Autophagy-deficient *Schizosaccharomyces pombe* mutants undergo partial sporulation during nitrogen starvation

Hiroyuki Mukaiyama,1,2,3 Shiro Kajiwara,1 Akira Hosomi,1 Yuko Giga-Hama,2 Naotaka Tanaka,1 Taro Nakamura4 and Kaoru Takegawa1,3

Correspondence
Kaoru Takegawa
takegawa@agr.kyushu-u.ac.jp

1Department of Life Sciences, Faculty of Agriculture, Kagawa University, Miki-cho, Kagawa 761-0795, Japan

2Research Center, Asahi Glass Co., Ltd, Kanagawa, Yokohama 221-8755, Japan

3Department of Bioscience and Biotechnology, Faculty of Agriculture, Kyushu University, Hakozaki 6-10-1, Fukuoka 812-8581, Japan

4Department of Biology, Graduate School of Science, Osaka City University, Sumiyoshi-ku, Osaka 558-8585, Japan

Received 6 September 2009
Accepted 23 September 2009

INTRODUCTION

Autophagy is triggered when organisms sense radical environmental changes, including nutritional starvation. During autophagy, cytoplasmic components, including organelles, are enclosed within autophagosomes and are degraded upon lysosome–vacuole fusion. In this study, we show that processing of GFP-tagged Atg8 can serve as a marker for autophagy in the fission yeast *Schizosaccharomyces pombe*. Using this marker, 13 Atg homologues were also found to be required for autophagy in fission yeast. In budding yeast, autophagy-deficient mutants are known to be sterile, whereas in fission yeast we found that up to 30% of autophagy-defective cells with amino acid auxotrophy were able to recover sporulation when an excess of required amino acids was supplied. Furthermore, we found that approximately 15% of the autophagy-defective cells were also able to sporulate when a prototrophic strain was subjected to nitrogen starvation, which suggested that fission yeast may store sufficient intracellular nitrogen to allow partial sporulation under nitrogen-limiting conditions, although the majority of the nitrogen source is supplied by autophagy. Monitoring of the sporulation process revealed that the process was blocked non-specifically at various stages in the *atg1*Δ and *atg12*Δ mutants, possibly due to a shortage of amino acids. Taking advantage of this partial sporulation ability of fission yeast, we sought evidence for the existence of a recycling system for nitrogen sources during starvation.

Abbreviations: DAPI, 4′,6-diamidino-2-phenylindole; DIC, differential interference contrast; FSM, forespore membrane.

Two supplementary tables are available with the online version of this paper.
Autophagy and forespore membrane formation in Sch. pombe

mediates a ubiquitination-like modification. Interestingly, Atg8p forms a conjugate not with a protein, but with phosphatidylethanolamine (PE), an abundant membrane phospholipid (Ichimura et al., 2000). For normal autophagosome formation, Atg8-PE must be deconjugated by the processing enzyme, Atg4p. Therefore, the cycle of conjugation and deconjugation is critical for normal progression of autophagy (Ichimura et al., 2000). In budding yeast, Atg8p is upregulated during autophagy and the Atg8-lipidation reaction is required for the membrane dynamics that are central to the process of autophagy. Thus, Atg8p could be a good marker for monitoring the autophagic process. In addition to these two autophagy-specific ubiquitin-like conjugation systems, two kinase complexes have also been described. One is the Atg1 protein kinase, which associates with Atg13p, Atg17p and Cvt9p (Matsuura et al., 1997; Straub et al., 1997). Atg13p is negatively regulated by Tor kinases (Chan et al., 2001; Kirisako et al., 1999). Once a starvation signal inactivates Tor, dephosphorylation of Atg13p occurs, activating Atg1p by conjugation with Atg1p-Atg13p, Atg17p and Atg11p, resulting in upregulation of autophagy.

In Sch. cerevisiae, all atg mutants that have been reported grow normally in rich medium, but lose viability during nitrogen starvation. A diploid homozygous for an atg mutation was found not to sporulate (Tsukada & Ohsumi, 1993). These mutants start to die after 2 days of starvation and lose almost 80% viability after 5 days (Tsukada & Ohsumi, 1993). This loss of viability may be caused by deficient recycling of endogenous proteins.

In the fission yeast Schizosaccharomyces pombe, nitrogen starvation stimulates large-scale protein degradation involving the starvation-specific serine protease Isis6p following initiation of autophagy (Nakashima et al., 2006). Kohda et al. (2007) recently reported that null mutants with deletions in ATG1, ATG8 and ATG13, which are orthologues of ATG1, ATG8 and ATG13, respectively, in budding yeast, also failed to undergo autophagy. These atg mutants were also reported not to undergo sexual differentiation and to lose viability during nitrogen starvation. Interestingly, atg1, atg8 and atg13 mutants that also harboured auxotrophic mutations exhibited a more drastic loss of viability during nitrogen starvation (Kohda et al., 2007). These data suggest that autophagy is also a critical system to ensure survival in fission yeast. However, because other ATG homologues have not been characterized in fission yeast, we undertook the present study. Here we show that several fission yeast Atg proteins, whose roles in autophagy had until now only been predicted based on homology, are indeed essential for the process. Moreover, we found that approximately 15% of prototrophic autophagy-defective cells were able to sporulate, and an autophagy-defective strain with amino acid auxotrophy also recovered sporulation in about 30% of cells when an excess of required amino acids was supplied. This observation suggested that the majority of the nitrogen source for de novo protein synthesis needed for sporulation is dependent on the autophagic protein degradation system. However, fission yeast may store sufficient intracellular nitrogen to allow partial sporulation to occur under nitrogen-limiting conditions. In this study, we sought evidence for the existence of a recycling system for nitrogen sources by taking advantage of this partial sporulation ability of fission yeast.

METHODS

Database searches of ATG genes. Fission yeast ATG genes were identified by screening the Sch. pombe genome database for new homologues of known Sac. cerevisiae ATG genes using a BLAST search of protein sequences. BLAST scores lower than 10^−8 were considered significant. The fission yeast Atg proteins were classified based on the most similar Sac. cerevisiae Atg proteins.

Strains, media and materials. Sch. pombe strains used in this study are listed in Supplementary Table S1, available with the online version of this paper. Escherichia coli strain XL1-Blue (Stratagene) was used for all cloning procedures. Sch. pombe strains were grown in yeast extract medium with supplements [YES: 0.5% Bacto-yeast extract (Becton Dickinson), 3% glucose and SP supplements (Qiobio) or in minimal medium (MM), of which 1000 ml contains 3 g potassium hydrogen phthalate, 2.2 g Na2HPO4, 5 g NH4Cl, 20 g glucose, 1.05 g MgCl2.6H2O, 11 mg CaCl2, 1 g KCl, 40 mg Na2SO4, 1 mg pantothenic acid, 10 mg nicotinic acid, 10 mg inositol, 10 μg biotin, 0.5 mg boric acid, 0.4 mg MnSO4, 0.4 mg ZnSO4.7H2O, 0.2 mg FeCl3.6H2O, 0.04 mg H3MoO4.2H2O, 0.1 mg KI, 0.04 mg CuSO4.5H2O, 1 mg citric acid, and 75 mg each of adenine, histidine and lysine]. A total of 37.5 mg uracil or 75 mg leucine was added per 1000 ml to cover auxotrophs. Sporulation was performed in sporulation medium (MEA or MM–N) (Moreno et al., 1999). Sch. pombe cells were transformed by the lithium acetate method or by electroporation as described previously (Morita & Takegawa, 2004; Okazaki et al., 1990; Suga & Hatakeyama, 2001). Standard genetic methods were as described by Alfa et al. (1993). Restriction enzymes and other DNA-modifying enzymes were purchased from New England Biolabs. All other chemicals were from Sigma-Aldrich or Wako Pure Chemicals Co.

Construction of GFP-Atg8p. The Sch. pombe atg8 ORF was amplified from a cDNA library by PCR, using the oligonucleotides 5’-GGTTTCCATATGGCTTCATTCAATTCAAGGACGAC-3’ and 5’-GTTTTGGATCCCATAAAAAGGAAACACTGTTCC-3’. The PCR products were digested with NdeI and BamHI, and cloned into the corresponding sites of pTN54, derived from pREP1 (Nakamura et al., 2001), which is a thiamine-repressible expression vector.

Cloning and disruption of Sch. pombe ATG and AVT homologues. Genes encoding Atg proteins were cloned into pGEM-T EASY or pGEM-T vectors (Promega) (Nakamura et al., 2001) digested with the restriction enzymes listed in Supplementary Table S2, followed by insertion of a urad4+ gene cassette to generate gene disruption constructs. Disruption of each atg or avt gene was performed by direct chromosomal integration as described by Bahler et al. (1998). Gene disruptions were confirmed by colony-PCR, using appropriate primers (Supplementary Table S2).

Immunofluorescence and fluorescence microscopy. Cells were fixed with glutaraldehyde and paraformaldehyde according to Hagan & Hyams (1988). Microtubules were stained with anti-α-tubulin antibody TAT-1 (Wood et al., 1989) and Cy3-conjugated anti-mouse IgG (Sigma) at 1:1000 dilution. The nuclear chromatin region was stained with DAPI (4’,6-diamidino-2-phenylindole) at 1 μg ml⁻¹.
Stained cells were observed under a fluorescence microscope (model BX-60; Olympus) and images were obtained using a Cool SNAP CCD camera (Roper Scientific).

**Western blot analysis.** Cells expressing GFP-Atg8 were suspended in 1 x PBS with appropriate protease inhibitors and disrupted using a Multi-Beads Shocker (YASUI KIKAI) with 0.5 mm glass beads. Following centrifugation at 15000 g for 15 min, cell-free extract was dissolved in an equal volume of 2 x SDS-PAGE sample buffer and incubated at 80 °C for 5 min. A total of 20 μl of sample was applied to an SDS-PAGE gel containing 10 % polyacrylamide and electro-botted onto a PVDF membrane (Bio-Rad). Immunodetection analysis was performed on the blotted membrane with SNAP i.d. (Millipore) using mouse polyclonal anti-GFP antibody (Molecular Probes) and horseradish-peroxidase-conjugated anti-rabbit IgG serum (Millipore). GFP-specific signals were visualized by enhanced chemiluminescence (ECL-plus, GE Healthcare) and were detected using a LAS4000 imaging system (Fuji Film Co.).

**Vacuole staining.** Vacuolar membranes were stained with FM4-64 [N-(3-triethylammoniumpropyl)-4-[(4-(diethylamino)phenyl)hexatrienyl]pyridinium-dibromide] (Molecular ProbesA) as described by Morishita et al. (2002) with a minor modification. Cells were harvested, resuspended in 0.5 ml liquid YE medium containing 0.5 μl 8 μM FM4-64 in DMSO, and then incubated with shaking at room temperature for 30 min. Stained cells were chased with YE medium for 60 min, and then cultured on MM–N starvation medium for the appropriate temperature. Stained cells were observed with a fluorescence microscope (model BX-60; Olympus) equipped with a U-MGFPHQ filter set (Olympus) for GFP, and a U-MWIG filter set (Olympus) for FM4-64. Images were captured with a SenSys Cooled CCD camera using MetaMorph (Roper Scientific).

**RESULTS**

**Western blot analysis of GFP-Atg8 in fission yeast ATG homologue mutants**

More than 20 autophagy-related (ATG) genes that are essential for autophagy have been identified in the budding yeast Sac. cerevisiae (Klionsky et al., 2007; Suzuki et al., 2001). In fission yeast, 15 ATG orthologues of the budding yeast genes were identified in a BLAST search using Sch. pombe GeneDB (http://www.genedb.org/genedb/pombe/) (Supplementary Table S2). Database analysis showed that SPAC589.07c, SPAC823.16c and SPAC458.06 possess two WD repeat domains that are putative orthologues of ATG18, named atg18b+ and atg18b− and atg18c+, respectively. Orthologues of ATG10, 11, 14, 15, 16, 19, 23, 27, 29 and 31 were not found in the Sch. pombe GeneDB because of low levels of similarity. From among these orthologues, Kohda et al. (2007) previously reported that atg1+ and atg8+ and atg13+, homologous with budding yeast ATG1, ATG8 and ATG13, respectively, were essential for autophagy induced by nitrogen starvation in fission yeast. We then constructed null mutants of the atg orthologues (Supplementary Table S1). In order to analyse the autophagy-specific requirements of the encoded Atg proteins, we introduced GFP-Atg8 into each atg mutant strain. In Sac. cerevisiae, Atg8p is a ubiquitin-like protein that is conjugated to phosphatidylethanolamine at the C-terminal glycine and which is essential for organization of the autophagosome (Kirisako et al., 2000). Once GFP-Atg8p on the autophagosome is delivered to the vacuole by the normal autophagic process, the GFP moiety is proteolytically removed and free GFP, which is relatively stable, is observed by immunohemocyt assay (Cheong et al., 2005; Hosokawa et al., 2006; Klionsky et al., 2007; Shintani & Klionsky, 2004). Accordingly, the appearance of free GFP can be used to monitor autophagy in Sch. pombe. The processing of GFP-Atg8p was examined in atg mutants expressing GFP-Atg8p under the control of the attenuated thiamine-repressible nmt promoter. Vegetatively grown cells were transferred to the nitrogen-free medium MM–N to induce autophagy. Cells were harvested at appropriate times after starvation and GFP was detected by immunoblot analysis using anti-GFP antibody (Klionsky et al., 2007). In wild-type cells expressing GFP-Atg8p, only full-length GFP-Atg8p was detected under nutrient-replete conditions, but free GFP increased during the course of starvation (Fig. 1a), indicating that processing of GFP-Atg8p was promoted during induction of autophagy. This phenomenon was also observed in atg8A cells expressing GFP-Atg8p, indicating that this fusion plasmid is functional.

**Autophagy deficiency in atg mutants in fission yeast**

In budding yeast, as cells are induced to undergo autophagy in the presence of the serine proteinase inhibitor PMSF, autophagy can be followed by monitoring accumulation of autophagic bodies inside the vacuoles. Under such conditions, the autophagic process is blocked prematurely and does not terminate normally (Kohda et al., 2007; Takeshige et al., 1992). Similarly, in fission yeast, addition of PMSF during nitrogen starvation resulted in exclusive accumulation of full-length GFP-Atg8p (Fig. 2, lane 5). An isp6Δ mutant, disrupted in a gene encoding a putative vacuolar serine protease, was previously reported to grow normally under nutrient-replete conditions, but was defective in large-scale protein degradation during nitrogen starvation (Nakashima et al., 2006). The addition of PMSF could inactivate Isp6p, resulting in arrest of the autophagic process. The above results suggest that processing of GFP-Atg8p is also dependent on nitrogen-induced autophagy in fission yeast. Among the other 13 atg null mutants, except for atg18b and atg18c, only full-length GFP-Atg8p was observed before and after nitrogen starvation (Fig. 1b). atg8A cells transformed with GFP-Atg8p accumulated both full-length GFP-Atg8p and the isolated GFP moiety under starvation conditions, indicating that GFP-Atg8p complements the autophagic deficiency of the atg8A mutant (Fig. 1b). Interestingly, atg18bΔ and atg18cΔ showed a diluted GFP signal. In contrast, atg18Δ or the atg18bΔatg18cΔ double mutant showed only a full-length GFP-Atg8p signal during nitrogen starvation (Fig. 1b). These phenomena suggest that a combination of either Atg18a-Atg18b or Atg18a-Atg18c was necessary for
autophagy, although all three Atg18 orthologues are essential for complete autophagic degradation. In contrast, the \( \text{atg22}^D \) mutant accumulated both the full-length fusion protein and the isolated GFP moiety, consistent with the results of \( \text{atg22}^D \) in budding yeast (Fig. 1a) (Yang et al., 2006). In budding yeast, Atg22p was reported to be a vacuolar membrane amino acid transporter, which could mediate amino acid efflux during autophagy. Therefore, it is unlikely that \( \text{atg22}^D \) is involved in the GFP-Atg8p processing reaction caused by autophagic degradation in the vacuole.

**Fig. 1.** Cleavage of GFP-Atg8p for monitoring autophagy. (a) Time-course processing of GFP-Atg8p. Cells were grown in MM containing required amino acids and were then shifted to MM–N medium. At the indicated times, aliquots were removed, and proteins were prepared as described in Methods. Full-length GFP-Atg8p and the GFP moiety were detected by immunoblotting using anti-GFP antibodies. The position of the GFP moiety alone indicates processed GFP-Atg8p. (b) Cleavage of GFP-Atg8p in \( \text{atg} \) mutant cells. The multicopy plasmid encoding GFP-Atg8p was introduced into various \( \text{atg} \) mutants. Cells were collected after 6 h of starvation, lysates were prepared and immunoblotting was performed as described above. The \( \text{atg} \) mutants analysed are indicated below the respective lanes. All mutants, except for \( \text{atg8}^D \), also expressed endogenous \( \text{ATG8} \).

**Processing of GFP-Atg8 under various autophagy-inducing conditions reported in budding yeast**

The conditions that induce autophagy in fission yeast are not the same as those in budding yeast. In budding yeast, glucose depletion also induces autophagy (Takeshige et al., 1992). Environmental glucose is monitored by a cAMP-PKA cascade in both budding and fission yeast (Isshiki et al., 1992; Maeda et al., 1990, 1994; Welton & Hoffman, 2000). Noda & Ohsumi (1998) reported that addition of a high concentration of cAMP repressed autophagy in budding yeast. In contrast, the addition of excess cAMP did not influence the induction of autophagy in fission yeast (Kohda et al., 2007). Our results are consistent with the results obtained upon cAMP addition, as GFP-Atg8p was not processed following the shift from nutrient-replete conditions to glucose starvation (Fig. 2) or to use of the non-fermentable glycerol as carbon source (data not shown). In budding yeast, vegetative cells undergo a nitrogen-starvation response induction of autophagy upon addition of rapamycin (Helliwell et al., 1994; Weisman, 2004; Weisman et al., 1997, 2001). In contrast, rapamycin treatment does not induce autophagy in fission yeast (Uritani et al., 2006). We tested whether processing of GFP-Atg8p occurred under such conditions. In nutrient-replete conditions, only full-length GFP-Atg8p accumulated in spite of the addition of rapamycin (Fig. 2). These data also indicate that the GFP-Atg8p processing assay strictly reflects the existence of an autophagic process.

**Fig. 2.** Cleavage of GFP-Atg8p under various conditions. WT (ARC039) and \( \text{atg1}^\Delta \) (SK16) cells were grown to mid-exponential phase in MM medium containing required amino acids and were then shifted to the conditions indicated below. Lysates were prepared from WT cells grown in nutrient-replete medium (lane 1), 6 h after shift to MM–N (lanes 2 and 7), 6 h after shift to MM–N containing 1 mM PMSF (lane 5), before shift to MM–N containing 0.2 \( \mu \)g rapamycin ml\(^{-1}\) (lane 3) and 6 h after shift to MM–N containing 0.2 \( \mu \)g rapamycin ml\(^{-1}\) (lane 4), and 6 h after shift to glucose-depleted MM (lane 6). Lysates from \( \text{atg1}^\Delta \) cells were prepared 6 h after shift to MM–N (lane 7).
We examined the localization of GFP-Atg8p in several atg mutants before and after starvation. Initial observations were made in atgΔ cells expressing GFP-Atg8p under the control of the attenuated nmt promoter. Fluorescence microscopy revealed that almost all GFP-Atg8p was localized in the cytosol, although some fluorescence was also detected in the nucleus, presumably due to overexpression by the nmt promoter. After 3 h of starvation, a few bright dots were localized near the vacuole. These bright dots may represent the preautophagosomal structure (PAS), which is the putative site where Atg components localize to compose the vesicle-forming machinery for autophagy and the Cvt pathway, or an autophagosomal structure (Fig. 3). After 6 h of starvation, GFP fluorescence was observed within the vacuole (Fig. 3). This translocation of GFP fluorescence suggests a similar autophagic process to that in budding yeast, as autophagosomes containing GFP-Atg8p fused with the vacuole and their contents, the ‘autophagic bodies’ were released within the vacuole. When localization of GFP-Atg8p was investigated in other atg mutants, including atg1Δ, atg3Δ, atg4Δ, atg5Δ, atg7Δ, atg9Δ, and atg12Δ (data not shown), GFP fluorescence was not observed within the vacuole after 6 h of starvation. These data also suggested that atg null mutants of Sch. pombe were defective in the autophagic process, for GFP-Atg8p could not be transported into the vacuole lumen.

**Fig. 3.** Localization of GFP-Atg8p expressed in an atg null mutant before and after starvation. atgΔ (SK23) cells were grown to mid-exponential phase in MM medium and then shifted to MM–N for 3 or 6 h. Staining of the vacuole with FM4-64 and observation by fluorescence microscopy were performed as described in Methods. Arrows indicate the vacuole.

**Rescue of sporulation deficiency by amino acid supplementation in autophagy-defective mutants**

Because defects in autophagy may interfere with sporulation signal transduction or with depletion of materials necessary for induction of sporulation during starvation, almost all Sac. cerevisiae atg mutants exhibit sporulation defects (Deutschbauer et al., 2002). We therefore tested whether a similar phenomenon occurred in atg mutants in fission yeast. In MEA sporulation-inducing medium, microscopic observations revealed that sporulation occurred in over 90% of TN8 cells, which are auxotrophic for leucine (Fig. 4c), whereas sporulation was rarely observed in a leucine-auxotrophic atg1Δ (SK29) strain derived from KJ100-7B or an arginine auxotrophic atg1Δ (SK49) strain (Fig. 4b). Mating was observed in only some cells (Fig. 5a). Further investigation revealed that a defect in sporulation was also observed in other leucine auxotrophic atg null mutants, including atg2α to atg9α, atg13α, atg15α and atg17α (data not shown). These results have previously been reported by Kohda et al. (2007), but we observed a novel aspect of the sporulation in atg null mutants during nitrogen starvation: sporulation was observed in some cells of atg null mutants, including atg1Δ, atg2Δ, atg12Δ and atg13Δ derived from the TN9 strain, which is not auxotrophic for amino acids. Each of the TN9-derived atg mutants exhibited sporulation in 8–15% of cells during nitrogen starvation (Fig. 4a), whereas over 90% of wild-type TN7 (non-auxotrophic) cells sporulated as well as TN8 cells (Fig. 4a, c). This result suggests that fission yeast is able to sporulate partially with a pooled nitrogen source. Moreover, it suggests that the majority of nitrogen essential for sporulation might be dependent on a nitrogen source supplied by the autophagic degradation process.

Next, we examined whether addition of amino acids to MEA sporulation medium could rescue the sexual differentiation defects of the KJ100-7B-derived atg mutants. In the atg1Δ mutant (SK29, leucine auxotroph), autophagy and sporulation were induced in MEA medium containing several different concentrations of leucine. As the leucine concentration in the medium increased, the rate of spore formation increased and became indistinguishable from that of the non-auxotrophic strain atg1Δ (Fig. 4a) by addition of 120 μg leucine ml⁻¹. About 30% of the cells sporulated in ME medium containing 240 μg leucine ml⁻¹ (Fig. 4b), corresponding to a sporulation efficiency that was higher than that of the non-auxotrophic atg1 null mutant.

Random spore analysis revealed that each spore derived from the atg mutants germinated and grew normally in nutrient medium (data not shown). These results were also observed in the other atg mutants investigated (Fig. 4c). In budding yeast, a defect in sporulation has been reported in atg null mutants; in fission yeast, however, mating ability was rescued by addition of leucine (Figs 4b and 5a) when cells were auxotrophic for leucine. This phenomenon was
not restricted to leucine auxotrophy. We constructed \( \text{atg}1 \Delta \) strains auxotrophic for both leucine and arginine (SK50) and for arginine alone (SK49). The sporulation defect of SK49 was partially rescued by addition of arginine alone, whereas addition of 240 \( \mu \text{g mL}^{-1} \) of both leucine and arginine was required to rescue the sporulation defect of SK50 (Fig. 4b). Sporulation efficiency was not increased by the addition of more than 240 \( \mu \text{g mL}^{-1} \) of either amino acid. These results suggest that the defect in sporulation of the \( \text{atg} \) mutants during nitrogen starvation was not caused by a genetic defect of proteins involved in the spore formation process, but rather by insufficient expression of proteins owing to a lack of amino acids in the cytosol. Kohda et al. (2007) showed that autophagy-defective mutants produced spores when 30 mM NH\(_4\)Cl was added after the induction of autophagy. This observation suggests that the sporulation defect of autophagy mutants was caused by a depletion of nitrogen source, but does not show whether the amino acids generated proteolytically in the vacuole through the autophagic process were indeed recycled for use in \textit{de novo} protein synthesis in the cytosol.

In budding yeast, seven genes have been predicted to be vacuolar amino acid transporters (AVT); Avt3p, Avt4p and Avt6p are reported to be effluxers of acidic or branched amino acids from the vacuole (Russnak et al., 2001), but substrates for Avt2p, Avt5p and Avt7p have not been identified as yet. Yang et al. (2006) showed that \( \text{atg}22 \Delta \) is also a vacuolar effluxer of leucine and other amino acids, functioning redundantly with Avt3p and Avt4p, and these proteins are partially required to supply amino acids for \textit{de novo} protein synthesis after the autophagic process. The fission yeast genome database revealed the existence of two AVT homologues, SPAC3H1.09C and SPBC1685.07C, the encoded proteins of which share 63% and 67% similarity with budding yeast Avt3p and Avt5p, respectively. But the function of these two homologues has not yet been determined. We generated null mutants of ASPAC3H1.09C and SPBC1685.07C.
and SPBC1685.07C (avt3+ and avt5+, respectively), and observed the sporulation efficiency of these mutants. As shown in Fig. 4(d), avt3Δ, avt5Δ and an atg22Δavt3Δavt5Δ triple mutant that is also leucine auxotrophic showed a sporulation defect similar to that observed in atg22Δ (Fig. 4c), although addition of leucine restored the rate of spore formation such that it was indistinguishable from that of the wild-type parent strain KJ100-7B. These data suggest that Sch. pombe Avt3p and Avt5p are also responsible for spore formation, but the avt-defective mutants are able to process GFP-Atg8p during starvation as observed in atg22Δ (data not shown). From the similarity in proteins, fission yeast Atg22p, Avt3p and Avt5p could be vacuole effluxers of amino acids. Our data suggest that amino acids that are proteolytically produced through the autophagic process might be recycled for maintenance of cellular function during nitrogen-starvation conditions in Sch. pombe cells.

Incomplete sporulation observed in atg1Δ or atg12Δ mutants

We observed that amino acid depletion led to incomplete sexual differentiation in atg mutants, but sporulation could be partially restored by amino acid supplementation. These data suggested that the sporulation process might be

---

Fig. 5. Development of the FSM during meiosis. (a) Mating and sporulation rate of GFP-Psy1p-expressing WT (YN68), atg1Δ (TN400) and atg12Δ (TN401). Cells were cultured on MEA plates with or without leucine for 2 days at 28 °C, and then observed by DIC microscopy. (b) WT (YN68), atg1Δ (TN400) and atg12Δ (TN401) mutants were sporulated on MEA medium for 2 days at 28 °C. The FSM was visualized by GFP-Psy1p. α-Tubulin was immunostained by TAT-1 antibody. DNA was stained by DAPI. Arrows indicated the visualized FSM by GFP-Psy1p. (c) Morphology of the cells upon forespore formation. Sporulation was performed as described above. DNA was stained by DAPI. Arrows indicate the FSM visualized by GFP-Psy1p.
influenced by amino acid depletion caused by a defect in the autophagic process. We then examined which process in sporulation of the atg mutant was affected. To this end, we monitored formation of the forespore membrane (FSM) by visualization with GFP-Psy1 in both atg1Δ (TN400) and atg12Δ (TN401) mutants. Psy1 is a fission yeast homologue of mammalian syntaxin 1A, which is a t-SNARE (soluble NSF attachment protein receptor) on the plasma membrane (Nakamura et al., 2001). We previously reported that Psy1 is translocated from the plasma membrane to the nascent FSM at meiosis II (Nakamura et al., 2001). GFP-Psy1 under the control of its native promoter was integrated into the Sch. pombe genome to facilitate monitoring of GFP fluorescence during sporulation. After induction of sexual differentiation in the absence of leucine, nuclear division and spore morphogenesis terminated normally in almost all wild-type cells. Formation of the FSM initiated normally near the spindle poles at meiosis II and proceeded normally to anaphase II (Fig. 5b). However, in atg1Δ and atg12Δ mutants, more than half of the cells appeared to exhibit a related deficiency in organization of the FSM and nuclear division (Fig. 5b). The atg1Δ and atg12Δ mutants exhibited abnormal elongation of the FSM. Chromosome segregations were suspended incompletely whereas the cells proceeded to anaphase II and the spindle microtubules were correctly organized (Fig. 5b). Moreover, some cells finished closure of the FSM without encapsulation of the nucleus (Fig. 5b, iv, vii and viii). In wild-type cells, closure of the FSM is typically observed more than 20 min after completion of anaphase II. We have never observed cells completing closure of the FSM without encapsulating the nucleus (Nakamura et al., 2008). Failure of the spore formation process was also observed in forespore formation. WT cells were completely enclosed by forespore membrane, whereas in atg1Δ and atg12Δ mutants, only a few cells sporulated normally (Fig. 5c, i of TN400, and iv of TN401), and the majority of cells failed to complete sporulation as evidenced by incomplete tetrads formation or by abnormal forespore organization (Fig. 5c, ii and iii of TN400, v and vi of TN401). This sporulation deficiency was unlikely to be caused by repression of sporulation-specific genes because the sporulation process was not blocked at a particular stage in the same strain. Whole-genome microarray analyses have revealed that gene expression profiles are altered extensively during sporulation (Chu et al., 1998; Mata et al., 2002; Primig et al., 2000) and this suggested that extensive de novo protein synthesis may be needed to execute the sporulation process. Depletion of nitrogen may decrease or halt de novo protein synthesis, resulting in a shortage of proteins critical for sporulation.

**DISCUSSION**

Autophagy is a crucial pathway for adaptation to changing environments, and thus mechanisms of autophagy are well conserved in eukaryotes. We report five major findings from this study, using fission yeast. (1) Processing of GFP-Atg8 during nitrogen starvation could also serve as a useful marker for monitoring autophagy in Sch. pombe. (2) Through use of this marker, almost all Atgs predicted by sequence analysis were experimentally demonstrated to be involved in the autophagic process. (3) Autophagy in fission yeast was induced only by nitrogen starvation, and not by glucose starvation or addition of rapamycin. (4) The fission yeast AVT homologue genes (avt3+ and avt5+) may be required for recycling of amino acids from the vacuolar compartment to the cytosol for maintenance of cellular function during nitrogen-starvation conditions in Sch. pombe. (5) Autophagy is responsible for supplying a large proportion of the amino acids required for de novo protein synthesis to adapt to starvation conditions.

Recent studies have also reported the existence of nitrogen-starvation-induced autophagy in fission yeast, and several budding yeast ATG orthologues (ATG1, ATG13 and ATG8) have been shown to be involved in the autophagic pathway (Kohda et al., 2007). Here, we identified 15 presumptive atg orthologues of budding yeast by sequence analysis of proteins in Sch. pombe GeneDB, and we suggest that they indeed function in autophagy on the basis of monitoring a GFP-Atg8p marker. However, several orthologues of budding yeast were not identified in the Sch. pombe genome database because of a low degree of similarity. Atg10p and Atg16p are small proteins that are critical for ubiquitin-like conjugation systems involving Atg12p. In *Pichia pastoris*, which was previously reported to undergo autophagy and pexophagy, an orthologue of ATG10 has not yet been identified (Mukaiyama et al., 2002). A homology search for ATG orthologues in budding yeast by sequence analysis of orthologues (ATG) of Sch. pombe has been shown to undergo autophagy on the basis of monitoring a GFP-Atg8p marker. However, we could not observe GFP-Atg8p in the vacuolar lumen in other atg null mutant cells (data not shown). Western blotting showed that GFP-Atg8p expressed in an atg8 mutant or in wild-type cells is present in two forms during nitrogen starvation: a full-length fusion protein or free GFP. In contrast, only full-length GFP-Atg8p was detected in the other atg null mutants expressing GFP-Atg8p, with the sole exception of atg22Δ. Moreover, addition of rapamycin or glucose starvation was not able to facilitate normal processing of GFP-Atg8p, consistent with studies described by Kohda et al. (2007) These observations also suggested that the GFP-Atg8p processing assay could provide a criterion for demonstrating autophagy in fission yeast.

The physiological role of autophagy is to maximize survival when cells are subjected to conditions of nutrient insufficiency. It is thought that cells can either degrade endogenous macromolecular constituents to provide nutrients until environmental conditions improve, or decrease dispensable functions, structures or organelles.
during survival. In budding yeast, it is assumed that the nutrients recycled by the autophagic process may be used for sexual differentiation, because wild-type cells are able to initiate sporulation during starvation (Takeshige et al., 1992). This amino acid recycling was not directly exhibited in budding yeast, however, because atg null mutants exposed to nitrogen starvation showed only cell death, and it was unclear whether nutrient shortage alone or also other factors such as apoptosis were triggers of this cell death.

Sporulation by atg null mutants (atg1Δ and atg12Δ) was assessed in the absence of auxotrophic requirements by monitoring formation of the forespore membrane (FSM) through visualization of GFP-Psy1. In these mutants, approximately 30 % of cells completed spore formation, but others formed incomplete tetrads caused by abnormal forespore organization or abnormal chromosome segregation (Fig. 5b, c). Interestingly, the sporulation process in these atg mutants was blocked at various stages. In budding yeast, autophagy-defective atg7Δ cells contain markedly smaller intracellular amino acid pools, and levels of de novo bulk protein synthesis are suppressed during nitrogen starvation (Onodera & Ohsumi, 2005). This amino acid depletion may cause rapid loss of viability and sporulation deficiency in atg mutants of budding yeast during nitrogen starvation. In budding yeast, atg13Δ or atg1Δ mutants are reported to lose 80 % viability after 5 days of nitrogen starvation (Funakoshi et al., 1997; Tsukada & Ohsumi, 1993). In contrast, fission yeast atg mutant cells retain 100 % viability after 7 days of nitrogen starvation (Kohda et al., 2007). This observation implies that fission yeast may possess larger pools of endogenous amino acids required for sporulation than budding yeast, and indeed we were able to observe partial complementation of the sporulation process during nitrogen starvation in fission yeast. In Sch. pombe or the filamentous fungus Aspergillus fumigatus, addition of ammonium chloride as a nitrogen source is able to initiate sporulation during nitrogen starvation (Kohda et al., 2007; Richie et al., 2007). This observation suggests that a nitrogen source is necessary for sporulation, but it does not reveal the pathway of amino acid recycling that follows autophagy.

Here, in fission yeast, we found that 8–15 % of non-axotrophic cells were able to sporulate despite the absence of autophagy during starvation. In contrast, sporulation was not observed in an atg1Δ mutant with amino acid auxotrophy, whereas atg1Δ in a non-axotrophic genetic background showed up to 15 % sporulation. These findings suggest that fission yeast is able to sporulate partially with a pooled nitrogen source despite an autophagy deficiency. On the other hand, these findings suggest that the majority of nitrogen essential for sporulation may be dependent on a source that is supplied by the autophagic degradation process.

The means by which yeast cells recycle degradation products generated by autophagy is of interest. In budding yeast, vacuolar amino acid permeases such as Atg22p, Atg3p and Atg4p are partially redundant vacuolar amino acid efflux pumps that mediate the efflux of leucine and other amino acids resulting from autophagy (Yang et al., 2006). Fission yeast also possesses ATG22, and an atg22Δ mutant was also starvation-sensitive, although atg22Δ cells have a much less pronounced sporulation defect than other atg null mutants (Fig. 4c). The fission yeast genome database revealed two AVT homologues, AVT3 and AVT5. Our investigation revealed that these two Avt proteins and Atg22p may function as vacuole effluxers of amino acids generated during the autophagic process (Fig. 4d), because null mutants of Avt3p and Avt5p showed almost the same sporulation defect as observed for atg22Δ. These data suggested that the amino acids generated by autophagy were effluxed redundantly by Atv3p, Atv5p and Atg22p. We then constructed an avt3Δavt5Δatg22Δ triple mutant; the sporulation rate of the triple mutant was almost same as that of the atg22Δ single null mutant (Fig. 4d). These results might suggest the existence of other redundant vacuole effluxers of amino acids. We recently reported that the fission yeast fnx1+ and fnx2+ genes, which are homologous to the budding yeast VBA (vacuolar transporter for basic amino acids) genes, are involved in vacuolar amino acid uptake in Sch. pombe (Chardwiriyapreecha et al., 2008). We tested sporulation of fnx1Δ and fnx2Δ cells, and found that they sporulate normally during nitrogen starvation (unpublished results). These results suggest that Fnx1p and Fnx2p function only in vacuolar amino acid influx, and may not be involved in vacuolar amino acid efflux in Sch. pombe. We are currently attempting to identify other proteins involved in the amino acid recycling that follows nitrogen starvation-induced autophagy.

ACKNOWLEDGEMENTS

We thank Drs Takashi Toda and Reiko Sugiura for providing Sch. pombe plasmids and rabbit anti-GFP serum. We thank Kohei Ohori for technical assistance, and Yoshimi Kakinuma (Ehime University) for valuable discussions. This work was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, and Culture of Japan, and the Project for Development of a Technological Infrastructure for Industrial Bioprocesses on R&D of New Industrial Science and Technology Frontiers by the Ministry of Economy, Trade & Industry (METI), as supported by the New Energy and Industrial Technology Development Organization (NEDO).

REFERENCES


Autophagy and forespore membrane formation in Sch. pombe.


