Arabidopsis HAP2 (GCS1) is a sperm-specific gene required for pollen tube guidance and fertilization

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In flowering plants, sperm cells develop in the pollen cytoplasm and are transported through floral tissues to an ovule by a pollen tube, a highly polarized cellular extension. After targeting an ovule, the pollen tube bursts, releasing two sperm that fertilize an egg and a central cell. Here, we identified the gene encoding Arabidopsis HAP2, demonstrating that it is allelic to GCS1. HAP2 is expressed only in the haploid sperm and is required for efficient pollen tube guidance to ovules. We identified an insertion (hap2-1) that disrupts the C-terminal portion of the protein and tags mutant pollen grains with the β-glucuronidase reporter. By monitoring reporter expression, we showed that hap2-1 does not diminish pollen tube length in vitro or in the pistil, but it reduces ovule targeting by twofold. In addition, we show that the hap2 sperm that are delivered to ovules fail to initiate fertilization. HAP2 is predicted to encode a protein with an N-terminal secretion signal, a single transmembrane domain and a C-terminal histidine-rich domain. These results point to a dual role for HAP2, functioning in both pollen tube guidance and in fertilization. Moreover, our findings suggest that sperm, long considered to be passive cargo, are involved in directing the pollen tube to its target.

KEY WORDS: Arabidopsis, Pollen tube guidance, Double fertilization, Sperm, Gamete interactions

INTRODUCTION

Reproduction in flowering plants is mediated by pollen tubes – polarized cellular extensions of pollen grains that germinate at the stigma surface, invade the pistil and migrate to an ovule where they deliver two immotile sperm to the female gametophyte (FG). A pollen grain (male gametophyte, MG) comprises three genetically identical haploid cells derived from one meiotic product: a vegetative cell (pollen tube cell) and two sperm that reside in the cytoplasm of the vegetative cell (McCormick, 2004).

The pollen tube interacts with many female sporophytic cells on its journey to the FG (Johnson and Preuss, 2002). The stigma surface binds pollen from a select set of species and subsequently perceives pollen signals that trigger the controlled hydration of the pollen grain, enabling tube germination (Swanson et al., 2004). Guidance cues provided by the female sporophytic tissues determine the initial polarity of pollen tube extension (Kandasamy et al., 1994; Kim et al., 2003; Lord, 2003; Park and Lord, 2003; Wolters-Arts et al., 1998), directing its growth through the extracellular matrix of the style and transmitting tract (Lord, 2003; Wu et al., 2000). After a pollen tube exits the transmitting tract, it emerges onto the septum and grows towards an ovule, navigating up the funiculus and into the micropyle, which provides access to a FG. The FG is a seven-celled haploid structure comprising an egg and two synergid cells at the micropylar pole, a large central cell, and three antipodal cells (Yadegari and Drews, 2004). Pollen tube growth is arrested within a synergid and the pollen tube tip bursts, releasing two sperm (Russell, 1992). This process, called pollen tube reception, is accompanied by the degeneration of the receptive synergid and is rapidly followed by the fusion of one sperm with the egg and one sperm with the central cell to produce the zygote and endosperm, respectively (reviewed in Faure and Dumas, 2001; Weterings and Russell, 2004).

Pollen tube guidance in the ovary is controlled by factors expressed by diploid floral cells and by haploid FG cells (Christensen et al., 2002; Hülskamp et al., 1995; Pagnussat et al., 2005; Palanivelu et al., 2003; Ray et al., 1997; Shimizu and Okada, 2000). Genetic experiments in Arabidopsis show that pollen tubes bypass incompletely formed ovules or those that lack a FG (Hülskamp et al., 1995; Ray et al., 1997). When ovules carry maa1 or maa3, mutations that delay FG development (Shimizu and Okada, 2000), pollen tubes grow up the ovule funiculus but fail to enter the microple, suggesting that the FG produces distinct signals for funicular and micropley guidance. Laser-ablation studies combined with an elegant in vitro pollen tube guidance assay using Torenia fournieri, showed that the synergids produce a short-range micropylar attractant (Higashiyama et al., 2001). A candidate FG-derived pollen tube attractant has recently been identified; Zea mays egg apparatus1 (ZmEA1) is expressed exclusively in egg and synergid cells, and encodes a 94 amino acid hydrophobic protein that is required for efficient microply guidance in a maize in vitro guidance system (Marton et al., 2005).

FG signals may act in concert with sporophytic pollen tube attractants produced by ovule integuments or by the funiculus. γ-amino butyric acid (GABA) may be one such signal; Arabidopsis pop2 mutants disrupt the GABA gradient near the microple, resulting in random pollen tube growth (Palanivelu et al., 2003). Additional signaling events take place after the pollen tube enters the microple. When pollen tubes enter ovules bearing feronia or sirene mutant FGs, the synergid degenerates, but the pollen tube does not stop growing and does not burst, suggesting that the FG produces a signal that controls pollen tube reception (Huck et al., 2003; Rotman et al., 2003). These results represent tremendous progress in understanding the female signals that guide the pollen tube to the ovule; however, there is little information on how the pollen tube perceives these signals and transmits them into changes in the direction of its growth.
To identify pollen-expressed genes that are important for pollen tube growth and guidance, we isolated a series of MG mutants by screening for distorted inheritance (Johnson et al., 2004). Mutants were induced by random genomic insertions of a T-DNA carrying an herbicide-resistance gene (Basta resistance, Basta®, as well as a cell-autonomous histochemical marker (β-glucoronidase, GUS) under the control of the post-meiotic pollen-specific promoter LAT52 (Twell et al., 1989). LAT52 is active during pollen tube growth, marking mutant pollen tubes from their initial interactions with stigmatic papillae cells to their arrival at an FG. Mendelian inheritance predicts that plants with one copy of the T-DNA insertion will produce 75% Basta® offspring when self-fertilized. By contrast, self-fertilization of hap2/HAP2 plants yielded ~50% Basta® progeny and no hap2/hap2 homozygotes were obtained (Johnson et al., 2004). This transmission defect was male-specific; reciprocal crosses of hap2/HAP2 with wild type generated Basta® progeny at 0.7% or 47.0% when hap2/HAP2 was used as the male or female, respectively (Johnson et al., 2004). Initial phenotypic characterization of hap2 pollen tube growth suggested that hap2 pollen tubes do not follow the wild-type path, growing chaotically within the ovary. We identified the hap2 T-DNA insertion site within a hypothetical gene of unknown function (At4g11720) (Johnson et al., 2004).

Recently, a generative cell-specific protein (GCS1) from lily was characterized, and a T-DNA insertion into its Arabidopsis homolog, At4g11720 (HAP2), indicated a role in fertilization. GCS1 is localized to sperm cells, and we confirm here that a HAP2-fusion protein is sperm-expressed. Importantly, with the LAT52-GUS insertion into HAP2, we were able to look at phenotypes prior to gamete fusion, showing that HAP2 is also required for pollen tube guidance. hap2 pollen tube length is not affected. However, hap2 pollen tubes are half as likely to be wild type to target ovules; after leaving the septum, hap2 tubes meander over ovule surfaces where wild-type pollen tubes do not typically grow. In the cases where hap2 pollen tubes reach ovules, hap2 completely blocks fertilization. This study thus provides genetic evidence for the active participation of sperm cells in their delivery to female gametes.

**MATERIALS AND METHODS**

**Plant growth and HAP2 cloning**

hap2-1, hap2-2 (Salk_152706) (Alonso et al., 2003) and control lines in the Col-0 background were grown at 21°C in 24-hour 100 μM fluorescent lighting or in ambient greenhouse conditions. Kanamycin resistance (Kan®; hap2-2) was determined on MS salts with 25 μg/ml kanamycin, and Basta® (hap2-1) was determined as by Johnson et al. (Johnson et al., 2004). Plant growth and transformation was performed as described (Clough and Bent, 1998), hap2-1/HAP2 homozygotes were obtained (Johnson et al., 2004). For in vitro analyses, pollen from stage-14 flowers (Smyth et al., 1990) was germinated for 3 hours in an inverted drop of medium (Hicks et al., 2004). Pollen tubes or grains were transferred to polylysine-coated slides and stained with DAPI (Park et al., 1998), Aniline Blue (0.01% in 50 mM KPO₄, 50% glycerol), FM 4-64 (3.4 μM in germination medium) or X-Gluc (for GUS activity) (Johnson et al., 2004). All images were captured on a Zeiss Axioskop (Carl Zeiss, Germany); pollen tube lengths were measured using ImageJ (http://rsb.info.nih.gov/ij/). Fertilization and embryo development was analyzed as previously described (Yadegari et al., 1994); indicated samples were first stained for GUS activity (Johnson et al., 2004).

**HAP2 expression**

Northern blotting was performed on 20 μg of total pollen RNA probed with HAP2 cDNA. RT-PCR was performed on 1 μg total pollen RNA using the HAP2 primers F, 5'-TTAATGGCTTGTACTCTCGG-3' and R, 5'-ACGACAGGCAATGGCGCTATTTGCC-3'. Amplified products were digested with SacI and HindIII, or SacI and NcoI, respectively, and introduced upstream of eYFP (Clonetech) followed by the CaMV polyadenylation sequence, and incorporated into the binary vector, pGREENII0229 (Hellens et al., 2000).

**Transgenic plants**

Transgenic plants were analyzed using a Zeiss Axiosplan 200 equipped with a Photometrics cooled CCD camera (CoolSNAP fxHQ, Roper Scientific, Tucson, AZ), or a confocal fluorescence microscope (SP2 A OBS, Leica Microsystems AG, Wetzlar, Germany) and analyzed with Openlab software (Improvision, Lexington, MA). For analysis of YFP fluorescence during pollen development, uninucleate, bicellular and tricellular pollen grains were released from anthers and stained with DAPI (Park et al., 1998). They were then analyzed using a Leica DMIRE2 Confocal microscope with a 63× water objective using Leica software. DAPI was excited with a 405 nm laser and detected at 410-581 nm, whereas the YFP was excited with a 514 nm laser and detected at 517-597 nm. Pollen tubes were grown for up to 6 hours in liquid medium on an inverted microscope slide (Hicks et al., 2004).

**RESULTS**

hap2 pollen tubes are defective in ovule targeting

We used the LAT52-GUS pollen-specific reporter gene, which highlights the cytoplasm of every hap2-1 pollen tube, to refine our analysis of the hap2 pollen tube growth and pollen tube-guidance phenotype. To determine whether hap2 pollen tubes have inherent growth defects, we germinated hap2-1/HAP2 pollen in vitro and stained them for GUS activity to differentiate between mutant and wild-type pollen (Fig. 1A). hap2 pollen tube germination was not...
GUS activity was observed in the synergid cells of approximately half of the ovules, as expected (116/234, 50%; Fig. 1B,C). By contrast, when hap2-1/HAP2 anthers were used, a smaller proportion of GUS+ pollen tubes entered a micropyle and burst (115/505, 23%; Fig. 1B,D). Furthermore, hap2-1 pollen tubes were observed growing on portions of the ovule where wild-type pollen tubes do not grow (Fig. 1E) and also stalled on the funiculus (Fig. 1F). These data indicate that hap2 pollen tubes have a diminished capacity to enter the micropyle and burst within synergids (~50% reduction from wild type) because of defects in funicular and/or micropylar guidance.

The hap2 ovule-targeting defect was not suppressed when competition from wild-type pollen tubes was decreased. We pollinated wild-type pistils with single hap2-1/HAP2 tetrads and, after 14 hours, fixed and stained the pistils with Aniline Blue to follow the route of hap2-1 and HAP2 pollen tubes. With a control tetrad donor, 100% of the pollen tubes that germinated were able to target and enter an ovule (n=35). By contrast, 69/89 (78%) of the pollen tubes from single hap2-1/HAP2 tetrads targeted an ovule, a significant difference from wild type (P<0.05, χ²). These experiments indicate that only half of hap2 pollen tubes reached their target – the same result as that obtained with excess pollinations. Thus, the observed hap2 pollen tube-guidance defect is not caused by an inability to compete with wild-type pollen tubes for access to ovules, but rather reflects an inherent pollen tube-guidance defect.

hap2 completely blocks fertilization

When hap2-1 or hap2-2 pollen were used to pollinate wild-type pistils, no mutant progeny were recovered (hap2-1, 363 F1 tested; hap2-2, 348 F1 tested), indicating that hap2 completely blocks transmission of the mutant allele through the male. Because hap2 disrupts pollen tube guidance, we addressed whether competition for available ovules from HAP2 pollen tubes masks rare hap2 fertilization events by performing limiting pollinations of wild-type pistils. We obtained 87 F1 seeds from ten crosses; none inherited the hap2-1 allele. This absolute block in transmission through pollen cannot be explained by an approximately 50% reduction in the ability of hap2 pollen tubes to target ovules. Therefore, hap2 must also disrupt a step in reproduction that occurs after the contents of the pollen tube are released into the synergid cell of the FG.

We examined the development of seeds in self-fertilized hap2/HAP2 flowers and found that, hap2-1/HAP2 plants averaged 37±7 seeds (742 seeds in total, 20 siliques), whereas HAP2/HAP2 plants average 56±8 seeds (564 seeds in total, ten siliques). hap2-1/HAP2 siliques had gaps (Fig. 2A,B) where ovules failed to develop into seeds, suggesting that the FGs in ovules targeted by hap2 pollen tubes do not get fertilized.

To test this hypothesis, we pollinated wild-type pistils with hap2-1/HAP2 pollen, allowed 48 hours for fertilization, early embryo and endosperm development, and then stained them for GUS activity to identify ovules that had been targeted by hap2-1 pollen tubes. Ovules targeted by HAP2 pollen tubes (no GUS activity) contained early globular embryos and obvious proliferation of endosperm nuclei (122/132 ovules analyzed were fertilized; Fig. 2D). By contrast, ovules targeted by hap2-1 pollen tubes (GUS activity in the synergid cell indicating that the pollen tube cytoplasm and sperm had been deposited) showed no indication of embryo or endosperm development (0/26 ovules analyzed were fertilized; Fig. 2F). Instead, we consistently observed only the unfertilized central cell nucleus in FGs targeted by hap2-1 pollen tubes. We analyzed 112 unstained ovules in wild-type pistils pollinated with hap2-1/HAP2 pollen and found that 18% contained only one central cell nucleus (Fig. 2G),
and that the remaining 82% contained an embryo and several endosperm nuclei (Fig. 2E); these values are consistent with the rate of hap2-1 ovule targeting and, when combined with the data from GUS-stained ovules, suggest that when hap2 sperm are released into the FG, they fail to fertilize the egg and central cell.

One of the two synergid cells degenerates either just before or at the same time as the pollen tube enters the micropyle (Faure et al., 2002). In ovules targeted by hap2 pollen tubes, the central cell nucleus is the only FG nucleus that remains 48 hours after pollination. We hypothesized that, in the absence of fertilization, the egg nucleus degenerates and that the second synergid degenerates shortly after the pollen tube bursts. Analysis of embryo and endosperm development at an earlier time point (24 hours after pollination) showed that both the egg and central cell remain in ovules targeted by hap2 pollen tubes (Fig. 2H), whereas an embryo and endosperm nuclei are clearly present in ovules targeted by HAP2 pollen tubes (Fig. 2I). These results confirm that hap2 sperm are incapable of fertilizing the egg or central cell and suggest that, in the absence of fertilization, the egg cell degenerates following pollen tube reception. Similarly, Mori et al. found that gcs1 sperm fail to fertilize and that they persist in the degenerating synergid 16 hours after pollination, whereas wild-type sperm do not (Mori et al., 2006).

Presumably, wild-type sperm were not observed because they are rapidly transported to the egg and central cell where they bind these target cells and undergo plasmogamy.

**hap2 sperm develop normally and migrate to the pollen tube tip**

To determine whether the hap2 fertilization defect is due to a defect in sperm development or in migration of sperm within the pollen tube, we analyzed hap2 pollen grains and tubes throughout their development. DAPI-staining revealed morphologically normal sperm and vegetative nuclei (n>500, Fig. 3A-D). Staining hap2/HAP2 pollen tubes either with Aniline Blue, which binds callose (β-1-3-glucan) in the pollen tube walls, or FM 4-64, which becomes incorporated into the membrane architecture of growing tubes, showed that hap2 pollen tubes were indistinguishable from wild type (data not shown). In newly germinated tubes, the vegetative nucleus consistently exited the pollen grain before the two sperm (hap2/HAP2, n=24; control, n=19), and, as tubes elongated, the sperm and vegetative nuclei were always in the subapical region of the tube (hap2/HAP2, n=138; control, n=117). Within 1 hour after pollination, hap2 vegetative nuclei emerged from the pollen grain ahead of the two sperm (n=11); this normal male germ-unit
Previously, we used TAIL PCR to map the histidine-rich C-terminus encoding a predicted membrane protein with pollen tube structure or sperm transport within the pollen tube. pollen tube guidance and fertilization are not the result of aberrant transmitting tract (organization was maintained as the tubes migrated through the.

**HAP2 encodes a predicted membrane protein with a histidine-rich C-terminus**

Previously, we used TAIL PCR to map the hap2-1 T-DNA insertion to the twelfth of 14 exons in the single-copy uncharacterized gene At4g11720 (Fig. 4A) (Johnson et al., 2004). No cDNAs or ESTs corresponding to this gene were present in public databases, so we used 5' and 3' RACE to generate a full-length cDNA and to annotate At4g11720, determining that the gene comprises 17 exons instead of the 14 predicted by the initial annotation of the Arabidopsis genome (GenBank DQ022676 and DQ022375; Fig. 4A). With PCR, we confirmed both hap2-1 T-DNA-genome junctions, as well as a 10 bp genomic deletion at the insertion site (exon 15). A second allele, hap2-2, with a T-DNA insertion in exon 9 (Fig. 4A) was identified from the SIGNAL collection (Alonso et al., 2003); this allele also caused distorted T-DNA segregation (46.2% KanR progeny from self-fertilization, n=600) and completely blocked transmission through pollen (0 KanR progeny when crossed with wild type, n=348). The location of the gcs1 allele is also indicated (Fig. 4A) (Mori et al., 2006).

To confirm that At4g11720 is indeed HAP2, we complemented the hap2 defect by transforming plants heterozygous for hap2-1 with a T-DNA carrying NPTII (confering KanR) and a wild-type HAP2 transgene (HAP2tr, a genomic fragment from 983 bp upstream to 277 bp downstream of the open reading frame; Fig. 4A). The progeny of primary hap2/HAP2 transformants were collected and BastaR and KanR were analyzed in ten transgenic families with a single-locus insertion of HAP2tr. The average rate of BastaR among these families was 68.6% (n=2362) and of KanR was 83.1% (n=2525). Complementation of both ovule-targeting and fertilization defects is expected to yield T2 progeny that segregate 67% (8/12) BastaR and 83% (10/12) KanR, failure would lead to approximately 50% BastaR, as observed in the progeny of self-fertilizing hap2-1/HAP2 plants. These results indicate that wild-type At4g11720 rescues the hap2-1 pollen tube-guidance and fertilization defects.

**Fig. 4. HAP2 and its predicted protein structure.** (A) HAP2 has 17 exons (black rectangles, untranslated regions are gray). hap2-1, hap2-2 and gcs1 (Mori et al., 2006) are T-DNA insertions in exons 15, 9 and 16, respectively. Black lines under the gene schematic indicate regions used for molecular complementation (HAP2tr), analysis of expression pattern (HAP2promoter:YFP) and subcellular localization (HAP2protein:YFP). (B) HAP2 encodes a 705 amino acid protein with a predicted 19 amino acid N-terminal signal sequence (S), a 23 amino acid transmembrane domain (T) and a C-terminus containing a 96 amino acid histidine-rich domain (His). (C) An alignment of the HAP2 His-rich region from Arabidopsis (A. thaliana), poplar (P. trichocarpa), lily (L. longiflorum) (Mori et al., 2006) and rice (O. sativa). The alignment includes the region of the HAP2 C-terminal to the transmembrane domain. HIS residues within the HIS-rich region are shaded gray. Conserved residues are indicated with a star. (D) Pairwise analysis of amino acid identity between Arabidopsis HAP2 and HAP2 sequences from other organisms; only HAP2 sequences from angiosperms have a C-terminal HIS-rich region.
Self-fertilization of hap2/HAP2;HAP2tr plants yielded hap2/hap2 homozygous progeny (all four members of tetrad are GUS+), the progeny of which were 100% BastaR; homozygous progeny were never observed when hap2/HAP2 is self-fertilized.

The HAP2 open reading frame is predicted to encode a 705 amino acid protein with a N-terminal signal sequence (amino acid 1-24), a single transmembrane domain (amino acid 560-582) and a C-terminal histidine-rich domain (Fig. 4B). HAP2 is not similar to any proteins with known functions and has no obvious functional motifs, although several genes in flowering plants and in more distantly related organisms have been described (Mori et al., 2006). Pair-wise comparison of amino acid identity between the Arabidopsis HAP2 and HAP2 from other flowering plants showed that the N-terminal region is conserved (mean identity 64%), whereas the C-terminal region is more divergent (mean identity 35%). An alignment of the C-terminal histidine-rich regions showed that the presence of histidine is conserved among these proteins, but that amino acid sequence is not (Fig. 4C). Interestingly, these histidine-rich domains are present in HAP2 from angiosperms, but not from other organisms (Fig. 4D).

HAP2 is only expressed in sperm

RT-PCR and northern blot analysis showed that HAP2 mRNA is only detected in tissue samples that contain mature pollen (Fig. 5A,B). This specific expression pattern is confirmed by hundreds of publicly available microarray experiments showing that HAP2 mRNA only accumulates in pollen (https://www.genevestigator.ethz.ch/). To determine the precise location of HAP2 expression, we fused a DNA fragment corresponding to 983 bp upstream of the HAP2 start codon (Fig. 4A) to the yellow fluorescent protein (YFP) coding sequence (HAP2promoter:YFP fusion protein) and generated transgenic plants expressing this construct. Accumulation of YFP was only observed in the two sperm cells contained within the cytoplasm of mature pollen grains (Fig. 5C,D); YFP was not observed in uninucleate microspores or in bicellular pollen (Fig. 5D), nor was it observed in other floral or vegetative cells (data not shown).

Protein localization algorithms predict that HAP2 is localized to the plasma membrane and/or the endoplasmic reticulum (ER). To determine where HAP2 is localized within sperm, we fused YFP to the penultimate codon of HAP2 exon 17 (Fig. 4A, HAP2protein:YFP fusion protein) and generated transgenic plants expressing this construct. Three independent transgenic lines were crossed with hap2-1/HAP2 plants and homozygous hap2-1 lines were obtained in the F2 generation of each cross, indicating that HAP2protein:YFP complemented hap2 pollen tube-guidance and fertilization defects, and suggesting that HAP2protein:YFP forms a functional and properly localized protein. We detected the fusion protein only in the sperm cells (Fig. 6A-D). Unlike the transcriptional fusion, which produced YFP distributed throughout the elongated, spindle-shaped sperm cytoplasm (Fig. 5C), the protein fusion was excluded from the nucleus and was predominantly perinuclear, forming a ring of fluorescence around sperm nuclei (Fig. 6B). However, fluorescence was not limited to the perinuclear region and in many sperm cells, fluorescence extended to the sperm plasma membrane (Fig. S1 in the supplementary material). These results, in combination with protein-localization predictions, suggest that HAP2 is predominantly localized to sperm ER membranes and that HAP2 may also reside in other endomembranes, including the plasma membrane.

DISCUSSION

HAP2 is necessary for targeting of the ovule microyle by the pollen tube

In addition to the previously reported role of HAP2 in fertilization (Mori et al., 2006), we have shown that hap2-1 pollen tubes grow the entire length of the pistil, yet grow aberrantly on ovule surfaces.
and often fail to enter the micropyle, resulting in a twofold reduction in ovule targeting. In vitro, hap2-1 pollen tubes grow slightly longer and, in the pistil, hap2-1 pollen tubes grow slightly faster than wild-type pollen tubes. This mild enhancement of pollen tube extension could reflect the lack of a tube-growth behavior that is required for optimum guidance. Interestingly, the ability of hap2 pollen tubes to target ovules does not improve when pistils are underpollinated, indicating that the hap2 pollen-tube-guidance defect is not a consequence of an inability of hap2 pollen tubes to compete with HAP2 pollen tubes for a limited number of ovules. Thus, hap2 specifically disrupts pollen tube guidance without diminishing pollen tube growth, making this mutant a unique resource for understanding how pollen tubes perceive and respond to guidance cues.

hap2-1 pollen tubes were tagged with the LAT52:GUS reporter gene, allowing quantitative analysis of ovule targeting success (Fig. 1B); this feature was crucial for detecting the gcs1 pollen-tube-guidance defect. By contrast, previous studies of the gcs1 allele of HAP2 did not detect a pollen tube-guidance defect (Mori et al., 2006). gcs1 pollen tubes are not tagged and analysis of pollen tube guidance by staining mutant and wild-type tubes with Aniline Blue, particularly when many pollen tubes are present, is not sufficiently sensitive to detect hap2 guidance differences. Nonetheless, consistent with our observations, pollinations of wild-type pistils with gcs1/GCS1 pollen always yielded a greater number of fully formed (targeted by GCS1 pollen) than aborted seeds (targeted by gcs1 pollen). These data suggest that the gcs1 allele may also disrupt pollen tube guidance.

### HAP2 is a sperm-specific protein

HAP2 mRNA only accumulates in mature pollen (Fig. 5A,B), HAP2 promoter activity is only detected in mature sperm (Fig. 5C,D), and HAP2 protein is only detected in the sperm during pollen development and tube growth (Fig. 6). In lily, expression of the HAP2 ortholog GCS1 is first apparent in the generative cell and persists after the generative cell divides during pollen tube growth to produce two sperm (Mori et al., 2006). This earlier onset of HAP2 expression probably reflects a difference in pollen development between these species. In Arabidopsis (which has tricellular pollen grains), the generative cell divides to produce two sperm before anthesis, whereas, in lily and other species with bicellular pollen grains, the generative cell does not divide until after the pollen tube has germinated. These expression studies, combined with the hap2 mutant phenotype and the finding that HAP2 is conserved among a diverse set of angiosperms (Fig. 4D) (Mori et al., 2006), support the hypothesis that HAP2 is a sperm-specific gene that is universally essential for double fertilization.

HAP2 is predicted to encode a 705 amino acid protein that shares no similarity with proteins of known function. However, it has three features that offer clues to its biochemical function; HAP2 has an N-terminal cleavable signal sequence, a single transmembrane domain and a C-terminal histidine-rich domain (Fig. 4B). Multiple algorithms predict that HAP2 is an integral ER or plasma-membrane protein and that the C-terminus is cytoplasmic (type 1a membrane protein). Lily GCS1 (HAP2 ortholog) was shown to be associated with membranes by cellular fractionation studies (Mori et al., 2006). The HAP2protein:YFP fusion protein we generated complements hap2-1, suggesting that it encodes a fully functional protein and that its localization pattern is that of the endogenous protein. HAP2protein:YFP is predominantly localized in a perinuclear ring (Fig. 6B) (consistent with ER localization), with extensions of HAP2protein:YFP to the plasma membrane (Fig. S1 in the supplementary material). These results are consistent with those recently obtained by immunofluorescence in both lily and Arabidopsis (Mori et al., 2006), and suggest that HAP2 is associated with membranes of the perinuclear ER and, perhaps, with secretory

#### Fig. 6. HAP2 protein is sperm-localized during pollen development and tube growth.

(A) A pollen tetrad and (B) sperm nuclei from a plant heterozygous for the HAP2protein:YFP fusion; DAPI fluorescence (left), YFP fluorescence (center), merged image (right). (C) DAPI (left) and YFP (right) fluorescence in pollen tetrads from homozygous HAP2protein:YFP transgenic plants at three stages of pollen development; see Fig. 5D for comparison with qrt. (D) DAPI (center) and YFP (right) fluorescence in growing pollen tubes from qrt, HAP2protein:YFP and LAT52:GFP transgenic plants. DIC images of growing pollen tubes (left). Signal from YFP is observed only in the sperm (HAP2protein:YFP) or throughout the entire pollen tube cytoplasm (LAT52:GFP). Scale bars: 20 μm A and C; 1 μm in B; 5 μm in C.
Potential roles for sperm-expressed HAP2 in pollen tube guidance

We have shown that HAP2 is required for pollen tube guidance and that it is sperm-specific. These results point to a previously unrecognized role for sperm in directing the growth of the pollen tube. The ability of a sperm protein to alter the efficiency of pollen tube guidance may suggest a checkpoint or sperm quality-control mechanism, such that pollen tubes carrying defective sperm could not efficiently target ovules.

HAP2 may be directly involved in transducing a pollen tube-guidance cue (Johnson and Lord, 2006). The sperm are associated with the pollen tube cytoskeleton and migrate near the tip of the pollen tube as it grows to the ovule (McCormick, 2004); they are well positioned to mediate events within the pollen tube cytoplasm that result in changes in the direction of tube extension. Interestingly, because sperm develop within the pollen tube cytoplasm, the majority of the predicted N-terminal portion of plasma membrane-localized HAP2 would reside in the pollen tube cytoplasm and could interact directly with pollen tube cytoplasmic factors involved in directing tube extension.

Multiple, overlapping chemotropism factors may guide the pollen tube to ensure optimal efficiency of ovule targeting and fertilization (Johnson and Lord, 2006). Therefore, mutations that diminish perception of a single pollen tube-guidance factor are not expected to completely block ovule targeting. This may explain why hap2-1 results in a reduction rather than a complete loss of ovule targeting. The finding that perturbations in the production of individual female guidance cues such as GABA (Palanivelu et al., 2003), ZmEA1 (Marton et al., 2005) and plantacyanin (Dong et al., 2005) do not completely block pollen tube guidance or seed production, supports this view. It will be interesting to test this hypothesis in the future by constructing plants with defects in production and/or perception of multiple pollen tube-guidance signals.

HAP2-mediated interactions between sperm and FG are required for fertilization

Approximately half of hap2-1 pollen tubes reach ovules, enter the micropyle and burst, releasing GUS activity and two sperm into the degenerating synergid (Fig. 1B). However, hap2 mutant progeny are never recovered when either hap2-1 or hap2-2 pollen is used to pollinate a wild-type pistil. This complete transmission block was also observed when the gcsl allele was characterized (Mori et al., 2006). These results indicate that HAP2 is essential for a step in fertilization that occurs after sperm have been delivered to the FG by a pollen tube. Initiation of embryo development and initiation of endosperm development are both completely blocked in ovules targeted by hap2-1 pollen tubes (Fig. 2F-H). Furthermore, gcsl sperm persist within the degenerating synergid, whereas wild-type sperm immediately migrate to their egg and central cell target membranes and fuse (Mori et al., 2006). Taken together, these results indicate that HAP2 is probably required for either sperm migration within the FG, or for binding/fusion of sperm to egg and of sperm to the central cell. Further analysis of the hap2 fertilization defect using transmission electron microscopy or live imaging in a system in which hap2 sperm and target membranes are tagged with fluorescent proteins offers an opportunity to determine the precise role for HAP2 in fertilization.

Insights into the mechanisms of double fertilization

hap2/gcsl are the only Arabidopsis mutants described so far in which two sperm are released into the degenerating synergid but fertilization does not occur. This affords a unique opportunity to clarify some of the basic mechanisms of double fertilization. Because hap2-1 blocks initiation of both embryo and endosperm development, there must be a single system in Arabidopsis that mediates interactions between sperm and egg and between sperm and central cell. Sperm are dimorphic in some flowering plants, with one sperm type preferentially fertilizing the egg and the other preferentially fertilizing the central cell (Roman, 1948; Russell, 1985). It will be interesting to determine whether these plants have an additional system to direct sperm of one type to a specific target or whether HAP2 functions to mediate specific gamete interactions in these systems.

In wild-type Arabidopsis, only one pollen tube is attracted to each ovule; attraction of multiple pollen tubes to a single FG would presumably decrease female fitness and could lead to polyspermy (Shimizu and Okada, 2000). Evidence for a repulsive cue that directs supernumerary pollen tubes away from an ovule that has already been targeted was recently obtained in vitro (Palanivelu and Preuss, 2006). Interestingly, the FG mutants sirena and sirene attract supernumerary pollen tubes; in these mutants, pollen tubes enter the microyle but fail to stop growing and burst (Huck et al., 2003; Rotman et al., 2003). This shows that pollen tube entry into the microyle is not sufficient to trigger production of a repellant. We do not observe supernumerary pollen tubes on ovules targeted by hap2-1 pollen tubes. Furthermore, we analyzed 26 ovules targeted by hap2-1 pollen tubes by staining for GUS activity in synergid cells (Fig. 4F) and did not find any that initiated seed development, indicating that supernumerary wild-type pollen tubes do not fertilize an ovule already targeted by a hap2-1 pollen tube. Taken together, these results indicate that the pollen tube repellent is produced after the pollen tube bursts but before fertilization, and suggest that production of a pollen tube repellent may be initiated by FG perception of a factor present either on the sperm surface or in the pollen tube cytoplasm.

A new view of sperm cells: no longer passive cargo

The data presented here challenge the assumption that sperm cells are passive cargo delivered to the FG by the pollen tube. We show that a sperm-specific gene, HAP2, is required for optimal ovule targeting by the pollen tube, suggesting that sperm function may impact the growth of the pollen tube. Recently, it has become clear that despite their compact chromatin structure, sperm are dynamic cells that express many genes (Engel et al., 2003; Engel et al., 2005; Xu et al., 1999); HAP2 is the first such gene with a demonstrated function in reproduction (Mori et al., 2006). It is likely that more sperm-expressed genes will be identified that play roles in pollen tube guidance and in fertilization.

Plasma membrane-localized HAP2 could directly mediate gamete-gamete interactions through its extracellular domain. There is substantial precedence in animal reproduction for similar sperm-egg interactions; for example, a sperm-expressed type 1a membrane protein is essential for sperm-egg fusion in mice (Inoue et al., 2005; Rubinstein et al., 2006). Alternatively, ER-localized HAP2 may indirectly mediate fertilization by regulating the processing or secretion of plasma-membrane proteins or by regulating calcium levels in sperm.
presents an opportunity to identify FG-expressed interacting factors that, together with HAP2, mediate double fertilization, a process that is crucial for agriculture, but about which we know very little at the molecular level.

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Supplementary material
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