The Sec1p/Munc18 (SM) protein, Vps45p, cycles on and off membranes during vesicle transport

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Protein phosphatase 1 (PP1, Glc7p) functions in the final stage of SNARE-mediated vesicle transport between docking and fusion. During this process, trans-SNARE complexes, formed between molecules in opposing membranes, convert to cis-complexes, with all participants in the same lipid bilayer. Here, we show that glc7 mutant cells accumulate SNARE complexes. These complexes are clearly different from those found in either wild-type or sec18–1 cells as the Sec1p/Munc18 (SM) protein Vps45p does not bind to them. Given that PP1 controls fusion, the SNARE complexes that accumulate in glc7 mutants likely represent trans-SNARE complexes. Vps45p dissociates from the membrane in the absence of PP1 activity, but rapidly reassociates after its reactivation. These data reveal that SM proteins cycle on and off membranes in a stage-specific manner during the vesicle transport reaction, and suggest that protein phosphorylation plays a key role in the regulation of this cycle.

Introduction

Intracellular membrane trafficking is a highly regulated process (Sudhof, 1995). SNAREs play a critical role in this process by regulating membrane docking and fusion (Sudhof, 1995; Weber et al., 1998). Transport vesicles contain membrane proteins (v-SNAREs), which specifically bind to cognate membrane proteins (t-SNAREs) in the appropriate target membrane. Large families of v- and t-SNARE proteins have been identified in eukaryotic cells with different members localizing to different compartments (Sudhof, 1995). The correct pairing of v- and t-SNAREs in opposing membranes is defined by the formation of a stable high affinity complex referred to as the trans- or SNARE core complex (Nichols et al., 1997; Sutton et al., 1998; Weber et al., 1998). v- and t-SNAREs contain α-helical domains that contribute to a four-helix bundle giving rise to the SNARE complex (Sutton et al., 1998).

SNARE complex assembly occurs in several discrete stages. Initially, in a priming step, cis-SNARE complexes in both donor and target membranes are disassembled through the ATPase action of NSF in conjunction with its attachment protein α-SNAP (Mayer et al., 1996). Once primed, tethering machinery may guide the SNAREs in each membrane into close proximity and a proofreading machinery likely ensures fidelity of the aligned v- and t-SNARE pairs (Zerial and McBride, 2001). Formation of the high affinity trans-SNARE complex represents the committed step of docking (Ungermann et al., 1998). This step is accompanied by conversion of trans- to cis-complexes (Lin and Scheller, 1997; Sutton et al., 1998). Although SNARE proteins are sufficient to catalyze docking and fusion of artificial membrane liposomes in vitro (Weber et al., 1998; McNew et al., 2000), other factors are essential in vivo, suggesting multiple levels of regulation.

The Sec1p/Munc18 (SM)* family plays an essential role in regulating membrane transport (Jahn, 2000). Disruption or deletion of any of the four SM proteins in Saccharomyces cerevisiae causes a block in vesicle transport (Jahn, 2000). SM proteins are peripheral membrane proteins. We have demonstrated previously that the SM protein Vps45p is dependent on its cognate t-SNARE Tlg2p for its membrane association (Bryant and James, 2001). Moreover, it has been shown that many SM proteins bind their cognate t-SNARE with high affinity in vitro (Pevsner et al., 1994b; Yamaguchi et al., 2002), suggesting that the stable association of SM proteins with membranes is mediated via this interaction. But how this interaction changes as the t-SNARE engages in core complex assembly during docking is not known. At
Results and discussion

Vps45p binds to monomeric Tlg2p and to the cis-SNARE–core complex

We have demonstrated previously that Vps45p binds to Tlg2p both in vitro and in vivo (Bryant and James, 2001). Other SM proteins, including Sly1p and Sec1p, bind to their respective SNARE complexes (Kosodo et al., 1998; Carr et al., 1999; Peng and Gallwitz, 2002). Importantly, Sec1p binds to the cis-core complex, indicating a role for SM proteins after vesicle fusion. Intriguingly, Vps45p binds to Tlg2p, Vti1p, HA-tagged Snc2p, and Vps45p in the immunoprecipitated complexes. (Kosodo et al., 2002; Peng and Gallwitz, 2002), binds to its cognate SNARE complex. Given that, we observed the association of Vps45p with SNARE complexes in sec18–1 cells, this likely corresponds to an association with cis-complexes, and is in agreement with previous studies (Carr et al., 1999; Grote et al., 2000).

We, and others, have shown that Vps45p binds to monomeric Tlg2p in vitro (Bryant and James, 2001; Dulubova et al., 2002; Yamaguchi et al., 2002). The observation that Sec1p binds to Ssop-containing SNARE complexes, but not to the monomeric t-SNARE (Carr et al., 1999), raises the possibility that the association observed between Tlg2p and Vps45p in vivo does not reflect the SM protein binding to the monomeric t-SNARE, but rather to the cis-SNARE complex. This is the case for the interaction between Sec1p and Ssop (Carr et al., 1999), as demonstrated by the lack of interaction between these two proteins in sec4–8 cells (Carr et al., 1999). SECA encodes the Rab protein involved in the fusion of secretory vesicles with the plasma membrane, and sec4–8 cells are defective in assembly of Ssop SNARE complexes (Grote and Novick, 1999). The Rab protein involved in VPS45-dependent membrane transport is encoded by VPS21 (Gerhardt et al., 2000). Fig. 2 shows that Tlg1p was not found in complex with its SNARE binding partners in...
SNARE complexes that accumulate in sensitive allele of coprecipitate with Tlg1p when cells harboring a temperature-fold increase in the amount of Tlg2p, Vti1p, and Snc2p that complexes (Peters et al., 1999). Our finding that Vps45p binds to both monomeric Tlg2p and to the cis-core complex may indicate that the interaction between this SM protein and the t-SNARE is maintained throughout the SNARE cycle. To test this model, and further characterize the interaction between Vps45p and its cognate SNARE complex, we set out to assess the ability of Vps45p to bind to a trans-SNARE complex. To generate trans-SNARE complexes in vivo we endeavored to find a mutant that blocks membrane transport between vesicle docking and bilayer fusion. One protein that has been implicated at this stage is protein phosphatase 1 (PP1). PP1 (Glc7p) has been shown to function at a late stage of vacuole fusion, likely during the bilayer mixing phase (Peters et al., 1999). A cell-free assay that reconstitutes homotypic vacuolar fusion has been used to define discrete stages in this reaction (Wickner, 2002). Inhibition of either Rab or SNARE function blocks at an early stage in this assay (Wickner, 2002). In contrast, inhibition of PP1 using either microcin or temperature-sensitive alleles of GLC7 block at a very late stage after docking (Peters et al., 1999). Addition to vacuolar fusion, it has also been shown that PP1 is involved in multiple intracellular fusion steps, including ER to Golgi complex transport and endocytic traffic (Peters et al., 1999). This suggests that PP1 is a general component of the membrane fusion machinery that, like Sec18p, operates in all vesicle transport reactions (Peters et al., 1999). One prediction from the model that PP1 (Glc7p) is involved at a late, post-docking stage of membrane fusion is that inhibition of PP1 action results in an accumulation of trans-SNARE complexes (Peters et al., 1999).

Fig. 3 demonstrates that there is a significant three- to five-fold increase in the amount of Tlg2p, Vti1p, and Snc2p that coprecipitate with Tlg1p when cells harboring a temperature-sensitive allele of GLC7 are incubated at the nonpermissive temperature (Fig. 3 A). Intriguingly, no Vps45p was found associated with the SNARE complexes that accumulate in these cells (Fig. 3 A, 37°C). This is in contrast to the cis-SNARE complexes that accumulate in sec18–1 cells (Fig. 1). The observation that Vps45p binds to SNARE complexes present in wild-type cells, and also to those detected in sec18–1 cells at the permissive temperature, indicates that these are cis-SNARE complexes, whereas those that accumulate in glc7–10 cells at 37°C are in the trans-configuration.

The above data raises important questions concerning SM protein function. If Vps45p dissociates from the trans-SNARE complex upon vesicle docking, does it remain membrane associated during this stage? To address this, we assessed the membrane association of Vps45p in wild-type, vps21Δ, sec18–1, and glc7–10 cells (Fig. 3 B). Consistent with previous studies, the majority of Vps45p was associated with membranes in wild-type cells (Cowles et al., 1994; Bryant and James, 2001). Vps45p retained its membrane localization in cells lacking Vps21, which are defective in SNARE complex assembly, presumably through its interaction with monomeric Tlg2p (Bryant and James, 2001; Fig. 2). Similarly, the SM protein was associated with membranes in sec18–1 cells at 37°C (Fig. 3 B). However, intriguingly, Vps45p was not found associated with membranes in glc7–10 cells at 37°C, but rather localized to the cytosol (Fig. 3 B). These data are consistent with our observation that Vps45p binds to the SNARE complexes that accumulate in sec18–1 cells (Fig. 1), but not to those that accumulate in glc7–10 cells at 37°C (Fig. 3 A).

To assess the physiological relevance of the loss of membrane association upon inactivation of PP1, we sought to ascertain whether the dissociation observed upon inactivation of PP1 was reversible upon reactivation of the phosphatase. Fig. 4 A demonstrates that the block in membrane trafficking caused by incubation of glc7–10 cells is reversible. It has been shown previously that the transit of the vacuolar hydrolase carboxypeptidase Y (CPY) through the secretory pathway is blocked in PP1 temperature-sensitive cells at 37°C (Peters et al., 1999). After its synthesis, CPY is translocated into the lumen of the ER, where it is core glycosylated into the p1 form. CPY receives further modifications as it transits through the Golgi apparatus. In the trans-Golgi network, the p2 form of CPY is recognized by its receptor Vps10p, which delivers the protein to the vacuole where it is cleaved into the mature form of the protease (Bryant and Stevens, 1998). Fig. 4 A demonstrates that incubation of glc7–10 cells at 37°C blocks the processing of CPY. Concomitant with this block in vesicle fusion is the dissociation of Vps45p from membranes, as demonstrated by the observation that the SM protein shifts from the P100 (membrane) to the S100 (cytosol) fraction obtained from these cells after 10 min at 37°C (Fig. 4 B). The block in processing of CPY was reversed by returning the cells to 24°C (Fig. 4 A). Importantly, with this recovery in vesicular transport, Vps45p reassociated with membranes (Fig. 4 B). These data
The SNARE assembly cycle depicted in Fig. 5 illustrates the dynamic equilibrium between the t-SNARE Tlg2p in its monomeric state, and as part of trans- and cis-complexes. Each one of these states defines an intermediate in the vesicle docking–fusion process. We have demonstrated that Vps45p binds to Tlg2p in this state before the formation of the trans-SNARE complex in a Rab-dependent process (Grote and Waters, 1997; Grote and Novick, 1999). We show that Vps45p dissociates at this stage of the cycle and is released into the cytosol. The conversion of trans-SNARE complexes to the cis-configuration defines membrane fusion (Ungermann et al., 1998), and also represents the starting point for another round of vesicle transport. It is here that Vps45p reenters the cycle by binding to the cis-complex. The cycle is completed after disassembly of cis-SNARE complexes with Vps45p bound by Sec18p presumably resulting in the Vps45p–Tlg2p complex that is then ready to receive incoming vesicles in the process of docking.

The formation of unifying models concerning SM protein function has been made difficult by conflicting observations concerning their binding properties: Munc18a binds to monomeric Syntaxin1a, but not to SNARE complexes (Yang et al., 2000). Sec1p binds to Sso–SNARE complexes, but not to the monomeric t-SNARE (Carr et al., 1999); although others, such as S1y1p, Munc18c, and now Vps45p, bind both to the monomeric t-SNARE and to the SNARE complex (Kosodo et al., 2002; Peng and Gallwitz, 2002; unpublished data). Some of these differences may reflect the different conformations undertaken by these different proteins in vitro, but they may also represent kinetic differences at various stages of the cycle outlined in Fig. 5 for different SNARE pairs. For example, in neurones there is an accumulation of unpaired vesicles (Sudhof, 1995), and therefore, presumably an accumulation of trans-SNARE complexes, whereas it is likely that the Sso-containing SNARE complexes observed in wild-type yeast cells are in the cis-configuration (Grote et al., 2000).

In a manner similar to the finding that Sec1p binds to SNARE complexes (Carr et al., 1999), we observed a robust interaction between Vps45p and Tlg2p in sec18-1 mutants (Fig. 1). It is noteworthy that in a previous study, Lupashin and Waters (1997) reported that there was no significant interaction between S1y1p- and Sed5p-containing SNARE complexes that accumulate in sec18-1 cells, despite the fact that S1y1p has subsequently been shown to interact with Sed5p-containing SNARE complexes formed in vitro (Kosodo et al., 2002; Peng and Gallwitz, 2002). However, in that study (Lupashin and Waters, 1997), sec18-1 mutants were incubated for times significantly longer than those used here, and we have found that the period of incubation of these cells at the nonpermissive temperature is critical in these experiments (unpublished data).

Our model raises a number of important questions that provide a framework for further investigation directed at understanding the role of SM proteins. Why does Vps45p dissociate from the membrane during the docking–fusion stage? Do SM proteins play a role, similar to Rab proteins, and cycle on and off membranes in synchrony with the arrival of vesicles at the docking site? In addition, our paper raises questions concerning the role of PP1 in docking–fusion events. What is the role of phosphorylation that appears to be so intimately linked to the docking–fusion transition of vesicle transport; and is the dissociation of the SM protein during this phase the cause, or an effect, of this? Intriguingly, a role for the phosphorylation of Tlg2p has been implicated in modulating endocytosis (Gurunathan et al., 2002), and phosphorylation of Munc18a may be important in regulating its interaction with Syntaxin1a (Fujita et al., 2000).
Finally, with our finding that Vps45p binds selectively to certain SNARE intermediates, could it be that there is a consensus in SM function that has been thus far difficult to realize? If phosphorylation plays an important role in the SM–SNARE interaction, replicating the conditions necessary to establish these interactions may not be trivial. Notably, Carr et al. (1999) stressed the importance of eliminating ATP from their cells before isolation of intact SNARE complexes. Answers to the above, and other, questions will further our understanding of this important family of proteins.

**Materials and methods**

**Antibodies**

Rabbit polyclonal antibodies against Tlg2p and Vps45p have been described previously (Bryant and James, 2001). Antibodies that specifically recognize Tlg1p and Vti1p were a gift from J. Coe (IMCB, Singapore) and W. Hong (IMCB, Singapore). The monoclonal antibody 16B12, which recognizes the influenza hemagglutinin (HA) epitope, was purchased from BabCo.

**Plasmids**

All DNA manipulations were performed using routine procedures. Plasmid pEG111, provided by E. Grote (Yale University, New Haven, CT) is an integrating vector encoding an HA-epitope–tagged version of Snc2p (Abeliovich et al., 1998). pEG111 was constructed by subcloning a BamHI-HindIII fragment encompassing the tagged Snc2p coding sequence from pEG111 into pRS306 (Sikorski and Hieter, 1989).

**Strains**

All yeast strains used in these studies are described in Table I. Yeast strains were constructed using standard genetic techniques and grown in rich media (YPD; 1% yeast extract, 1% peptone, 2% dextrose) or standard minimal medium using either glucose, or raffinose and galactose as carbon sources. NOzY23, and NOzY24 were derived from SF838–9D (Rothman and Stevens, 1996). Finally, with our finding that Vps45p binds selectively to certain SNARE intermediates, could it be that there is a consensus in SM function that has been thus far difficult to realize? If phosphorylation plays an important role in the SM–SNARE interaction, replicating the conditions necessary to establish these interactions may not be trivial. Notably, Carr et al. (1999) stressed the importance of eliminating ATP from their cells before isolation of intact SNARE complexes. Answers to the above, and other, questions will further our understanding of this important family of proteins.

**Metabolic labeling and pulse-chase immunoprecipitation of CPY**

The fate of newly synthesized CPY in glc7–10 cells was followed by immunoprecipitation of the protein as described previously (Bryant and James, 2001).

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**Table I. Yeast strains used in this study**

| Strain     | Genotype                  | Source                        |
|------------|---------------------------|-------------------------------|
| SF838–9D  | MATa ura3–52 leu2–3,112 his4–519 ade6 gal2 pep4–3 | Rothman and Stevens, 1986 |
| SGY79     | MATa ura3–52 leu2–3,112 his4–519 ade6 gal2 pep4–3 vsplΔ::Kan | Gerrard et al., 2000 |
| NOzY24    | MATa ura3–52 leu2–3,112 his4–519 ade6 gal2 pep4–3 vsplΔ::Kan SNC2::[LEU2, GAL1-SNC2-HA] | This study |
| NOzY21    | MATa ura3–52 leu2–3,112 his4–519 ade6 gal2 pep4–3 SNC2::[LEU2, GAL1-SNC2-HA] | This study |
| NOzY22    | MATa ura3–52 leu2–3,112 sec18–1 gal2 SNC2::[LEU2, GAL1-SNC2-HA] | This study |
| PAY704–1  | MATa ade2–1 his3–11,15 leu2–3,112 ura3–1 glc7::LEU2 trpl–1::TRP1 can1–100 sds1–d2 | Peters et al., 1999 |
| NOzY23    | MATa ade2–1 his3–11,15 leu2–3,112 ura3–1 glc7::LEU2 trpl–1::TRP1 can1–100 sds1–d2 SNC2::[URA3, GAL1-SNC2-HA] | This study |

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The authors noticed a duplication of data in Fig. 3 B between the panels representing subcellular fractionations of wild-type and vps21Δ cells. Given the time that has elapsed since the original date of publication, the original data could not be found to correct the figure, so a new version of Fig. 3 B from a recent repeat of the experiment has been provided below.

The html and pdf versions of this article have been corrected. The error remains only in the print version.