect is apparent shortly after the sperm enters the egg. The sperm nucleus remains tightly condensed and located at the egg cortex and no sperm aster is produced. We also reported that the sperm nucleus stains readily with DAPI, a membrane permeable with chromatin dye but variably so, or not at all, with membrane impermeable dyes. We therefore proposed that the defect is due to persistence of a plasma membrane around the head of snky mutant sperm, preventing access to activating factors in the egg cytoplasm. To obtain more direct evidence for this proposal, we expressed an integral membrane protein, the rat CD2 protein, during spermatogenesis to provide a sperm plasma membrane marker. Previous studies showed that CD2, a single pass plasma membrane protein, can be expressed in Drosophila cells and detected with a specific monoclonal antibody (Dumin-Borkowski and Brown, 1995). Our transgenic line expressed the CD2 gene under the control of a testis-specific promoter in snky+ homozygotes. Immunostaining showed that CD2 was a membrane marker in primary spermatocytes and all subsequent stages of spermatogenesis. Localization was observed along the entire length of elongating spermatids and mature sperm, including the head (Fig. 1A,B). The CD2 epitope was retained along the sperm after entry into the egg and for at least 30 minutes after egg deposition (Fig. 1C,D,E; n=9 eggs), providing evidence that snky mutant sperm fail in plasma membrane breakdown (PMBD).

Assays for Snky-GFP and CD2 expression

To monitor Snky-GFP in testes, y w; snky-GFP; snky1 eye/mes males were dissected in 2% paraformaldehyde in PBS (130 mM NaCl, 7 mM KCl, 3 mM Na2HPO4, 3 mM K2HPO4). Testis squashes were prepared on poly-L-lysine coated slides, frozen in liquid nitrogen, submerged in 95% cold ethanol, rinsed in PBS, then stained with 0.1 μg/ml DAPI (4′,6-diamidine-2-phenylindole) to label nuclei. To label the mitochondrial derivative, larval testes were incubated with 400 mM/l Mitotracker Dye (MT-CMXRs, Molecular Probes), then processed as described for adult testes. To assay Snky-GFP in sperm in the reproductive tracts of females and in eggs, wild-type females were mated to y w; snky-GFP; snky1 eye/mes males. Sperm storage organs were dissected then prepared as described above. Eggs were collected within 15 minutes of deposition, dechorionated in 50% bleach, then fixed in 4% paraformaldehyde in PBS overlaid with heptane. After vitelline envelopes were removed by hand, eggs were processed without squashing as described above. All preparations were mounted in Vectashield (Vector Laboratories). Images were acquired at 600× magnification using a Bio-Rad Radiance 2000 confocal microscope equipped with a 488 nm Kr/Ar laser. Optical sections were typically 0.45 μm. Z-series stacks were assembled using NIH Image J (http://rsb.info.nih.gov/ij/) and images were edited using Adobe Photoshop.

Testes were isolated from adult males carrying the rCD2 transgene and fixed in 4% paraformaldehyde. For immunostaining, we used a 1:100 dilution of the primary antibody to CD2 monoclonal antibody (Harlan Sera-Labs) and Alexa-488 goat anti-mouse antibody (Molecular Probes) as secondary antibody. Nuclei were counterstained with 1 μg/ml propidium iodide. The tissue was mounted in Vectashield for confocal microscopy. To track CD2 in embryos, wild-type females were mated to snky1 male carrying the rCD2 transgene. Eggs were collected within 20 minutes of deposition, aged for 30 minutes, then dechorionated in 50% bleach and transferred to poly-L-lysine coated slides. Eggs were squashed under a coverslip, and the slide was frozen in liquid nitrogen then submerged in 95% ethanol for 10 minutes. Tissue was fixed and incubated with the secondary antibody as described for testes. Secondary and tertiary fluorescent labeling of OX-34 was performed with Alexa 488 Signal-Amplification Kit (Molecular Probes) using the manufacturer’s protocol. Nuclei were counterstained with DAPI. Images were obtained using a Nikon fluorescent microscope equipped with a CCD camera and edited with Adobe Photoshop.
The *snky* gene corresponds to predicted gene CG11281 and encodes a testis transcript

We previously mapped *snky* to the 69F-70A cytogenetic interval (Fitch and Wakimoto, 1998). To refine localization, we generated deficiencies in the region using P-element-mediated male recombination starting with the *P[PZ] Syx1301470* insertion. The strategy yielded a small deficiency, denoted *Df(3L) Syx1301470*, that was homozygous viable and conferred the *snky*- phenotype to surviving males. Molecular mapping of the deficiency breakpoints defined a 185 kb genomic interval within which we identified a restriction site polymorphism between *snky* and its parent chromosome. The region overlapped with CG11281, a gene predicted by the *Drosophila* Genome Project but for which no gene. Two additional observations showed that CG11281 corresponded to the *snky* gene. Northern analysis revealed a CG11281 transcript with an expression profile consistent with the specific effect of *snky* mutations on male fertility. As shown in Fig. 2A, a genomic fragment containing CG11281 hybridized to a rare 2.7 kb polyadenylated RNA that was found in testes, but not in carcasses (bodies lacking testes) of wild-type adult males. A corresponding transcript that was reduced in size and abundance was detected in testes of *snky* males (Fig. 2B). A hybridizing transcript was absent in females (data not shown). Definitive evidence to assign CG11281 as the *snky* gene was achieved by transgenic rescue of the *snky* male sterility by a 7.3 kb genomic *Sal*I fragment that included CG11281 but no other predicted genes. Three independent insertions of the transgene were obtained and each one conferred male sterility by a 7.3 kb genomic *Sal*I fragment that included CG11281, a gene that was expressed sequence tag or cDNAs had been reported.

We determined the *snky* transcript structure using RT-PCR and 5’ RACE. This analysis revised the CG11281 predicted structure and revealed a gene with a single intron and an ORF of 715 amino acids. Sequence analysis of two EMS-induced alleles and their parent *bw; st* line identified a single lesion in the ORF in both cases. In *snky*, a change from *T* to *A* results in a missense mutation that replaces a Cys with a Ser at residue 258. In *snky*, a transition mutation of *C* to *T* results in a stop codon at residue 379.

**Snky is a predicted transmembrane protein with a RING finger domain**

The Snky protein is predicted to be a protein with multiple transmembrane domains. The following predictive algorithms were used to examine potential topologies: TMHMM 2.0 (Krogh et al., 2001), HMMTOP 2.0 (Tusnady and Simon, 2001), PHOBIUS (Kall et al., 2004), SOSUI (Hirokawa et al., 1998) and ConPred II (Arai et al., 2004). These programs gave conflicting results probably due to the relatively high content of positively charged residues in Snky. However, all programs predict a minimum of four transmembrane domains and one, ConPred II, predicts eight transmembrane domains. The topology shown in Fig. 3A is based on the SOSUI prediction, which identifies a signal sequence within the 2145 bp ORF (black box), the 72 bp intron and the predicted polyadenylation site are also indicated. We determined the *snky* transcript structure using RT-PCR and 5’ RACE. This analysis revised the CG11281 predicted structure and revealed a gene with a single intron and an ORF of 715 amino acids. Sequence analysis of two EMS-induced alleles and their parent *bw; st* line identified a single lesion in the ORF in both cases. In *snky*, a change from *T* to *A* results in a missense mutation that replaces a Cys with a Ser at residue 258. In *snky*, a transition mutation of *C* to *T* results in a stop codon at residue 379.

Fig. 1. The rCD2 protein marks the sperm plasma membrane. The panels show sperm produced by males homozygous for *snky* and a transgene expressing rat CD2 gene. The rCD2 protein (green) was detected by immunolocalization and nuclei (red) by PI or DAPI staining. In a cyst of elongating spermatids (A) and mature sperm (B), rCD2 is located on the plasma membrane. After entry into the egg, sperm retain a condensed nucleus (C) and rCD2 (D). The merged image (E) shows overlapping rCD2 and nuclear staining consistent with retention of the plasma membrane surrounding the head. Scale bar: 10 μm.

Fig. 2. Expression and structure of the *snky* transcript. (A,B) Northern blots probed with a genomic fragment that contained CG11281 detected a 2.7 kb transcript that was present in testis, absent in male carcasses (A) and reduced in size and abundance in *snky* testes compared to its parental strain (B). Bottom panel shows levels of rp49 mRNA in each lane as a loading control. (C) Transcript structure was determined by RT-PCR. Primers used for cDNA amplification are indicated by arrows. The transcript is contained within the Aval genomic fragment, which was used as a probe for northern analysis. Fragment endpoints are labeled according to *Drosophila* Genome Project Release 4.0 coordinates. Transcription initiation site (+1) determined by 5’ RACE is nucleotide 3L 13,131,973. Positions of the start and stop codons of the 2145 bp ORF (black box), the 72 bp intron and the predicted polyadenylation site are also indicated.

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proteins include: a mosquito protein (11X)-C-(2-4X)-C-(4X)-C-(2X)-C-(7X)-C-(2X)-C. The Snky proteins also share additional features. All are predicted to have multiple transmembrane domains. Each also has the patterned 6 Cys motif in the first 18 residues and predicts the 6 hydrophobic membrane-spanning domain most commonly predicted by the suite of programs we used.

Snky has two regions with noteworthy Cysteine residue patterns (Fig. 3A,B). One region is located in the largest predicted extramembrane loop and contains six Cys that are separated by eight to 12 amino acids. The functional significance of this region, which we refer to as the patterned 6 Cys motif, is indicated by the snky<sup>20566</sup> mutation, which changes the two Cys to a Ser. The second region is located near the carboxyl end and consists of four pairs of C-X<sub>2</sub>-Cs (where X is any amino acid) that are linked by four to ten residues. This second pattern corresponds to a variant of the Pfam C3HC4 RING finger (pfam PF00097) (Finn et al., 2006). In Snky, a Cys is substituted for the His resulting in a C4-C4 variant. Additionally, a coiled-coil domain is predicted in Snky from residue 192 to 218 with the consensus pattern: C-(10X)-C-(12-13X)-C-(8X)-C-(9-12X)-C. These proteins also contain a RING finger with the consensus pattern: C-(2X)-C-(10-11X)-C-(2-4X)-C-(4X)-C-(2X)-C-(7X)-C-(2X)-C. These proteins include: a mosquito protein (Aedes aegypti, EAT46485, conceptual translation) with 30% amino acid identity; a zebrafish protein (XP683798, conceptual translation) with 22.2% identity; a human protein (BAB71440) with 22% identity; and a mouse protein (XP994048) with 21.8% identity. The human and mouse protein sequences are supported by full-length testis cDNAs. Although expressed sequence tags have also been isolated from other tissues, comparison of available sequence indicates the possibility of testis-specific isoforms in humans. CLUSTAL W alignment (Thompson et al., 1994) revealed three regions, which are the most highly conserved among Snky family members. These regions are denoted a, b and c in Figs 3 and 4. Regions b and c overlap with the ends of the region that defines the DC-STAMP sequence family (Pfam PF07782). In Snky, the DC-STAMP-like region extends 192 amino acids, from amino acid 406-597.

Snky is more distantly related to other proteins that had been previously recognized as containing DC-STAMP-like regions. They include the human and mouse DC-STAMP-Domain Containing-2 Proteins, the Caenorhabditis elegans sperm protein SPE-42 (Kroft et al., 2005) and a Drosophila protein encoded by the CG6845 gene. These proteins contain a RING finger and a Cysteine-containing region spaced similar to the patterned 6 Cys motif in Snky. However, compared with proteins described above, they show a reduced level of identity with Snky at the amino acid level (10-17% identity), particularly in regions a, b and c. Included in this group is a predicted sea urchin protein (XP795449) with 15.1% identity to Snky. Even more distantly related are the human and mouse DC-STAMP, which contain the DC-STAMP domain but lack a RING finger and a patterned 6 Cys motif.

**Localization of a Snky-Green fluorescent protein fusion during spermatogenesis**

We generated transgenic flies that contained a snky-Green fluorescent protein fusion gene expressed from the snky promoter. The fusion protein contained the entire Snky protein and Enhanced GFP at the carboxyl terminus. Four independent transgenic lines were recovered and in each line, the transgene significantly rescued fertility to a level comparable to that conferred by the snky<sup>+<sup> mutation. Hence, the Snky-GFP fusion protein was highly active and could be used as a tool to deduce the localization of the normal Snky protein.

To examine tissue expression of Snky-GFP, we examined larvae and adults that were homozygous for a snky<sup>GFP</sup> transgene and the snky<sup>+</sup> mutation. We detected expression only in the testis. To determine when Snky-GFP is expressed, we distinguished the different stages of spermatogenesis by the characteristic morphology of nuclei and mitochondrial derivatives (A. D. Tates, PhD thesis, University of Leiden, 1971) (Fuller, 1993). Nuclei were monitored by DAPI staining and mitochondrial derivatives were visualized by MitoTracker Red-CMXRos staining. Snky-GFP was first detected in primary spermatocytes as a diffuse cytoplasmic signal (Fig. 5A), consistent with localization to the endoplasmic reticulum and as expected for an integral membrane protein. Following meiosis, at the stage in which the male pronucleus is visible, and comparably sized mitochondrial derivatives, a prominent cluster of Snky-GFP spots was seen just adjacent each nucleus (Fig. 5B). The structures at this stage corresponded in size and location to the aggregated Golgi complexes that Tates (A. D. Tates, PhD thesis, Development 133 (24))

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**Table 1. Rescue of the snky phenotype by transgenes**

<table>
<thead>
<tr>
<th>Strain (snky&lt;sup&gt;+&lt;/sup&gt;)</th>
<th>Genotype</th>
<th>n*</th>
<th>% Fertile crosses</th>
<th>Average progeny yield</th>
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<tr>
<td>Control (snky&lt;sup&gt;-&lt;/sup&gt;)</td>
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<td>0.0</td>
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<tr>
<td>Transgenic</td>
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<td>20</td>
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<tr>
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<td>0.06</td>
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<tr>
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<td>20</td>
<td>85</td>
<td>110.0</td>
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<tr>
<td>Transgenic</td>
<td>y w/ Y; Df snky, P(w&lt;sup&gt;amc&lt;/sup&gt;, snky&lt;sup&gt;am&lt;/sup&gt; t 73)C / snky&lt;sup&gt;1&lt;/sup&gt;</td>
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<tr>
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<td>0.06</td>
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<tr>
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<td>86.4</td>
<td>88.4</td>
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<sup>*</sup>Number of single male crosses.<br>† Crosses yielding >5 progeny (see Materials and methods).
University of Leiden, 1971) referred to as the acroblast. With continued differentiation, as nuclear condensation began and mitochondrial derivatives and sperm tails elongated, Snky-GFP was present as multiple irregular spots throughout the cytoplasm. However, one spherical Snky-GFP signal, generally larger than the others, was located adjacent to each nucleus (Fig. 5C). This site of Snky-GFP was the only visible signal retained as spermatids became fully elongated (Fig. 5D,E). In individualized mature sperm, the Snky-GFP signal exhibited a thin oval shape located at the tip of the sperm, with its distal end slightly overlapping with apical end of the needle-shaped nucleus (Fig. 5F). This pattern of localization and the predicted structure of Snky suggest that it is an integral membrane protein targeted to the acrosome during spermatogenesis.

**The fate of Snky-GFP and the acrosome during fertilization**

Snky-GFP allowed us to examine the fate of Snky and the acrosome during normal fertilization. In *Drosophila*, female store sperm after mating. We examined seminal receptacles (sperm storage organs) of wild-type females mated to snky1 males that carried two copies of the Snky-GFP transgene. The Snky-GFP signal we observed in stored sperm appeared identical to that seen in mature sperm from the testis (data not shown).

Fertilization occurs within the reproductive tract of females. Sperm are released from the seminal receptacle and enter the egg as it passes down the uterus. The events from sperm entry into the egg to the completion of the first embryonic cell cycle occur rapidly (estimated <17 minutes) and are often completed before the egg is laid. To capture the earliest stages, eggs fertilized by sperm from Snky-GFP males were collected and fixed within 15 minutes of egg deposition, counterstained with DAPI and examined by confocal microscopy. Even with this rapid processing, the majority of embryos examined had progressed beyond cycle 2. Of the 17 fertilized eggs and embryos captured before metaphase of cycle 1, we observed a Snky-GFP signal in 16. The signal was located in close proximity to the sperm nucleus before visible evidence of nuclear decondensation (Fig. 6A, n=1), and more distantly as decondensation progressed (Fig. 6B, n=3). During pronuclear migration and pronuclear apposition, Snky-GFP was seen peripheral to what was judged to be the male pronucleus based on the state of chromatin condensation or position in the egg (Fig. 6C, n=11, with one without a GFP signal). During prometaphase of cycle 1, the Snky-GFP signal was observed near the condensing chromosomes (Fig. 6D, n=2). Although the position of the Snky-GFP signal relative to the sperm chromatin changed during these stages of fertilization, neither the shape nor the intensity of the signal appeared to change. Five embryos were found at stages between metaphase of cycle 1 and 2 and only one, which was anaphase of cycle 1, exhibited a GFP signal (data not shown). We did not detect GFP signals in control eggs (fertilized by sperm of males lacking Snky-GFP), which were captured before prometaphase of cycle 1 (n=7, data not shown).

These studies revealed two surprising discoveries. The first of these was that sperm contributed Snky-GFP to the egg. The second remarkable finding was that the GFP signals observed in the egg and early cycle 1 embryos consistently appeared similar to those observed in mature sperm. We considered two possibilities to account for the retention of bright GFP signals in the egg cytoplasm. The paternally inherited structure could be an acrosomal vesicle, with the Snky-GFP signal marking the boundaries of an intact acrosome. Alternatively, the GFP signal could reflect retention of a large membrane remnant from a spent acrosome. To distinguish between these two possibilities, we obtained a transgenic line that expressed a soluble form of GFP in the acrosome. This line (gift of J. Brill) expresses the GFPsecr protein under the control of a testis-specific promoter. GFPsecr was designed and characterized by Pfeiffer et al. (Pfeiffer et al., 2000; Pfeiffer et al., 2002), and it contains the signal peptide from the Wingless protein fused to GFP. When expressed in embryonic or imaginal disc epithelial cells, GFPsecr is targeted to the secretory pathway, packaged in secretory vesicles and released into the extracellular space upon secretion (Pfeiffer et al., 2002). These properties predict that if GFPsecr is present in the acrosome, the GFP signal will dissipate upon acrosome exocytosis.

We examined eggs fertilized by sperm expressing GFPsecr. Of the 22 eggs captured between earliest stages of sperm nuclear decondensation (Fig. 6E) to prometaphase of cycle 1 (Fig. 6H), 21 showed a GFPsecr signal. In each case, the appearance was similar to that observed with Snky-GFP (compare higher magnification insets of Fig. 6A-H). These data are consistent with the retention of an intact acrosomal vesicle by the sperm during fertilization, the release...
of the vesicle into the egg cytoplasm after PMBD, and the persistence of the acrosome at least as late as prometaphase of the first embryonic cycle.

DISCUSSION

Fertilization in *Drosophila melanogaster* is unorthodox in that it does not involve a membrane fusion event between the sperm and egg. The mechanism used by the sperm to penetrate through the egg plasma membrane remains an interesting mystery. In her ultrastructural studies of fertilization in *D. melanogaster* and *D. montana*, Perotti (Perotti, 1975) observed that the entire sperm enters the egg, including the excessively long tail surrounded by its plasma membrane. She noted that there was no evidence for 'extra' membranes that would support uptake into the egg by endocytosis. While her studies did not capture the sperm before nuclear decondensation, Perotti described one case in which a decondensing sperm nucleus was surrounded by what appeared to be remnants of the sperm plasma membrane. Her studies support the idea that the *Drosophila* sperm head must undergo PMBD in the egg cytoplasm. This step is required for the sperm nucleus to gain access to...
activating cytoplasmic factors that promote nuclear decondensation and replication, and for the centrosome to elaborate the sperm aster (Fitch et al., 1998). Our studies support this sequence of events and implicate Snky function in an event upstream of PMBD. Our original proposal that snky mutant sperm fail in sperm activation because they arrest before PMBD was based on their poor accessibility to membrane impermeant chromatin dyes (Fitch and Wakimoto, 1998). Further support was obtained by Ohsako et al. (Ohsako et al., 2003), who used an antibody to a proposed cell surface proteoglycan to demonstrate retention on the sperm head before and after insemination. In our current study, we ectopically expressed the rat CD2 protein on the sperm plasma membrane and showed that immunoreactivity to this specific integral membrane protein was retained on the head of snky1 sperm for at least 30 minutes after entry into the egg. These observations provide strong support for the proposal that snky sperm do not shed the plasma membrane surrounding the head. They also suggest that understanding the function of the Snky protein should provide clues about how PMBD is initiated or accomplished at the molecular level.

Molecular studies reported here show that Snky is a member of a family of related membrane proteins that are present in animals but are apparently absent in other lineages. Conservation among Snky family members points to three domains of potential functional significance. The most striking motif is the C4-C4 RING finger, which has been noted in at least four other proteins (Hanzawa et al., 2001; Kellenberger et al., 2005; Pugh et al., 2006; Arioli et al., 1998). In one of these, hNOT4, the C4-C4 RING has been shown to fold and bind zinc in a cross-brace fashion similar to the more common C3HC4 RING finger (Hanzawa et al., 2001), suggesting structural and functional similarity between these variants. Although RING finger proteins have been implicated in a broad variety of cellular functions, recent studies suggest that their unifying role is in mediating protein-protein interactions in large multiprotein assemblages (Borden, 2000). Thus, Snky may play a role in organizing and holding together macromolecular complexes at the membrane via its C4-C4 RING. The second Cys-containing region is the patterned 6 Cys motif, the functional significance of which is indicated by conservation and by the recovery of a male sterile snky allele that mutates the second Cys to a Ser. Cysteines in this region may form disulfide bonds to create a binding pocket or otherwise allow interactions with additional proteins. The third region is the DC-STAMP-like region, named after Dendritic cell specific transmembrane protein, a plasma membrane protein that was first described for its expression in human dendritic cells (Hartgers et al., 2000). Thus far, the function of only a few DC-STAMP-domain-containing proteins have been examined through the analysis of mutations or other knockdown strategies. The general classification of these proteins has been as members of a new class of putative receptors. Mouse DC-STAMP is upregulated in differentiating osteoclasts, and required for osteoclast fusion to form multinucleate cells (Kukita et al., 2004; Yagi et al., 2005). The C. elegans SPE-42 is required in sperm and is proposed to act at a step in fertilization just before or during sperm-egg membrane fusion (Kroft et al., 2005). Snky is the third DC-STAMP-domain-containing protein to have its function studied and, like Spe-42, it has a role in sperm function. Although the precise molecular function of the DC-STAMP domain remains unknown, these three examples support a role in mediating membrane-membrane interactions.

The predicted structure of Snky, with its multiple transmembrane domains, and our Snky-GFP localization studies provide evidence that Snky is an acrosomal membrane protein. This localization presents the intriguing question of how an acrosomal membrane protein is able to influence the integrity of the sperm plasma membrane. The findings also have broader implications for acrosome function. The acrosome is a Golgi-derived membrane-bound organelle found at the apical end of sperm, and its function has been extensively studied in marine invertebrates and mammals. In these organisms, the acrosome is best known as a specialized secretory vesicle that undergoes exocytosis. Like many secretory

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**Fig. 6. Localization of Snky-GFP and GFPsecr during fertilization.**

(A-D) GFP (green) was monitored in eggs fertilized by sperm from snky/H9262 males that carried two copies of a snky-GFP transgene. Nuclei (red) were stained with DAPI. Insets to the right of each picture show higher magnification view of the GFP signal. (A) A single GFP signal is observed just apical to the condensed sperm nucleus and (B) more distantly as the sperm nucleus decondenses. (C) GFP is seen near the apposing male and female pronuclei and (D) by the chromosomes during prometaphase of the first embryonic cycle. (E-H) In eggs fertilized by sperm from males expressing GFPsecr, the GFP signals appear similar to those described for Snky-GFP. Scale bars: 3 μm in A,B,E,F; 6 μm in C,D,G,H; 2 μm in the higher magnification insets.
events, a rise in intracellular Ca$^{2+}$ is required for acrosome exocytosis. This increase in Ca$^{2+}$ requires influx into the sperm as well as efflux from internal stores. The acrosome has been identified as an internal source of Ca$^{2+}$ and is believed to release Ca$^{2+}$ to contribute to its own exocytosis (Walensky and Snyder, 1995; Herrick et al., 2005). Ultrastructural studies show that exocytosis involves vesiculation of the outer acrosomal membrane and overlying plasma membrane. This results in the release of contents of the acrosome, which include hydrolytic enzymes and other components that facilitate binding and penetration through the egg coats. Exocytosis also exposes the inner acrosomal membrane, resulting in a new membrane patch and associated acrosomal molecules on the surface of the sperm. In marine invertebrates, this newly exposed region is the site of binding and membrane fusion with the egg (Colwin and Colwin, 1967; Lopo et al., 1982), providing a direct physical link between the requirement for acrosome exocytosis and membrane fusion. In mammals, acrosome exocytosis is also a prerequisite for sperm to bind to and fuse with the egg. However, the plasma membrane that lies over the equatorial segment of the acrosome, and not the acrosome membrane itself, is believed to be the point of membrane fusion with the egg (Yanagimachi, 1994). Experimental studies of hamster sperm by Takano et al. (Takano et al., 1998) suggest that fusion competency of this specialized region of mammalian sperm requires changes that occur immediately before or during acrosome exocytosis, as well as the contents of the acrosome.

Considering these known acrosome functions, it is interesting that acrosomes are not universal features of animal sperm. Acrosomes are not present in the amoeboid sperm of nematodes, and they are occasionally absent or reduced in species that otherwise possess the flagellated sperm typical of animals (Baccetti, 1979). For instance, the absence or reduction of an acrosome in mature sperm of teleosts (Coward et al., 1996) and certain insect species (Baccetti, 1972; Dallai et al., 2003) is well documented and is generally considered a derived condition (Baccetti, 1979). Hence the requirement for the acrosome during fertilization has been eliminated or bypassed in some lineages during the course of evolution. Ultrastructural studies show that an acrosome is typical of insect sperm (Baccetti, 1972). However, few studies have examined the role of the insect acrosome during fertilization. Studies of fertilization in the house fly Musca domestica suggested ‘loosening or loss’ of the sperm plasma membrane before entry into the micropyle of the egg, followed by exocytosis of acrosomal contents during passage of the sperm through the micropyle (Degrujillier and Leopold, 1976).

Our studies revealed a different fate for the Drosophila acrosome. The observation that Snky-GFP was a paternally contributed molecule to the early egg was a surprising finding. The persistence of a single prominent Snky-GFP structure, with an intensity and shape in eggs that appeared similar to those seen in mature sperm, suggests the possibility that the inherited structure was an intact acrosome. This possibility was further supported by studies tracking GFP$^{\text{act}}$, a soluble protein that is secreted into the extracellular space when expressed in other Drosophila cells (Pfeiffer et al., 2002). Its robust and identical appearance to Snky-GFP argues against exocytosis, at least until after prometaphase of the first embryonic cell cycle.

These cytological observations of the fate of the acrosome during normal fertilization, combined with the defect in PMBD observed in snky$^+$ mutant sperm, suggest that the acrosome may be acting primarily as a signaling vesicle to elicit changes in the overlying sperm plasma membrane. This activity requires the Snky acrosomal membrane protein, but occurs without acrosome exocytosis. Snky may be serving as a receptor that permits communication between the acrosome and plasma membrane. Alternatively, Snky or its associated proteins may serve to initiate or maintain contact between the membranes, or modify membrane lipids or proteins in preparation for PMBD. In this sense, Snky, DC-STAMP and SPE-42 may share a common mechanism in promoting membrane interactions (Yagi et al., 2005; Kroft et al., 2005). However, in the case of Snky, the pathway would lead to breakdown of the overlying plasma membrane, rather than fusion between two membranes.

In Drosophila, Snky is required specifically for male fertility. It will be interesting to determine whether Snky family members are required for sperm function in zebrafish, which have sperm that lack acrosomes, and for acrosome function in marine invertebrate and mammalian sperm. If human Snky-like proteins are specifically required for sperm function, then they may be potential targets for male contraceptives. More immediately, our studies of Snky provide tools for further investigating how the membrane events that occur during Drosophila fertilization compare to conventional views of membrane dynamics during sperm activation and fertilization in animals. Research on the acrosome has focused primarily on its function as a specialized secretory or Ca$^{2+}$ storage vesicle. Our studies suggest a primary role as signaling vesicle in Drosophila, with a newly identified acrosomal membrane protein communicating directly or indirectly with the plasma membrane to affect changes in membrane integrity. Comparisons among species should continue to shed light on the intriguing ways in which sperm structures and fertilization molecules, such as Snky, may be selected for conservation or diversification during the course of evolution.

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References


Drosophila fertilization requires Snky


