RESEARCH ARTICLE

The cytoplasmic domain of the gamete membrane fusion protein HAP2 targets the protein to the fusion site in Chlamydomonas and regulates the fusion reaction

Yanjie Liu1, Jimin Pei2, Nick Grishin2 and William J. Snell1,*

ABSTRACT

Cell-cell fusion between gametes is a defining step during development of eukaryotes, yet we know little about the cellular and molecular mechanisms of the gamete membrane fusion reaction. HAP2 is the sole gamete-specific protein in any system that is broadly conserved and shown by gene disruption to be essential for gamete fusion. The wide evolutionary distribution of HAP2 (also known as GCS1) indicates it was present in the last eukaryotic common ancestor and, therefore, dissecting its molecular properties should provide new insights into fundamental features of fertilization. HAP2 acts at a step after membrane adhesion, presumably directly in the merger of the lipid bilayers. Here, we use the unicellular alga Chlamydomonas to characterize contributions of key regions of HAP2 to protein location and function. We report that mutation of three strongly conserved residues in the ectodomain has no effect on targeting or fusion, although short deletions that include those residues block surface expression and fusion. Furthermore, HAP2 lacking a 237-residue segment of the cytoplasmic region is expressed at the cell surface, but fails to localize at the apical membrane patch specialized for fusion and fails to rescue fusion. Finally, we provide evidence that the ancient HAP2 contained a juxta-membrane, multicysteine motif in its cytoplasmic region, and that mutation of a cysteine dyad in this motif preserves protein localization, but substantially impairs HAP2 fusion activity. Thus, the ectodomain of HAP2 is essential for its surface expression, and the cytoplasmic region targets HAP2 to the site of fusion and regulates the fusion reaction.

KEY WORDS: HAP2, GCS1, Gamete membrane fusion reaction, Cell-cell fusion, Chlamydomonas

INTRODUCTION

Although gamete fusion during fertilization is a fundamental event in eukaryotes and has been long studied in many model organisms, we know little about the molecules and cellular and molecular mechanisms that underlie the membrane fusion reaction (Evans, 2012; Inoue et al., 2013). The protein Izumo is the only sperm-specific gene shown by gene disruption to be essential for gamete fusion in a vertebrate (Inoue et al., 2005, 2013; Ellerman et al., 2009; Evans, 2012). And recent work has shown that Izumo and its newly discovered receptor Juno on the oocyte are likely required for membrane adhesion, but not for the subsequent merger of the lipid bilayers (Bianchi et al., 2014). Several C. elegans genes are known to be essential for fertilization, but whether they function directly in the membrane fusion reaction is unknown because of the difficulty of experimentally defining distinct steps in gamete interactions (Singson et al., 2008). To date, the sole, broadly conserved protein shown by gene disruption to be essential for the gamete membrane fusion reaction in any system, including all model organisms, is the membrane protein HAP2 (also called GCS1), which is present in plants and protists, and in some multicellular animals (but notably absent in vertebrates) (Mori et al., 2006; von Besser et al., 2006; Liu et al., 2008, 2010; Hirai et al., 2008; Goodman and McFadden, 2008; Cole et al., 2014; Steele and Dana, 2009; Ebchuin et al., 2014; Kawai-Toyooka et al., 2014).

Early reports on HAP2 in Arabidopsis concluded that it was required for gamete attachment (Mori et al., 2006), but by exploiting the ease of experimentally identifying and quantifying the location and properties of HAP2 at individual steps in gamete fusion in the green alga Chlamydomonas and the malaria pathogen Plasmodium (Sinden, 1983), we showed that HAP2 is required late in the membrane fusion reaction, after species-specific membrane adhesion (Liu et al., 2008; Wong and Johnson, 2010). Chlamydomonas hap2 minus gamete mutants undergo tight membrane adhesion with wild-type plus gametes at the sites specialized for gamete fusion, but fusion is abrogated (Fig. 1). In addition to defining the step in gamete fusion that requires HAP2, these studies were the first to establish in any system that membrane adhesion and membrane merger per se during the gamete membrane fusion reaction are carried out by distinct membrane proteins. The adhesion receptor on the Chlamydomonas minus mating structure is still unknown, but plus gametes use the species-limited FUS1 protein for membrane adhesion (van Dijk et al., 2001). Thus, adhesion depends on species-limited proteins, whereas merger uses broadly conserved HAP2. This new concept in fertilization has since been confirmed in Arabidopsis and Tetrahymena (Sprunk et al., 2012; Cole et al., 2014; Mori et al., 2014; Dresselhaus and Snell, 2014).

The genetically demonstrated conservation of a role for HAP2 at the membrane merger step of fertilization in Chlamydomonas, Plasmodium, Tetrahymena and Arabidopsis suggests that the last eukaryotic common ancestor of protists and higher plants likely used HAP2 for gamete fusion. Furthermore, the properties and broad conservation of HAP2 in choanoflagellates and other protists, and in sponges, cnidarians and some bilaterian animals (including Drosophila) further indicates that understanding the molecular properties of HAP2 could offer new insights into fundamental mechanisms of gamete fusion.
Work in Arabidopsis and Plasmodium has begun such a molecular dissection (Wong et al., 2010; Mori et al., 2010). A truncated form of Plasmodium berghei HAP2 composed of just the ectodomain and the transmembrane domain (TMD) rescues ookinete (zygote) formation in the P. berghei hap2 mutant (Mori et al., 2010). By contrast, truncated HAP2 containing the ectodomain plus TMD in Arabidopsis failed to support seed formation (used as an indicator of gamete fusion), indicating that the cytoplasmic region was required at some step either in the delivery of HAP2 to the site of fusion or during fusion per se (Wong et al., 2010). Conflicting results have been reported about the parts of the cytoplasmic domain of the Arabidopsis protein that are required for seed formation. One group has shown that histidine-rich regions of the cytoplasmic domain are important, and another group reported that a form of HAP2 containing the ectodomain, the TMD, and a 34-residue cytoplasmic segment adjacent to the TMD followed by GFP was sufficient to rescue seed formation (Wong et al., 2010; Mori et al., 2010).

The difficulty of experimentally accessing gametes and of determining the cellular location of the protein continues to be a major challenge with dissecting the properties of HAP2 domains in many model organisms. Indeed, only recently was it discovered that Arabidopsis HAP2 is absent from the surface of sperm before it encounters the egg and present solely in intracellular vesicles. The protein is redistributed to the sperm surface only after signals generated by sperm-egg interactions trigger exocytosis of HAP2-containing storage vesicles (Mori et al., 2006, 2010; Liu et al., 2008; Sprunck et al., 2012; Snell, 2013). Thus, the previously described mutated/truncated forms of Arabidopsis HAP2 might have failed to rescue fusion in the hap2 mutant, not because the mutated forms failed to support fusion per se, but because they failed to be trafficked to the appropriate storage vesicles, because they failed to be redistributed appropriately to the cell surface during sperm signaling or because they failed to localize to the site of fusion during interactions with the egg.

In Chlamydomonas, HAP2 is constitutively present on the cell surface at a specialized, apically localized membrane patch, the mating structure (Fig. 1), the surface area of which represents less than 0.1% of the surface area of the cell (Liu et al., 2008). The ease of determining HAP2 surface expression, localization and fusion competence in this organism overcomes the limitations of such studies in other systems, because it is straightforward to distinguish mutant forms that fail to localize properly from those that localize properly, but fail to support fusion. Here, we have tested the function of HAP2 domains in protein localization and gamete fusion in Chlamydomonas. We find HAP2 without its ectodomain fails even to be expressed at the cell surface and that a segment in the cytoplasmic domain is required to target surface-expressed HAP2 to the fusogenic site. Furthermore, we determined that the presence of multiple cysteines just below the TMD is an ancient feature of the protein, and that disruption of a cysteine dyad in the Chlamydomonas multi-cysteine motif has no effect on protein localization, but strongly impairs HAP2 fusion capacity. Thus, the HAP2 ectodomain in Chlamydomonas is not an autonomous functional unit in the membrane fusion reaction. Rather, the fusion function of HAP2 is regulated by its cytoplasmic domain, which also contains motifs that target the protein to the site of fusion.

RESULTS

The predicted extracellular region (∼600 residues) of HAP2 family members contains 18 widely conserved cysteine, which are present in two regions, C-rich 1 near the N terminus and C-rich 2 near the transmembrane domain (TMD), separated by a less well-conserved region whose length varies across organisms (Liu et al., 2008; Fig. 2A). Several other amino acid residues also are broadly conserved. Thus, the entire extracellular region of HAP2 represents a conserved cysteine rich domain, which includes a previously described, 50-residue conserved region termed the HAP2/GCS1 (H/G) domain (Pfam10699). Compared with the ectodomain, the predicted cytoplasmic region shows lower overall conservation. We uncovered one major exception, however, which is the presence of a multi-cysteine motif near the TMD in HAP2 homologs in members of the major evolutionary groups across kingdoms, including the Excavata, Rhodophyta, Chlorophyta, Viridiplantae, Alveolata, Ameobozoa and Opisthokonta (Fig. 2B). Thus, the ancient HAP2 possessed motifs in both the ectodomain and the cytoplasmic domain that remain in present-day organisms.

The HAP2 ectodomain, including the conserved H/G domain, influences expression at the cell surface

We examined the role of the ectodomain in HAP2 function and properties by expressing in hap2 cells a transgene, HAP2-Δ76-627, whose expression was driven by the endogenous promoter and encoded a truncated protein containing only the signal peptide and the adjacent 55 residue segment, followed by the TMD and the cytoplasmic domain (with a 3× HA tag inserted after residue 702) (Δecto; Fig. 3A). As we showed previously, the wild-type, HA-tagged form of HAP2, which rescues fusion in the hap2 mutant, is expressed as two forms, and only the upper form is expressed on the cell surface, as evidenced by its trypsin sensitivity in live gametes (Liu et al., 2008; Fig. 3B). HAP2-Δ76-627 gametes expressed only low
levels of HAP2-Δ76-627 (which appeared as a single band), as shown by immunoblotting (Fig. 3B), and they failed to fuse when mixed with wild-type plus gametes. We were unable to detect the protein on the mating structures, whereas a strong signal was seen at the mating structures in cells expressing the wild-type, full-length HAP2-HA (Fig. 3E). The HAP2-Δ76-627 on live cells was resistant to trypsin treatment (Fig. 3B), indicating that the ectodomain is required for HAP2 trafficking to the cell surface.

To examine the function of the conserved H/G domain, we generated HAP2 forms with mutations/deletions in several parts of the domain (Fig. 3C). A chimeric HAP2 (PbCr) made by replacing the Chlamydomonas H/G domain with the corresponding Plasmodium berghei domain failed to be expressed at the cell surface or at the mating structure and, thus, failed to rescue fusion (Fig. 3C-E). Similarly, a form of HAP2 in which the conserved DKVG in the H/G domain was deleted (ΔDKVG) was not expressed at the cell surface or mating structure, and hence also failed to rescue fusion (Fig. 3C-E).
fusion (Fig. 3C-E). Furthermore, HAP2-Δecto proteins (see Materials and methods for a description of methods used to determine the percentage of fusion). (B) Left panels, immunoblots of wild-type and HAP2-Δecto gametes. Right panels, immunoblot assessing trypsin sensitivity of wild-type and HAP2-Δecto gametes. Unlike the upper form of wild-type HAP2, HAP2-Δecto is insensitive to trypsin. The lower panels are loading controls showing tubulin. (C) Modifications of the H/G domain of Chlamydomonas HAP2 (Cr-H/G domain) and corresponding fusion abilities. The modified residues in the H/G domain (352-400) are highlighted with larger font or underlined. Blue, predicted β-sheet; red, predicted α-helix. (D) Left panels, immunoblots of gametes with HAP2 modified in the H/G domain. Right panels, immunoblot assessing trypsin sensitivity. Tubulin is shown as a loading control. (E) Anti-HA immunofluorescence images of the indicated gametes. Arrowheads indicate mating structures stained with wild-type HAP2-HA or HAP2-C366A gametes.

**The ectodomain and TMD are sufficient for trafficking HAP2 to the cell surface**

We tested for roles of the cytoplasmic domain and the TMD in HAP2 properties by use of cells expressing truncated proteins containing the HAP2 signal peptide and just the ectodomain (HAP2-ecto) or the ectodomain and the TMD (HAP2-ecto+TMD) (both followed by a C-terminal HA tag). As shown in Fig. 4A,B, in the cells expressing HAP2-ecto, a single form of HAP2 was detected. It failed to be expressed at the cell surface, as shown by lack of trypsin sensitivity, it was not localized at the mating structure, and it failed to rescue fusion (Fig. 4A-E). We anticipated that because of its missing TMD and cytoplasmic region, it might be secreted, but we were unable to detect HAP2-ecto in the culture medium, even after 3 h of gamete activation brought about by mixing with wild-type plus gametes (Liu et al., 2010; Fig. 4D).
In cells expressing HAP2-ecto+TMD, the protein was trypsin-sensitive on live cells, indicating that it was on the cell surface (Fig. 4C). On the other hand, HAP2-ecto+TMD failed to localize to the mating structure and failed to rescue gamete fusion (Fig. 4A-C,E). To test whether the absence of the protein at the mating structure was a consequence of the low expression of the upper form of HAP2-ecto+TMD, we incubated the gametes with di-butyryl cAMP (db-cAMP), a treatment that leads to upregulation of HAP2 transcription and translation (Liu et al., 2010; Ning et al., 2013). Such activated cells still lacked HAP2-ecto+TMD at the mating structure, and the activated HAP2-ecto+TMD cells were incapable of fusion with plus gametes (Fig. 4E,F). These results indicated that the HAP2 ectodomain and TMD were sufficient for trafficking the protein to the cell surface, but the cytoplasmic region was required for targeting the protein to the mating structure and rescuing fusion.

**Motifs in the cytoplasmic region target HAP2 to the fusogenic membrane patch**

To identify cytoplasmic regions that influenced HAP2 localization and function, we generated several additional mutant forms of the protein. The fusion ability of cells expressing HAP2 lacking the C-terminal 31 amino acids (HAP2-1108; Fig. 5) was indistinguishable from that of cells expressing wild-type HAP2 (1139 residues). Cells with HAP2 lacking the C-terminal 85 residues (HAP2-1054, Fig. 5A-C) expressed less of the upper form of the protein (and also possessed a much smaller fragment of uncertain derivation), but trafficked the upper form to the cell surface and supported low levels of fusion (Fig. 5C). Although we did not detect HAP2-1054 at the mating structure in resting gametes, it became detectable there when gametes were induced to express higher amounts of the protein by incubation in db-cAMP (Fig. 5D,E), and the db-cAMP-activated cells were capable of wild-type levels of fusion. Thus, the C-terminal 85 residues influenced localization, but were not essential for localization or fusion competency.

Analysis of hap2 gametes expressing a HAP2 that was C-terminally truncated to residue 760 (HAP2-760) showed that the protein was expressed at the cell surface (Fig. 5A-C). However, we did not detect the protein at the mating structures of resting or activated gametes, and activated gametes showed less than 2% fusion (Fig. 5A,D,E). Addition of the C-terminal 998-1139 fragment to HAP2-760 resulted in some surface expression of the upper form of HAP2-Δ761-997 (Fig. 5A-C), but no localization to the mating structure was detected in resting or activated cells (Fig. 5D-E) and activated HAP2-Δ761-997 gametes showed only very low levels of fusion (6%) (Fig. 5A).

Although HAP2-1054, HAP2-Δ761-997 and HAP2-760 were not detectable at the mating structures in resting gametes, we detected prominent intracellular staining (Fig. 5E). The smaller fragments of HAP2-1054 and HAP2-760 were not sensitive to trypsin, confirming that they were intracellular (Fig. 5C); optical sectioning also confirmed that the stain was internal in HAP2-760...
cells (see Movies 1–3 in the supplementary material). Taken together, these results indicated that the HAP2 segment comprising residues 761-997, which contains low complexity regions and is enriched in repetitive sequences, was essential for localization to the mating structure.

**A cysteine dyad near the TMD regulates the fusion capacity of HAP2**

As shown in Fig. 2B, the cytoplasmic regions of HAP2 homologs in members of all major evolutionary groups possess multiple cysteine residues near the TMD, suggesting that this multicysteine motif was a feature of the ancient HAP2. Because inspection of HAP2 alignments (Fig. 2B) indicated that the HAP2 proteins of many species contain a dicysteine motif in the cytoplasmic region near the TMDs, we tested for a possible role of the Chlamydomonas CC661-2 dyad in fusion. Cells expressing HAP2 with just the first of the cysteines mutated, HAP2-C661S, localized the protein to the mating structure, and were somewhat reduced in fusion capacity. Protein location and fusion capacity of cells expressing the protein with the second of the cysteines mutated, HAP2-C662S, were indistinguishable from wild type. Simultaneous mutation of both cysteines to serines (HAP2-CC661-2SS), however, strongly impaired fusion, even in gametes activated by db-cAMP (Fig. 6A). When minus gametes expressing wild-type HAP2 are mixed with wild-type plus gametes, fusion occurs rapidly, and pairs of gametes adhering by their mating structures are rarely detected in fixed samples examined by light microscopy. In the mixtures of HAP2-CC661-2SS minus gametes with wild-type plus gametes, however, many pairs were observed, indicating that membrane adhesion at the mating structures was unaffected in the mutant, but that fusion was blocked (Fig. 6E). Notably, except for being impaired in fusion ability, the properties of the HAP2-CC661-2SS mutant form of the protein were indistinguishable from those of wild type HAP2. HAP2-CC661-2SS was on the cell surface as assessed by trypsin sensitivity, and it was detected at the mating structure at levels

---

**Fig. 5. The cytoplasmic domain contributes to both HAP2 targeting to the mating structure and to its function in fusion.** (A) Diagrams and fusion abilities of HAP2 cytoplasmic domain mutants. Results in parentheses show fusion of gametes that had been activated with db-cAMP before mixing with wild-type plus gametes. (B) All of the mutant HAP2 proteins were expressed as two forms. Tubulin is shown as a loading control in the lower panels. (C) Immunoblots showing effects of trypsin treatment on the upper form of HAP2 in the mutants. The basis for the only partial trypsin sensitivity of the upper band in the HAP2-Δ761-997 gametes is unknown, as is the origin of the third band in that sample. (D) The amounts of HAP2-1054, HAP2-Δ761-997 and HAP2-760 protein (arrowhead) increased when gametes were activated with db-cAMP. (E) Immunolocalization of HAP2 in the cytoplasmic region of mutants. Arrowheads indicate mating structure localization. Arrows show internal staining.
equivalent to that of wild-type gametes (Fig. 6A-D). Similar localization and functional results were obtained with three independent HAP2-CC661-2SS transformants. Previously, we have shown that hap2 mutant gametes adhering by their mating structures failed to exhibit membrane lipid exchange with their plus partners (Liu et al., 2008). In fluorescent lipid experiments with HAP2-CC661-2SS gametes, we also found no evidence for lipid mixing (e.g. hemifusion) between the adherent gametes (Fig. 6E). Thus, the dicysteine motif of Chlamydomonas HAP2 regulates the capacity of the protein to accomplish membrane fusion.

**DISCUSSION**

Although the membrane protein HAP2 is essential for gamete membrane fusion in disparate evolutionary groups, the molecular features of the protein that regulate its location and function are poorly understood. The present study demonstrates that the ectodomains of the three cysteine mutants. Results in parentheses show fusion of C661-2SS gametes activated with db-cAMP before mixing with wild-type plus gametes. (B) Quantification of fusion at the indicated times after mixing with wild-type plus gametes. (C) Immunoblots of the HAP2 cysteine mutants. The upper form of HAP2-CC661-2SS is trypsin sensitive (right panels). (D) Immunofluorescence shows that all three HAP2 cysteine mutant proteins localize at the mating structure (arrowheads). The lower panels are high-magnifications views documenting that HAP2-CC661-2SS is localized at the mating structure, which is at the apical end of the cell between the two flagella. This cell is resting on its side. (E) Membrane merger fails between HAP2-CC661-2SS minus gametes and wild-type plus gametes. Wild-type plus cells were labeled with PKH26 and then mixed with wild-type minus gametes (upper panels) or HAP2-CC661-2SS minus cells (lower panels). Whereas the PKH26 dye transferred rapidly after mixing wild-type minus and wild-type minus gametes, no dye transfer was detected when PKH26-labeled plus gametes were mixed with HAP2-CC661-2SS minus gametes (arrowheads), even though they formed pairs of cells that were tightly adherent at their mating structures. QFC, quadriflagellated cell.

The finding that HAP2-ecto+TMD was expressed on the cell surface demonstrated that the cytoplasmic region of the protein was dispensable for trafficking through the secretory pathway and is consistent with the earlier findings that the ectodomain of *Plasmodium* HAP2 is sufficient for fusion (Mori et al., 2010). These results also indicated that the as yet uncharacterized post-translational modification that underlies the appearance of two forms of HAP2 must occur on the ectodomain or TMD. On the other hand, the result that HAP2 containing the first 55 residues of the ectodomain along with the TMD and cytoplasmic region failed to reach the cell surface makes it likely that the ectodomain actively participates in trafficking. Possibly, HAP2 forms homomeric or heteromeric complexes via features of its ectodomain, including glycosylation sites, that are important for targeting to the cell surface (Isaji et al., 2006; Gupta et al., 2008). Similarly, mutations in the H/G domain impaired (C366A) or prevented (PbCr, ΔDKVG and L391G/Q394P) HAP2 expression at the cell surface, possibly because the mutations altered the structure of the protein and prevented normal trafficking. These findings indicate that assessing functional properties of regions of HAP2 is complex, and being able to conclude that a domain is essential in the membrane fusion.
reaction per se requires demonstrating that the mutant form of the protein is expressed at the cell surface.

It is more difficult to provide an explanation for the results that mutations of any of three conserved residues (two of them charged) within the H/G domain (D367, K368, G372) had no influence on HAP2 fusion capacity. Possibly, our bioassays do not assess the full range of the fusion capacity of the protein, or perhaps these residues make subtle contributions to structural features of the protein that are preserved when only a single conserved residue is altered.

Our combined results, that HAP2 containing only the ectodomain+TMD was expressed at the surface, but was not targeted to the fusogenic membrane patch and that adding the contiguous 111-residue cytoplasmic segment (as found in HAP2-760) also failed to rescue targeting to the mating structure or fusion, indicated that targeting was influenced by even more C-terminal regions of HAP2. The additional finding that HAP2-1054 rescued localization and fusion capacity in activated gametes indicated that residues between 760 and 1054 were crucial for trafficking to the mating structure. A test of that model in the experiments with HAP2-Δ761-997 confirmed that the 761-997 segment played a crucial role in localization. The ability of both HAP2-760 and HAP2-Δ761-997 to rescue any fusion (albeit at very low levels) after gamete activation (compared with the hap2 mutant, which is completely incapable of fusion), suggests that as long as the HAP2 proteins are at the cell surface, the low amounts (~0.1% of the total) that would likely be present at the mating structure could function in fusion. By contrast, the failure to detect any fusion in cells expressing HAP2-ecto+TMD, which was present on the cell surface, emphasizes the importance of cytoplasmic motifs in the fusion reaction.

Finally, our discovery that mutation of the pair of cysteines in the ancient, multi-cysteine motif near the TMD had no effect on HAP2 localization to the mating structure, but strongly crippled fusion further indicated that the cytoplasmic region of Chlamydomonas HAP2 participates in regulating the fusion reaction. In future experiments, it will be interesting to determine whether the multi-cysteine motif in HAP2 proteins of other organisms also are important for fusion. The mechanism through which the dicysteine motif exerts its control is unknown, but one possibility is that it becomes palmitoylated, which thereby allows it to interact with the lipid bilayer. Several integral membrane proteins become palmitoylated on membrane-proximal cysteine residues, including integrins, tetraspanins and viral fusion proteins (Yang et al., 2004; Delandre et al., 2009; Veit, 2012; Shmulevitz et al., 2003) (see supplementary material Table S1). On the other hand, the motif might be unrelated to palmitoylation, and serve a HAP2-specific function that was lost during evolution in some species. Experiments to determine whether Chlamydomonas HAP2 is palmitoylated on CC661-2 should help in our understanding of the function of the dicysteine motif.

In light of our results and knowing that Arabidopsis HAP2 trafficking is temporally and spatially complex, it will be interesting to determine whether the previously described HAP2 mutants that failed to support seed formation in Arabidopsis indeed are capable of being targeted to the cell surface, or if they failed to function because their trafficking was disrupted. If the histidine-rich motif of the cytoplasmic domain of Arabidopsis HAP2 functions directly during fusion as proposed (Wong et al., 2010; Wong and Johnson, 2010), possibly, the multi-cysteine motifs originally fulfilled this function, but were replaced by the histidine-rich motif during evolution of higher plants.
Immunoblotting and fluorescent microscopy
Gametes (1×10^7 cells) suspended in 25 μl HMDEK buffer containing a protease inhibitor cocktail were mixed with an equal volume of 2× SDS-PAGE sample buffer and analyzed by SDS-PAGE and immunoblotting. Anti-hA monoclonal antibody (Roche Applied Science) and monocolonal anti-acetylated tubulin antibody (Sigma) were used as primary antibodies for immunoblots. Differential interference contrast (DIC) microscopy and immunofluorescent staining of HAP2-HA transgenic cells were as previously described (Belzile et al., 2013). All images were obtained with a 63× objective lens. Membrane lipid mixing was detected in experiments using lipid dye PKH26 (Sigma). Wild-type plus gametes were incubated with PKH26 (Liu et al., 2008) and then mixed with the indicated minus gametes. Samples were observed under fluorescence and DIC microscopy. Images were prepared using Image J (NIH) and Adobe Photoshop (Adobe Systems). Methods for generating supplementary image stacks are described in the supplementary material.

Acknowledgements
We thank Dr Timothy Springer (Harvard Medical School) for alerting us to the presence of the membrane-adjacent cysteine dyad of HAP2. We thank Drs Kate Luby-Phelps and Abhijit Budge (University of Texas Southwestern Medical Center Live Cell imaging Core) for guidance with microscopy.

Competing interests
The authors declare no competing or financial interests.

Author contributions
Y.L. designed the experiments in collaboration with W.J.S.J.P. and N.G. provided guidance in evolutionary analysis of HAP2 and constructed the HAP2 dendrogram. Y.L. performed the experiments, and Y.L. and W.J.S.J.P. analyzed the results and prepared the manuscript.

Funding
Aspects of this work were performed in laboratories constructed with support from the National Institutes of Health [C06 RR 30414]. This work was supported by the Welch Foundation [I-1505 to N.G.] and the National Institutes of Health (GM-094575 to N.G. and GM-56778 to W.J.S.). Deposited in PMC for release after 12 months.

Supplementary material
Supplementary material available online at http://dev.biologists.org/lookup/suppl?doi=10.1242/dev.118844/-/DC1

References


Supplementary methods

Generation of 40D4 mutant

A minus fusion-defective mutant (40D4) was generated by insertional mutagenesis of *Chlamydomonas* strain B215 with plasmid pMN56 (Nelson et al., 1994) encoding the nitrate reductase gene. After screening ~ 4000 insertional mutants, clone 40D4 was identified with fusion defective phenotype. 40D4 underwent flagellar adhesion with wild type plus gametes and also formed pairs of gametes adhering at their apical ends, but failed to fuse, which is identical to the phenotype of the hap2 mutant 63B10 (Liu, 2008). As expected, 40D4 was rescued for fusion by transformation with the wild-type HAP2 gene (Fig. 3 in main text). Diagnostic PCR confirmed that the HAP2 gene was disrupted in 40D4 (Fig. S1). The following primers were used:
P2, 5'-CTGGCTGTGAGCAGCAGCGCGAA-3';
P3, 5'-CACGCCAGGTATCTCTGTCCGAGT-3';
P15, 5'-ACTGAGTCTCAGAGCTGGTGCAGTGC-3';
P22, 5'-CGTTGCAGCCACATGCGCTCCCACA-3';
P26, 5'-ATCCGCGGACGCCGCGGTGTCG-3';
P61, 5'-CCCAGCTGGTCGTCAAGCCCTCCGG-3'.

As shown in Figure S1, the HAP2 gene was disrupted near the 3’ end in the coding region in 40D4 as documented with primers (P61-P22). Control PCR analysis using the parent strain B215 is also shown. Sequencing confirmed the identity of the PCR products.

pHAP2-HAm plasmid

pHAP2-HAm plasmid sequence: lower case, cloning vector PUC19; upper case, HAP2 gene sequence; boxed, BgII or NruI site; green, HAP2 coding sequence; red, the first intron; purple, 3HA tag. Note that the HAP2 cDNA encoded by this plasmid contains a Q at residue 697 (rather than L697 in cDNA GI:288563867), which corresponds to the Q at that site encoded in HAP2 gene model Cre01.g066100.

As shown in Figure S1, the HAP2 gene was disrupted near the 3’ end in the coding region in 40D4 as documented with primers (P61-P22). Control PCR analysis using the parent strain B215 is also shown. Sequencing confirmed the identity of the PCR products.
Immunofluorescence image stacks for hap2, HAP2-HA and HAP2-760 gametes

hap2, HAP2-HA and HAP2-760 gametes were stained with anti-HA for immunofluorescence analysis. The serial Z-section image stacks were taken from the top to bottom of the cells using fluorescent microscopy and Micro-Manager-1.4 software. The stacks were saved using ImageJ software (NIH).
Table S1. Predicted palmitoylation sites in *Chlamydomonas* HAP2 from online server ([http://csspalm.biocuckoo.org/online.php](http://csspalm.biocuckoo.org/online.php)). Low threshold was used for the prediction (Veit, 2012).

<table>
<thead>
<tr>
<th>Site</th>
<th>Peptide</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>******MCRAIAYAL</td>
<td>42.224</td>
</tr>
<tr>
<td>71</td>
<td>ALEFSLSCLNSPDGR</td>
<td>10.84</td>
</tr>
<tr>
<td>136</td>
<td>LRPSNKVC KDGDWED</td>
<td>4.397</td>
</tr>
<tr>
<td>164</td>
<td>VADSQGFCCECSSSQ</td>
<td>4.397</td>
</tr>
<tr>
<td>661</td>
<td>LASLAASSCGGGGA</td>
<td>9.477</td>
</tr>
</tbody>
</table>
Fig. S1. Diagram and DNA gel image show diagnostic PCR results using B215 and 40D4 genomic DNA as template. The location of primers is shown in the diagram of the HAP2 gene. The PCR amplifications from primer sets P3-P2 and P26-P15 are positive in both B215 and 40D4. There is no PCR product when using primer P61-P22 in 40D4 indicating that the HAP2 gene is disrupted at the 3’ end.
Movies 1-3. Movie 1 (hap2-Z.avi), Movie 2 (HAP2HA-Z.avi) and Movie 3 (HAP2-760-Z.avi) are anti-HA immunofluorescence image stacks of *hap2, HAP2-HA* and *HAP2-760* gametes, respectively.
Supplementary Reference: