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Journal Title: Current Biology
Volume: Volume 25, Number 24
Publisher: Elsevier (Cell Press) | 2015-12-21, Pages 3225-3231
Type of Work: Article | Post-print: After Peer Review
Publisher DOI: 10.1016/j.cub.2015.10.056
Permanent URL: https://pid.emory.edu/ark:/25593/rvz66

Final published version: http://dx.doi.org/10.1016/j.cub.2015.10.056

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Accessed October 17, 2018 12:29 AM EDT
The Immunoglobulin-like Gene spe-45 Acts during Fertilization in Caenorhabditis elegans like the Mouse Izumo1 Gene

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SUMMARY

The Caenorhabditis elegans spe-9 class genes, which show specific or predominant expression in the male germline, are indispensable for fertilization [1, 2]. However, due to the rapid evolution of genes involved in reproduction, we do not currently know if there are spe-9 class genes in mammals that play similar roles during fertilization to those found in C. elegans. In mice, the Izumo1 gene encodes a sperm-specific transmembrane (TM) protein with a single immunoglobulin (Ig)-like domain that is absolutely required for gamete fusion [3, 4]. In this study, we hypothesized that C. elegans has a new member of the spe-9 class genes coding for an IZUMO1-like protein. We screened C. elegans microarray data [5, 6] to identify male germline-enriched genes that encode membrane proteins with Ig-like domains. A deletion (tm3715) in one such gene (F28D1.8) caused hermaphrodites to show a male germline-dependent self-sterility, so we have named it spe-45. Mutant spe-45 worms seemed to normally undergo spermatogenesis (spermatid production by meiosis) and spermiogenesis (spermatid activation into actively motile spermatozoa). spe-45 mutant spermatozoa, however, could not complete gamete fusion, which is a characteristic of all spe-9 class mutants [1, 2]. Moreover, spe-45 self-sterile worms were rescued by a transgene expressing chimeric SPE-45 protein where its Ig-like domain was replaced by the Ig-like domain from mouse IZUMO1. Hence, C. elegans SPE-45 and mouse IZUMO1 appear to have retained a common function(s) that is required during fertilization.

RESULTS AND DISCUSSION

Gamete fusion during fertilization is required to create a zygote. Several studies have revealed that the sperm immunoglobulin (Ig)-like protein IZUMO1 is essential for sperm-oocyte fusion in the mouse [3, 4, 7-9], but it is not yet clear how IZUMO1 is involved in gamete fusion.
*Caenorhabditis elegans* is a useful model to investigate the molecular basis of gamete fusion for two reasons: Firstly, *C. elegans* spermatozoa directly bind to and fuse with the oocyte plasma membrane during fertilization [1, 2]. Secondly, mutants lacking any of the SPE-9 class proteins (SPE-9 [10-12], SPE-38 [13, 14], SPE-41/TRP-3 [14, 15] and SPE-42 [16, 17]) have been recovered, all of which have defects exclusively during fertilization.

We postulated that *C. elegans* spermatozoa might possess an IZUMO1-like protein(s) that is required for fertilization. This study was undertaken to test this hypothesis.

**F28D1.8 Was Identified as a Candidate Mouse Izumo1-like Gene**

As shown in Table S1, we searched for candidate genes in the *C. elegans* genome (release number: WBcel235), using the SMART program [18]. Mouse *Izumo1* shows testis-specific gene expression and it encodes a single-pass transmembrane (TM) protein with a single Ig-like domain (Figure S1A). Therefore, among the 62 predicted Ig-like *C. elegans* genes, we first chose F28D1.8, F28E10.2b, B0273.4c, K04D7.4a, C01G6.8a, T02C5.3b, T04A11.3 and Y32G9A.8, all of which possess one Ig-like and one TM domain.

To look for genes with elevated expression in the male germline, we compared the DNA microarray data of masculinized *fem-3(q23gf)* worms and feminized *fem-1(hc17ts)* worms [5, 6] (shown as “male-to-female” (M/F) ratios in Table S1). M/F ratios of the spe-9 class genes such as *spe-9*, *spe-38* and *spe-41/trp-3* were 5.54, 2.73 and 6.59, respectively. Hence, if the M/F ratio of a certain gene was more than 2.50, we judged it to be a good candidate. Among eight candidates, F28D1.8 showed the highest ratio (M/F = 4.72) and Y32G9A.8 had no available expression data. Thus, sex-dependent expression of these two genes was further examined by reverse transcription (RT)-PCR (Figure 1A). Similar experiments were also carried out for *spe-42*, which has male germline-specific expression, and ubiquitously expressed *rpa-1* as controls [16]. Our RT-PCR analysis demonstrated that F28D1.8, but not Y32G9A.8, has male germline-enriched gene expression.

F28D1.8 is ~2.4 kbp in length and it is composed of eight exons on *C. elegans* chromosome IV (Figure 1B). The *tm3715* allele deletes 418-bp nucleotides from the F28D1.8 sequence (Figure 1B). The predicted F28D1.8 protein (492 amino acids) contains a hydrophobic region and acidic and basic amino acid clusters, as well as one Ig-like and one TM domain (Figure 1C). *tm3715* deletes a part of F28D1.8 that encodes the TM and cytoplasmic tail domains, likely resulting in a nonfunctional or absent protein.

**F28D1.8 Is a spe Gene**

We examined the self-fertility of wild-type (N2) and *tm3715* hermaphrodites (Figures 2A and 2B). N2 hermaphrodites produced ~290, ~290 and ~140 self-progeny at 16, 20 and 25°C, respectively, whereas *tm3715* hermaphrodites produced no progeny at any tested temperature by self-fertilization (Figure 2A). The same *tm3715* mutants, however, laid ~181, ~340 and ~190 unfertilized oocytes at 16, 20 and 25°C, respectively (Figure 2B). Numbers of unfertilized oocytes that had been laid by N2 worms were, as expected (Figure S2), fewer than those by *tm3715* worms (~40, ~140 and ~5 unfertilized oocytes at 16, 20 and 25°C, respectively) (Figure 2B). When *tm3715*, *spe-9(eb19); him-5(e1490)* and
fem-1(hc17ts) hermaphrodites were outcrossed to him-5(e1490) males, which are proficient in mating and produce fertilization-competent sperm, ~210, ~240 and ~110 F1 progeny, respectively, were produced at 20°C (Figure 2C). The spe-9(eb19) [10-12] and fem-1(hc17ts) [13, 16] hermaphrodites produce fertilization-competent oocytes, but self-fertilization does not occur due to defective or no self-sperm. Therefore, the data shown in Figure 2C suggests that oocytes of spe-45 mutants are at least equally competent to be fertilized, as compared with those of spe-9 and fem-1 mutants.

If tm3715 affects a spe-9 class gene, males would produce sperm that could outcompete hermaphrodite-derived sperm after copulation [13, 16, 19] (see also Figure S2). Since dpy-5(e61) is a recessive mutant that causes a Dpy phenotype (smaller and fatter worm shape than wild type) [20], we used dpy-5 mutant hermaphrodites to distinguish self- and outcross-progeny. As shown in Figure 2D, unmated dpy-5 mutants produced only self-progeny (~60 worms) [13, 16, 19]. After mating to non-Dpy him-5 males, dpy hermaphrodites produced ~80 non-Dpy outcross progeny, while Dpy progeny were reduced (~40 worms). Outcrossing of dpy-5 mutants to tm3715; him-5 males, again, resulted in reduced numbers of Dpy progeny (~30 worms), but this time non-Dpy progeny were not observed. Thus, the fertilization-incompetent sperm of tm3715 males are capable of outcompeting dpy-5 self-sperm.

These data suggest that the tm3715-induced self-sterility was restricted to male germline functions, exhibiting typical Spe (spermatogenesis-defective) phenotypes [1, 2]. F28D1.8 was originally named oig-7 (one Ig domain-7), but this name is based on just its protein structure [21]. Therefore, we renamed this gene spe-45, hereafter, based on its loss-of-function phenotype.

Production and Activation of spe-45(tm3715) Spermatids Occurs Normally

C. elegans male germline functions are divided into three pivotal steps: spermatid production during meiosis (spermatogenesis), spermatid activation into spermatozoa (spermiogenesis) and fertilization. Dissected him-5(e1490) and spe-45(tm3715); him-5(e1490) males each released spermatids that are indistinguishable in number (Figures 2E and 2H) and cytology (Figures 2F and 2I), suggesting that spermatogenesis occurs normally in spe-45 mutants.

We next examined spermatid activation into spermatozoa in sperm medium (SM) [22, 23] containing the bacterial protease mixture Pronase [24]. Spermatozoa from spe-45; him-5 males (Figure 2J) showed similar cytology and activation rate to those observed for him-5 male-derived spermatozoa (Figure 2G).

We also evaluated whether spe-45(tm3715) male-derived spermatids can be activated into spermatozoa in vivo (see Figure 2K-2M’). This experiment used fem-1(hc17ts) worms, because they have no self-sperm at 25°C [25]. Consistent with this phenotype, 4’,6-diamidino-2-phenylindole (DAPI)-stained, unmated fem-1 hermaphrodites lacked detectable sperm within the spermatheca (Figures 2K and 2K’). In contrast, fem-1 worms were crossed to either him-5 (Figures 2L and 2L’) or spe-45; him-5 (Figures 2M and 2M’) males, and both had many spermatozoa within their spermathecae after mating. Therefore,
male-derived spermatids were able to activate into spermatozoa in the uterus of fem-1 hermaphrodites and subsequently to crawl into the spermatheca, suggesting normal in vivo spermiogenesis of spe-45 male spermatids.

**spe-45(tm3715) Spermatozoa Cannot Fertilize Oocytes in the Spermatheca**

As shown in Figure S2, ~300 wild-type self-sperm are all consumed by fertilization that occurs in the spermatheca [26]. For this study, fourth larval stage (L4) hermaphrodites were incubated at 20°C for either 24 or 72 h. Then, those worms were fixed and DAPI-stained to visualize countable self-sperm (Figure 3 and Table S2). In each spermatheca of wild-type N2 hermaphrodites, there were ~140 self-sperm at 24 h post the L4 stage, but their numbers were reduced to almost zero at 72 h. Similar data were also obtained in him-5(e1490) hermaphrodites (unpublished results). In the known “spe-9 class” mutants spe-9(eb19) [10] and spe-42(tm2421) [16] and also in spe-45(tm3715) worms, like wild type, there were numerous self-sperm in each spermatheca at 24 h (~90 spe-9 sperm, Figures 3B and 3B’; ~220 spe-42 sperm, Figures 3C and 3C’; and ~180 spe-45 sperm, Figures 3D and 3D’).

However, unlike wild type, many self-sperm still resided in the spermathecae of spe-9 (~50 sperm, Figures 3F and 3F’), spe-42 (~220 sperm, Figures 3G and 3G’) and spe-45 (~110 sperm, Figures 3H and 3H’) hermaphrodites even at 72 h. Intriguingly, numbers of spe-9 and spe-45 self-sperm at 72 h were, respectively, reduced to 52 and 63% of those at 24 h, while numbers of spe-42 self-sperm at 24 h were similar to those at 72 h. Such reduction of spe-9 self-sperm was also observed previously in hermaphrodites bearing different mutant alleles [27].

These data suggest that spe-9, spe-42 and spe-45 self-sperm cannot complete fertilization. spe-42 is possibly involved in the sperm binding to the oocyte plasma membrane, whereas spe-9 and spe-45 self-sperm might be able to contact and bind to oocytes but are not capable of undergoing gamete fusion. It is worth noting that mouse sperm lacking IZUMO1 can bind to, but not fuse with, the oocyte plasma membrane [3, 4].

**A Chimeric SPE-45/IZUMO1 Retains in vivo Function in C. elegans**

Since Ig-like domains have considerable sequence diversity but similar three-dimensional structure [28, 29], we tested whether the IZUMO1 and SPE-45 Ig-like domains are functionally similar. Constructs encoding wild-type SPE-45 (IgWT) or chimeric SPE-45, where the SPE-45 Ig-like domain was replaced with the mouse IZUMO1 Ig-like domain (IgIZUMO1), were created (Figure 4A). As a control, we created a chimeric construct that encoded SPE-45 where the natural Ig-like domain was replaced with that of C. elegans IGCM-3, a somatic protein with no obvious role during fertilization [21] (IgIGCM3; Figure 4A). These three constructs were used to create transgenes that were evaluated for rescue of spe-45 self-sterility (Figure 4B). Intriguingly, spe-45 hermaphrodites bearing the IgIZUMO1 or IgIGCM3 (control) transgene had self-broods that were, respectively, 76.7% or 0% of those with the IgWT transgene. These data suggest that the Ig-like domains of SPE-45 and IZUMO1 have a common function(s) during sperm-oocyte fusion.

As shown in Figure 4C, while the SPE-45 Ig-like domain is well conserved among four Canorhabditis species (~75-83% identities), there are only limited primary sequence
identities of the Ig-like domains between *C. elegans* SPE-45 and mouse, human IZUMO1 or *C. elegans* IGCM-3 (~12-17% identities). When the entire sequences were compared (Figure S3 and Table S3), *C. elegans* SPE-45 and mouse IZUMO1 showed only 8.7% sequence identity, while *Caenorhabditis* SPE-45 orthologs showed only modest identities (~36-61%). Our data suggest that *C. elegans* SPE-45 is orthologous to mouse IZUMO1, but this is not detectable by BLAST (http://blast.ncbi.nlm.nih.gov/Blast.cgi) because of low sequence identity. Prior work showed that the sequences of many fertilization-related proteins are poorly conserved, even among closely related species [30-32], so orthologous proteins that participate in reproduction might be best defined based on their functions, rather than sequence identity.

**Diverse Species Use Proteins with Ig-like Domains during Gamete Interactions**

Like SPE-45 and IZUMO1, a diverse group of membrane proteins required for fertilization contain Ig-like domains. *Chlamydomonas* FUS1 [33, 34] and *Arabidopsis* GEX2 [35, 36] are single-pass TM proteins containing Ig-like filamin repeat domains, and they participate in gamete attachment and fusion, respectively. In mice, disruption of the *Bsg* (Basigin) gene, which encodes a single-pass TM protein with dual Ig-like domains, results in sterility of both males and females and in arrest of spermatogenesis [37]. Pre-treatment of sperm with antibodies to the BSG protein blocks sperm interactions with the cumulus cells and the zona pellucida [38]. These data all indicate that proteins with Ig-like domains play important roles during fertilization.

**What Function Does SPE-45 Play during *C. elegans* Fertilization?**

Besides the Ig-like domain, SPE-45 exhibits several structural features with unknown roles. Firstly, an N-terminal region of ~150 amino acids might be involved in association with an oocyte partner(s). The Izumo domain [7], which is also an N-terminal region of mouse IZUMO1, has been recently demonstrated to function in gamete fusion through the binding to JUNO, an oocyte IZUMO1 receptor [4, 9]. Secondly, SPE-45 has a α-helical hydrophobic region between the Ig-like and TM domains (Figure 1C). This region is possibly an interface to form a multimer, as is the case for mouse IZUMO1 [7]. Thirdly, the extracellular region contains two, while the intracellular region has one, basic amino acid cluster(s) (Figure 1C). The positively charged regions in SPE-45 might associate with negatively charged substances such as sulfated proteoglycans and phospholipids. An acidic sequence in the SPE-45 intracellular domain possibly folds and binds to the cytoplasmic, basic region within a single SPE-45 protein molecule. At any rate, these structural features are probably prerequisites to regulate the function(s) and localization of SPE-45.

In summary, we identified *C. elegans spe-45*, which shows male germline-enriched gene expression and encodes an Ig-like TM protein that is essential for fertilization, like mouse *Izumol*. Moreover, our domain-swapping experiments suggested that the Ig-like domains of SPE-45 and IZUMO1 might share a common function(s) during fertilization.

**EXPERIMENTAL PROCEDURES**

The Experimental Procedures are described in the Supplemental Information.
SUPPLEMENTAL INFORMATION

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGMENTS

We thank Andrew Singson (Rutgers University) for sharing unpublished data and for critical reading of our manuscript. We are also grateful to Takeshi Iihihara (Kyushu University), Andrew Fire (Stanford University) and Masaru Obake (Osaka University) for their kind gifts of pMW118, pPD118.20 and mouse Izumo1 cDNA, respectively. Shozo Yokoyama (Emory University) and Naoyuki Iwabe (Kyoto University) provided helpful comments about spe-45 evolution. Our gratitude is extended to Shohei Mitani as a representative of the National BioResource Project for providing spe-42(tm2421) and spe-45(tm3715) worms. Some strains were provided by the Caenorhabditis Genetics Center, which is funded by the NIH Office of Research Infrastructure Programs (P40 OD010440). This work was supported by MEXT KAKENHI Grant Number 24112716 (to H.N.) and JSPS KAKENHI Grant Number 24570241 (to H.N.), Japan. We were also supported by grants from the NSF (to S.W.L., IOB-0544180) and the NIH (to S.W.L., GM082932 and HD066577) and by funds from Emory College, USA. All experiments using worms were carried out under approval by the Institutional Animals Care and Use Committees of Setsunan University and Emory University.

REFERENCES


Figure 1. The C. elegans F28D1.8 Gene Is a Mouse Izumo1-like Gene (Related to Figure S1 and Table S1)

(A) RT-PCR analysis of candidate C. elegans genes encoding Ig-like TM proteins. Sex-specific expression of the C. elegans genes F28D1.8 and Y32G9A.8, in addition to spe-42 (specific to the male germline) and rpa-1 (common to the male and female germlines), were examined. M, male germline (using fem-3(q23gf) worms); F, female germline (using fem-1(hc17ts) worms).

(B) The genomic structure of F28D1.8. F28D1.8 is a ~2.4-kbp gene consisting of eight exons (E1-E8). A red, thick bar shows the area deleted in the tm3715 allele. Arrows indicate the annealing sites for the HN64 (forward) and HN63 (reverse) primers that were used for PCR analyses of the tm3715 deletion. For this study, we used the DNA sequence that was revised by Dr. A. Krauchunas and Dr. A. Singson (for details, see accompanying paper in this issue of Current Biology).

(C) The predicted protein structure of F28D1.8. The SOSUI program predicts a hydrophobic region (HP) outside of the transmembrane domain (TM) (http://harrier.nagahama-i-bio.ac.jp/sosui/). The deduced amino acid sequence also contains positively (+) and negatively (−) charged regions, and numbers of the “+” and “−” symbols represent relative numbers of basic and acidic residues, respectively. AA, amino acid; Ig, immunoglobulin-like domain.
Figure 2. Phenotypic Analysis of F28D1.8 (spe-45) Mutant Worms (Related to Figure S2)

(A and B) The deletion allele tm3715 of F28D1.8 (spe-45) causes hermaphroditic self-sterility. N2 (n = 26) and spe-45(tm3715) (n = 24-30) worms were grown at 16, 20 and 25°C, and the numbers of self-progeny (A) and unfertilized oocytes (B) produced by those hermaphrodites were determined. Data for N2 wild-type (light blue bars) and spe-45(tm3715) (red bars) hermaphrodites are shown as mean ± SEM.

(C) The self-sterility of spe-45(tm3715) worms is due to a male germline defect. After tm3715 (n = 15, red bar), spe-9(eb19); him-5(e1490) (n = 13, green bar) and fem-1(hc17ts) (n = 10, light blue bar) hermaphrodites were mated with him-5(e1490) males, numbers of outcross progeny were determined and shown as mean ± SEM.

(D) spe-45 male spermatozoa can outcompete hermaphrodite-derived spermatozoa for oocytes. dpy-5(e61) worms (n = 10) were sired by mock (self-progeny only; a no mating negative control), him-5(e1490) or tm3715; him-5(e1490) males, and numbers of self-progeny (Dpy, light blue bars) and outcross-progeny (Non-Dpy, green bar) were counted (mean ± SEM).

(E-J) Spermatids of spe-45 males can be activated into spermatozoa in vitro. Spermatids were released from him-5(e1490) (n = 10, E-G) or spe-45(tm3715); him-5(e1490) (n = 10, H-J) males in the absence or presence of Pronase, an in vitro spermatid activator [24].
Round, sessile spermatids (E, F, H and I) could be transformed into amoeboid, motile spermatozoa by Pronase treatment (G and J). We counted more than 100 cells after Pronase-induced activation and found that 84.0 ± 1.6 and 85.6 ± 2.2% (mean ± SEM) of total cells were activated spermatozoa in him-5 (n = 11) and spe-45; him-5 (n = 11) males, respectively. Arrows point at the pseudopods of spermatozoa. Scale bars represent 100 μm for (E) and (H), and 10 μm for (F), (G), (I) and (J).

(K-M and K’-M’) spe-45 male-derived spermatids activate into spermatozoa in vivo. Mock (no male mating; K and K’), him-5(e1490) (L and L’) or spe-45(tm3715); him-5(e1490) (M and M’) males were mated to feminized fem-1(hc17ts) worms, which contain functionally normal oocytes but no self-sperm. After staining with DAPI to visualize sperm nuclei (K’-M’), the mated females were observed under a fluorescent microscope to examine the presence of male spermatozoa in the spermatheca. Orange broken lines outline the spermatheca. DIC, differential interference contrast microscopy. A scale bar indicates 50 μm for (K) to (M) and (K’) to (M’).
Figure 3. Self-fertilization Is Not Observed in spe-45 Mutant Worms (Related to Figure S2 and Table S2)

At 24 and 72 h after the L4 stage, N2 (A, A’, E and E’), spe-9(eb19); him-5(e1490) (B, B’, F and F’), spe-42(tm2421) (C, C’, G and G’) and spe-45(tm3751) (D, D’, H and H’) hermaphrodites were fixed, treated with DAPI to stain self-sperm nuclei, and then observed to check if self-sperm numbers are reduced due to participation in fertilization. Orange broken lines highlight the position of the spermatheca. DIC, differential interference contrast microscopy. A scale bar of 50 μm shown in panel (A) applies to all of the images in this figure. See also Table S2 that summarizes the number of self-sperm in each spermatheca of tested worm strains.
Figure 4. Ig-like Domains Can Be Interchangeable between SPE-45 and IZUMO1 (Related to Figure S3 and Table S3)

(A) Transgenes used for the rescue assay in this study. We constructed three transgenes encoding SPE-45 protein in which the Ig-like domain was the one naturally found in SPE-45 (IgWT) or it was replaced by those of mouse IZUMO1 (IgIZUMO1) or Caenorhabditis IGCM-3 (IgIGCM3).

(B) The self-sterility of spe-45 mutant worms is rescued by the IgIZUMO1 transgene. Non-transgenic spe-45(tm3715) hermaphrodites (tm3715) produced no F1 progeny (n = 15). Normalizing for spe-45 worms expressing the IgWT transgene (tm3715 + IgWT) as having a relative brood size of self-progeny at 100.0 ± 15.0% levels (mean ± SEM, n = 12), the relative brood sizes of the same hermaphrodites expressing the IgIZUMO1 transgene (tm3715 + IgIZUMO1) and the IgIGCM3 transgene (tm3715 + IgIGCM3) were 76.8 ± 9.7% (n = 14) and 0% (n = 15), respectively.

(C) Alignment of Ig-like domains. The amino acid sequences of the Ig-like loop regions in Caenorhabditis SPE-45 orthologs, human (NCBI: NP_001018013.1) and mouse (NCBI: NP_001018013.1) IZUMO1s and Caenorhabditis IGCM-3 (WormBase: WBGene00020160) were aligned. Red and green letters indicates those residues that are, respectively, identical or chemically similar to those of Caenorhabditis SPE-45. Blue letters indicate residues that are conserved in all of those proteins.