Actin cables and the exocyst form two independent morphogenesis pathways in the fission yeast

Felipe O. Bendezú* and Sophie G. Martin*
Center for Integrative Genomics, Faculty of Biology and Medicine, University of Lausanne, CH-1015 Lausanne, Switzerland

ABSTRACT Cell morphogenesis depends on polarized exocytosis. One widely held model posits that long-range transport and exocyst-dependent tethering of exocytic vesicles at the plasma membrane sequentially drive this process. Here, we describe that disruption of either actin-based long-range transport and microtubules or the exocyst did not abolish polarized growth in rod-shaped fission yeast cells. However, disruption of both actin cables and exocyst led to isotropic growth. Exocytic vesicles localized to cell tips in single mutants but were dispersed in double mutants. In contrast, a marker for active Cdc42, a major polarity landmark, localized to discreet cortical sites even in double mutants. Localization and photobleaching studies show that the exocyst subunits Sec6 and Sec8 localize to cell tips largely independently of the actin cytoskeleton, but in a cdc42 and phospholipid phosphatidylinositol 4,5-bisphosphate (PIP2)–dependent manner. Thus in fission yeast long-range cytoskeletal transport and PIP2–dependent exocyst represent parallel morphogenetic modules downstream of Cdc42, raising the possibility of similar mechanisms in other cell types.

INTRODUCTION
Polarized exocytosis is a fundamental cell biological process in which secretory vesicles are transported by motor proteins along a polarized cytoktoskeleton and tethered, docked, and fused at a landmark-defined surface region. Fusion of vesicles with the plasma membrane relies on the formation of a soluble N-ethylmaleimide-sensitive factor attachment protein receptor (SNARE) complex (Sudhof and Rothman, 2009), whose assembly is facilitated by the exocyst, an eight-subunit tethering complex initially identified in the budding yeast (TerBush et al., 1996; He and Guo, 2009). The budding yeast model system has been instrumental in defining the simple linear sequence of events for polarized exocytosis (Pruyne et al., 2004). Activated Cdc42 forms the initial cortical polarizing cue, which activates actin nucleators of the formin family to build polarized actin cables (Evangelista et al., 1997, 2002; Imamura et al., 1997; Sagot et al., 2002; Dong et al., 2003). These cables form tracks for the vectorial transport of myosin V–driven exocytic vesicles toward the site of polarization (Pruyne et al., 1998). At the plasma membrane, vesicles are tethered by the exocyst complex and undergo SNARE-mediated exocytosis for cell morphogenesis. Localization of exocyst components to the growth site relies on two distinct actin cable–dependent and independent mechanisms. Two exocyst subunits, Sec3 and Exo70, directly bind to Cdc42 and the phosphoinositide phosphatidylinositol 4,5-bisphosphate (PIP2; Finger et al., 1998; Boyd et al., 2004; He et al., 2007; Zhang et al., 2008). All other exocyst subunits are transported toward the site of polarization with exocytic vesicles along actin cables, where they join the other two subunits to form a functional tethering complex (Ayscough et al., 1997; Pruyn et al., 1998; Roumanie et al., 2005; Zajac et al., 2005; Zhang et al., 2005). Thus polarized exocytosis is directly dependent on cytoskeletal organization. Accordingly, disruption of myosin V or exocyst components in budding yeast leads to a complete loss of polarized growth (Novick et al., 1980; Johnston et al., 1991).
To probe the conservation of cell morphogenesis mechanisms, we use the fission yeast Schizosaccharomyces pombe, which is phylogenetically distant from the budding yeast and displays distinct rodlike morphology. Here again, Cdc42 is likely to form the most upstream polarizing cue and activates the formin For3 for assembly of polarized actin cables from cell ends (Feierbach and Chang, 2001; Nakano et al., 2002; Martin et al., 2007; Rincon et al., 2009). Along these cables, type V myosin, Myo52, transports vescicular cargoes containing the glucan synthases Bgs1 and Bgs4 necessary for cell wall remodelling and polarized growth at cell tips (Feierbach and Chang, 2001; Motegi et al., 2001; Win et al., 2001; Cortes et al., 2005; Mulvihill et al., 2006). Surprisingly, deletion mutants of for3 or myo52 are viable and, despite a partial loss of rod shape, cells remain competent for polarized cell growth. Fission yeast encodes two additional formins, Fus1 and Cdc12, and one other type V myosin, Myo51, but none of these have reported roles in polarized growth (Petersen et al., 1995; Chang et al., 1997; Motegi et al., 2001; Win et al., 2001). Cells with gene disruption in essential components required for actin cable formation, such as profilin and tropomyosin, are likewise able to polymerize growth (Balasubramanian et al., 1992, 1994). Microtubules are also not required for polarized growth, although they provide spatial information in part by recruiting the formin For3 to cell tips (Martin et al., 2005). Core components of the exocytic machinery, such as the v-SNARE Syb1, are essential for cell morphogenesis (Edamatsu and Toyoshima, 2003), but the exocyst, while essential for cell separation and viability, is dispensable for polarized cell growth (Wang et al., 2002). These observations suggest there may be significant variations in the process of cell morphogenesis in diverse cell types.

Here we show that polarized cell growth can occur independently of cytoskeletal transport in fission yeast. We show that transport of vesicles along actin cables and their tethering at cell tips by the exocyst form two parallel morphogenesis modules, individually dispensable, but together essential, for polarized cell growth. Localization of these modules to cell tips is under control of Cdc42 but independent of each other. Specifically, localization of the exocyst is largely independent of the actin cytoskeleton but depends on PIP2, indicating that membranes can polarize a cell in the absence of linear cytoskeletal elements.

RESULTS
Actin cable-and microtubule-independent polarized cell growth
We created a triple formin mutant with the nonessential for3a and fus1a deletions and the temperature-sensitive allele cdc12-112. Upon inactivation of cdc12-112 at the restrictive temperature of 36°C for 5 h, the cells became elongated due to a block in cytokinesis but grew in a polarized manner as shown by fluorescent lectin staining (Figure 1, A and B). Actin cables were absent in these mutants, although short, wavy weakly-stained actin filaments could occasionally be detected (Supplemental Figure S1), as previously notched in for3a single mutants (Nakano et al., 2002). Thus disruption of all formins does not prevent polarized cell growth. This finding is in agreement with the fact that loss-of-function alleles or deletion mutants of tropomyosin (cdo8 or profilin cdc3), essential for actin cable stability and formation, respectively, still permit polarized growth (Balasubramanian et al., 1992, 1994). In addition, we confirmed that complete deletion of all myosin V motors (in a myo51a myo52a double mutant) does not abrogate polarized cell growth (Motegi et al., 2001; Win et al., 2001; see Figure 1D). Addition of the microtubule-stabilizing drug methyl benzimidazole-2-yl-carbamate (MBC) led to defects in the placement of growth sites but did not abrogate polarized cell growth in either triple formin mutant, tropomyosin or profilin mutant, or double myosin V deletion mutant (Figure 1, C and E, and unpublished data). Thus fission yeast can polarize growth, albeit less efficiently, in the absence of both actin cable- and microtubule-based transport, suggesting that transport of vesicles along linear cytoskeletal filaments is not essential for this process.

To substantiate this finding, we examined the localization of exocytic vesicles by monitoring green fluorescent protein (GFP)-tagged cargoes (the glucan synthases Bgs1 and Bgs4) and v-SNARE (Syb1; Figure 1F and unpublished data). In wild-type cells, these fluorescent markers localize to sites of growth, labeling the cell end cortex, and mark internal sites that probably represent Golgi or recycling compartments (Cortes et al., 2002, 2005; Edamatsu and Toyoshima, 2003). Consistent with the ability of actin cable-less cells to polarize growth, we found that exocytic vesicle markers still localized to cell ends and to internal sites in for3Δ, myo51Δ myo52Δ, and cdc3-313 cells grown at restrictive temperature for 90 min, although cell end accumulation was in some cases less prominent (Figures 1F and 4B). In this and all subsequent experiments, we used the for3a single mutant, rather than the triple formin mutant, because fus1 and cdc12 did not appear to play any role in cell elongation or actin cable formation. In addition, fluorescence recovery after photobleaching (FRAP) experiments in which we photobleached GFP-Bgs1 signal from the cell tip either in the presence or absence of MBC showed no significant difference in the rate of recovery between wild-type and myo51Δ myo52Δ cells (Figure 1, G and H). Finally, we found that for3a or myo51Δ myo52Δ cells secreted acid phosphatase as efficiently as wild-type cells, suggesting no significant defect in general exocytosis (Figure 1I). Thus cells devoid of cytoskeletal long-range transport are able to polarize vesicles to cell ends, suggesting the existence of an independent pathway for polarized exocytosis.

Actin cables are dispensable for the localization of the exocyst to cell tips
In search of this second pathway, we investigated the localization of the exocyst. In wild-type cells, the exocyst localizes to septum and cell tips (Wang et al., 2002). In for3Δ or myo52Δ cells, the exocyst subunit Sec6-GFP localized to cell ends and septum correctly (Figure 2A). We also imaged Sec8-GFP but discovered that for3a sec8-GFP or myo52A sec8-GFP cells displayed highly aberrant morphologies, suggesting that the Sec8-GFP fusion is not fully functional. However, even in these aberrantly shaped cells, Sec8-GFP localized correctly to identifiable tips and septa (Figure 2A). Further disruption of microtubules with MBC had no effect on either exocyst subunit localization (Supplemental Figure S2). These results suggest that exocyst localization to cell tips is independent of long-range cytoskeletal transport.

To test whether the exocyst was able to actively localize to cell tips in the absence of F-actin, we used for3a cells or wild-type cells treated with latrunculin A (LatA) to disrupt actin cables or all actin structures, respectively, and performed FRAP experiments. In control dimethyl sulfoxide (DMSO)-treated cells and for3Δ cells, Sec6-GFP fluorescence recovered rapidly at cell tips, with a half-time of about 5 s, and efficiently to about 65% of the initial signal (Figure 2, B, D, and E). The amount of signal bleached corresponded to about 25% of the total cellular signal, with a maximum possible recovery of 75%, suggesting a nonexistent or very small immobile fraction. Five minutes after

Volume 22 January 1, 2011 Actin cable and exocyst in fission yeast | 45
LatA addition, Sec6-GFP was still localized at or in the vicinity of cell tips in most cells. After 30 min, Sec6 was still cortical in all cells, and its localization was either polar or displaced from the cell tip toward cell sides (Figure 2C). Upon photobleaching, Sec6-GFP fluorescence recovered with a half-time of about 10 sec, even when it was displaced from cell tips, but only to about 40% of the initial signal (Figure 2, B–D). Thus complete actin depolymerization does not prevent the localization of Sec6 to cell tips but causes a larger immobile fraction. Because complete actin depolymerization disrupts actin patches in addition to cables, and thus endocytosis, one possibility is that the changes observed in Sec6 behavior may be due to endocytic recycling defects. Similarly, Exo70–red fluorescent protein (RFP) localized to cell tips independently of the actin
Loss of both exocyst and actin cables results in failure to polarize growth

The localization of the exocyst at cell tips suggests that it may be involved in polarized exocytosis for polar growth. However, previous genetic examination of exocyst function revealed an essential role for cell division but not polarized growth (Wang et al., 2002). Temperature-sensitive inactivation (sec8-1) or depletion (nmt81-sec8) of Sec8 in haploid cells and sporulation of sec8 deletion from diploids led to arrest of multiseptated, yet elongated, cells. We confirmed this finding by sporulating a double heterozygous mutant sec6Δ/sec6+ sec8Δ/sec8+: Single- or double-deletion mutant spores exhibited the same terminal phenotype of elongated, often septated, cells (Figure 3A). sec8Δ exo70Δ and sec8-1 exo70Δ double-mutant cells showed similar phenotype. Thus in an otherwise wild-type background, the exocyst is not essential for polarized cell growth.

In contrast, when we combined exocyst and actin cable mutants, double-mutant cells were spherical or misshapen, suggesting a failure to properly polarize growth (Figure 3, B and C, and Supplemental Figure S5). This phenotype was observed at 25°C in combinations of for3Δ or myo52Δ with sec8-1, exo70Δ, or sec8 depletion (nmt81-sec8). Double mutants with sec8-1 or exo70Δ also exhibited synthetic lethality or sickness at 25°C, respectively, although these cells could be maintained alive by growth in 1 M sorbitol, which alleviates the temperature-sensitive lethality of sec8-1 single mutants (Martin-Cuadrado et al., 2005). As mentioned above, for3Δ sec8-GFP and myo52Δ sec8-GFP were also sick and formed round and aberrantly shaped cells, suggesting that sec8-GFP represents a mild loss-of-function allele of sec8, which is deleterious for polarized growth in absence of functional actin cables. Finally, a double mutant of profilin cdc3-313 allele and sec8-1 also led to isotropic growth at restrictive temperature, as shown by fluorescent lectin staining (Figure 3D). Thus even mild disruption of the exocyst (sec8-GFP or exo70Δ) in cells devoid of actin cable transport leads to isotropic growth, while more complete disruption of the exocyst in cells with intact cables (sec6Δ sec6Δ, sec8Δ exo70Δ, or sec8-1 exo70Δ) still permits polarized growth.

Exocytic cargoes fail to polarize in the absence of cables and exocyst

We also examined the localization of exocytic vesicles upon Sec8 depletion in wild-type and for3Δ cells using the markers described above. In the nmt-sec8 strain, all three markers localized to cell ends, in agreement with the fact that this strain still polarizes growth (Figure 3, E and F, and unpublished data). However, the markers assumed a distinct appearance from wild-type or for3Δ cells: First, they localized predominantly in the vicinity of cell tips and showed a reduced signal at the cell tip cortex, especially GFP-Syb1. Second, other cellular regions were largely devoid of signal. Similar observations were made in the sec8-1 strain, with the cortical signal decreasing over time at restrictive temperature (Figure 4B and unpublished data). This suggests that in the absence of a functional exocyst, exocytic vesicles accumulate at cell tips, where they are able to fuse, albeit less efficiently than in wild-type cells. This may create a bottleneck in membrane trafficking, leading to gradual accumulation of all vesicles near cell tips.

By contrast, tip accumulation of exocytic vesicles was undetectable when Sec8 was depleted in the for3Δ background (Figure 3, G and H). Instead, large numbers of internal sites were labeled. We also detected weak uniform cortical staining of both Bgs1 and Bgs4 cargoes, but not Syb1, suggesting that vesicles may still inefficiently fuse with the plasma membrane but without spatial constraints. Similarly, cdc3-313 sec8-1 double mutants that had not yet undergone

cytoskeleton (Supplemental Figure S3; Sharifmoghadam et al., 2010). Taken together, our experiments demonstrate that the exocyst can localize to cell tips largely independently of the actin cytoskeleton.

Conversely, we also tested the localization of For3 and Myo52 in exocyst mutants: Both proteins localized normally to cell tips in nmt-sec8 depletion strains (Figure S4). In addition, actin cables formed normally in sec8-1 mutants. Thus actin cables are functional for transport in the absence of a functional exocyst.
visible shape change after 90 min of growth at 36°C mostly lacked tip enrichment of RFP-Bgs4 (see Figure 4B). Residual tip localization was observed in only 21% of cells (n = 103), whereas it was retained in over 74% in wild type and each single mutant. In summary, exocytic cargoes can concentrate to cell tips in absence of either actin cables or exocyst but not in absence of both. Thus actin cables and exocyst provide distinct but partly redundant input for polarized exocytosis.

**Actin cable and exocyst pathways lie downstream of Cdc42**

Because disruption of both actin cables and exocyst leads to isotropic growth, we investigated whether the polarity establishment machinery was compromised in double mutants. To label regions of cell growth, we investigated whether the polarity establishment machinery was largely intact in cells lacking morphogenesis information.

The above results suggest that both actin cables and exocyst may function downstream of Cdc42. We previously showed that For3 localization and activity are controlled by Cdc42 (Martin et al., 2007; Rincon et al., 2009). In cdc42-1625 cells, in which Cdc42 localizes correctly to cell tips (Martin et al., 2007) but displays severely compromised activity, both Sec6-GFP and Sec8-GFP failed to efficiently localize to cell tips (Figure 4C). Similar observations were made in a second cdc42 mutant allele, cdc42-879 (Rincon et al., 2009). Thus both formin and exocyst are under control of Cdc42.

We investigated the localization of active Cdc42 upon actin disruption. Five minutes after LatA addition, CRIB-GFP was still localized at or in the vicinity of cell tips in most cells. After 30 min, CRIB-GFP was still cortical, but its localization was either polar or displaced from the cell tip toward cell sides (Figure 4D). This behavior upon LatA treatment is similar to that of Sec6-GFP. Examination of For3-3GFP localization after 5 and 30 min of LatA treatment also showed initial cell tip localization followed by cortical displacement (Figure 4D; Martin and Chang, 2006). This suggests that active Cdc42 may recruit formin and the exocyst to these ectopic sites.

**Exocyst pathway is dependent on PIP2**

Because all cytoskeletal transport is dispensable for the localization of the exocyst to cell tips, we tested whether it depends on the lipid composition of the membrane. In myo1Δ, a deletion in a type I myosin essential for ergosterol domain organization (Takeda and Chang, 2005), Sec8-GFP was localized correctly to cell tips, suggesting that ergosterol domains do not significantly contribute to the localization of the exocyst (unpublished data). In its3-1 cells, which bear a mutation in the major phosphatidylinositol 4-phosphate 5-kinase and show vastly reduced levels of PIP2 (Zhang et al., 2000), both Sec6-GFP and Sec8-GFP were delocalized from cell tips after 90 min at restrictive temperature (Figure 5A). Careful examination of their localization in single focal sections, however, revealed that they were still cortical but not enriched at tips (unpublished data). In contrast, CRIB-GFP and Myo52-GFP localized correctly to...
DISCUSSION
Polarized exocytosis is fundamental for many cellular processes, including cell morphogenesis. We report here that exocytic vesicle transport along actin cables and tethering by the exocyst—two processes often thought to function sequentially—can sustain cell morphogenesis in the fission yeast independently of each other.

We present multiple lines of evidence to support the conclusion that the actin cable machinery and the exocyst form two autonomous “morphogenetic modules.” First, actin cables polarize independently of the exocyst. Second, the exocyst localizes independently of the cytoskeleton and instead relies on PIP2. Third, the two modules are genetically redundant for cell shape. Finally, the localization of both modules is under control of the small GTPase Cdc42. In contrast, Cdc42 localization and activity are not affected by the disruption of either or both morphogenetic modules, a finding that raises important questions regarding the mechanisms of Cdc42 localization. Together these results define a clear hierarchical organization where Cdc42 establishes a polar landmark, which activates parallel cytoskeleton-dependent and membrane-dependent morphogenetic modules that translate this polar localization in actual polar growth (Figure 6).

Cell morphogenesis in the absence of cytoskeleton-dependent vesicle transport
Cytoskeletal transport, along either microtubules or linear actin filaments, underlies the targeted delivery of cargoes. As such it is thought to play fundamental roles for cell morphogenesis in many cell types. For instance, actin cables are essential to sustain polarized growth through the cell cycle in the budding yeast. Similarly, class II formins and thus the actin structures they assemble are essential for cell morphogenesis in the moss Physcomitrella patens (Vidali et al., 2009). The flagellated protozoan parasite Giardia intestinalis lacks formins altogether (Chalkia et al., 2008) but completely depends on microtubules for cell morphogenesis (Mariante et al., 2005). In contrast, we show that simultaneous disruption of both actin cables and microtubules in fission yeast still permits significant polarized cell growth throughout the cell cycle, indicating the existence of alternative cytoskeleton-independent morphogenesis pathways.

How prevalent are these alternative pathways? Although, to our knowledge, fission yeast is the only organism shown to date to sustain polarized cell growth and survive in absence of cytoskeletal vesicular transport, two recent studies have also suggested the existence of additional actin cable-independent morphogenesis mechanisms in the budding yeast. First, cells exiting from prolonged

FIGURE 4: Cdc42 activity is independent of actin cable and exocyst and is necessary for exocyst localization. (A) CRIB-GFP in wild-type, for3Δ, nmt-sec8, and nmt-sec8 for3Δ cells depleted for Sec8. (B) RFP-Bgs4 (red) and CRIB-GFP (green) in wild-type, cdc3-313, sec8-1, and cdc3-313 sec8-1 cells grown for 90 min at 36°C. (C) Sec6-GFP and Sec8-GFP in wild-type (left panels), cdc42-1625 (middle panels), and cdc42-879 mutant cells. CRIB-GFP in cdc42-1625 mutant is also shown as labeled. (D) Localization of CRIB-GFP and For3-3GFP in wild-type cells treated with LatA for 5 and 30 min. Arrows indicate polar and arrowheads lateral localization of fusion proteins. Bars, 5 μm.
transport–independent pathways contribute to shape cells. Small bud, this nevertheless suggests that alternative cytoskeletal components of the endocytic machinery. Although in neither contrast to the first example, this small bud growth requires growth in the absence of functional formins or tropomyosins but not in the absence of functional myosin V (Yamamoto et al., 2010). Intriguingly, it is unclear whether the fission yeast genome encodes any Sec3 homologue (Wang et al., 2002) and Exo70 is nonessential (Wang et al., 2007; Wu et al., 2010). These may thus represent conserved mechanisms to anchor the exocyst at the plasma membrane. In S. cerevisiae, only two exocyst subunits—Sec3 and Exo70—localize to the bud tip independently of actin cable–mediated transport by directly binding Cdc42 and PIP2 (Zhang et al., 2001, 2008; Boyd et al., 2004; He et al., 2007; Wu et al., 2010). It is therefore unknown whether the specific interaction domains of the exocyst with PIP2 or Cdc42 are conserved.

Exocyst-independent polarized exocytosis

That fission yeast cells can polarize growth until the next cell division in the absence of a functional exocyst raises the question of the mechanisms for exocyst-independent polarized exocytosis. The accumulation of vesicular markers beneath the cell tips in exocyst mutants suggests that polarized exocytosis is much less efficient in this situation. We show that this depends on actin cables and type V myosin. We can envisage two nonexclusive hypotheses. First, exocyst-independent tethering events. The recent observation that budding yeast cells devoid of actin cables, but not of type V myosin, are able to form small buds also suggests the possibility that type V myosin may play an additional transport-independent function in this organism (Yamamoto et al., 2010). Thus the fission yeast model may prove particularly useful in dissecting these exocyst-independent tethering events.

Spatial determinants of exocyst localization

We have shown that in fission yeast, one alternative morphogenetic pathway requires the exocyst, as this complex is essential for polarized growth in the absence of actin cables. This complex thus provides key spatial information to identify the tips as zones of growth. How is the exocyst localized to cell tips? Our live microscopy and FRAP experiments demonstrate that the cytoskeleton is largely dispensable while both the phosphoinositide PIP2 and the small GTPase Cdc42 are required for exocyst accumulation to cell tips. Interestingly, actin cables are not required for tip localization, but complete disruption of F-actin caused a larger fraction of Sec6 to remain at the cortex and, over time, spread laterally. This displacement is also observed for CRIB-GFP, labeling active Cdc42, and For3. One interpretation is that actin patches, and thus endocytosis, participate in the recycling of active Cdc42 off the membrane and may be important for maintaining tip localization. Displaced Cdc42 may remain competent at recruiting formin and the exocyst, suggesting that this small GTPase is a key spatial determinant. The role of the phosphoinositide PIP2 is less clear as it is not apparently polarized in fission yeast (Zhang et al., 2000). However, both Cdc42 and PIP2 may function to link the exocyst with the plasma membrane at cell tips.

Interactions between the exocyst and both PIP2 and Cdc42 or other small GTPases have been shown to mediate cortical attachment to link the exocyst with the plasma membrane at cell tips. The localization of the exocyst, but not of active Cdc42 or Myo52, is dependent on PIP2. (A) Sec6-GFP, Sec8-GFP, CRIB-GFP, and Myo52-3GFP signals in wild-type and its3-1 mutant cells grown at 36°C in EMM for 90 min. (B) its3-1 sec8-1 and its3-1 for3a double-mutant and control cells. Bar, 5 μm.

FIGURE 6: Model for parallel morphogenesis pathways under the control of Cdc42. Cdc42 sets up cell polarity and regulates two parallel morphogenetic modules for polarized cell growth, the formin-dependent actin cable module and the exocyst module, contributing to transport and tethering of exocytic vesicles, respectively. The exocyst is also controlled by PIP2 levels at the plasma membrane. Direct links between Cdc42, PIP2, and the exocyst are as yet unknown.
Parallel or linear organization of morphogenesis modules

Our results indicate that actin cable-mediated transport and the exocyst form two largely independent morphogenesis modules in fission yeast. This contrasts with the budding yeast situation, where, except for the initial formation of small buds mentioned above, both modules are essential for morphogenesis. The composition of both modules appears to be conserved in the two systems, with the possible exception of Sec3. But the mechanism of exocyst localization is distinct: While most exocyst subunits are transported along actin cables in budding yeast (Boyd et al., 2004), exocyst localization has been uncoupled from actin cable transport in fission yeast. This suggests that the two modules are in a parallel configuration in the fission yeast but in a linear relationship in the budding yeast. Thus whereas the modules are likely conserved, the wiring between them is different between the two species.

Are there evolutionary advantages for these distinct wiring designs? These may represent adaptations that underlie diverse cellular morphologies. One can speculate that a linear link between the two modules promotes the transport of exocyst and vesicles through a narrow bud neck and ensures accuracy in the site of vesicle delivery. In contrast, the fission yeast morphology may tolerate a broader zone of vesicle fusion, and a parallel configuration would provide robustness to the system. Given the vast array of cell morphologies in eukaryotes, it will be interesting to test whether distinct wiring of largely identical modules also underlies shape and functional diversity in other cell types.

MATERIALS AND METHODS

Strains, growth conditions, and pharmacological inhibitor

S. pombe strains used in this study are listed in Supplemental Table S1. Standard genetic methods and growth conditions were used. Unless otherwise stated, cells were grown in Edinburgh minimal media (EMM) supplemented with appropriate amino acids (ALU) or YESS at 25°C. Tetrad were germinated in YESS at 25°C, and synthetic lethal strains were imaged directly on this medium. MBC (Sigma, St. Louis, MO) was used at a final concentration of 25 μg/ml from a stock of 2.5 mg/ml in DMSO. A 100x stock solution of Latrunculin A in DMSO (Phillip Crews, UC Santa Cruz) was used at a final concentration of 200 μM. Control experiments with DMSO alone had no effect on polarized growth or GFP fusion protein localization.

For construction of sec6::nat and exo70::nat mutants, a PCR-based approach was used with plasmid pFA6a-NatMX6 and oligos with homology to 78 nt directly upstream of the start codon and 78 nt downstream the stop codon. Strains were confirmed by diagnostic PCR for both sides of the gene replacements.

For depletion of Sec8 from the nmt-sec8 strain, precultures were grown in EMM lacking thiamine and diluted for 20 h in either YESS, which naturally contains thiamine, or EMM supplemented with increasing amounts of thiamine. We experimentally determined the best concentration of thiamine to use (Supplemental Figure S4). Strong depletion of Sec8 with 5 μg/ml thiamine led to the rapid appearance of the multiseptated phenotype, which probably masked the role of Sec8 in polarized cell growth in the for3Δ background. In contrast, milder depletion of Sec8 with lower concentration of thiamine permitted cell division to proceed for a longer time and led to formation of round cells in the for3Δ background. We thus routinely used 0.25 μl/ml thiamine grown for 20 h for Sec8 depletion.

Microscopy

Microscopy was performed with either a spinning disk confocal microscope or a wide-field fluorescence microscope, essentially as described (Martin and Berthelot-Grosjean, 2009). Stacks of Z-series confocal sections were acquired at 0.3-μm intervals with either UltraVIEW or Velocity (PerkinElmer, Waltham, MA) software. All images of GFP, RFP, and phallolidin fluorescence are two-dimensional maximum-intensity projections of Z-series slices. For3-3GFP images in Figure 4D were acquired as described previously (Martin and Chang, 2006). All differential interference contrast, lectin, and calcofluor imaging was done by wide-field microscopy acquired with the Leica AS AF software (Leica MicroSystems, Bannockburn, IL). Figures were prepared with ImageJ 1.41 and Adobe Photoshop Elements 6.

FRAP experiments were performed with the Photokinesis module attachment for the spinning disk confocal microscope (PerkinElmer). Photobleaching was accomplished by applying 488-nm laser to cell tips or side wall. Images were acquired before photobleaching, immediately after, and subsequently at regular intervals. For FRAP analysis of Sec6-GFP, cells were overlaid on a 2% agarose EMM-ALU pad made with DMSO or LatA, sealed with VALAP, and imaged within 5 min. For GFP-Bgs1 FRAP, cells were incubated with DMSO or MBC for 30 min before imaging on glass slides. Analysis of FRAP was done as described previously (Martin and Chang, 2006).

Imaging of cells at 36°C (Figures 4B and 5A) was performed with an objective heater and Delta T specimen warming dish from Biotech (Butler, PA). Cells were adhered to Delta T dishes with equal volume of 100 μg/ml lectin (Bandeirea simplicifolia; Sigma) washed with and grown in EMM. All other imaging was done at room temperature (23°C).

Fluorescent lectin and actin staining

Cells were grown overnight in EMM at 25°C to log phase and stained with 5 μg/ml tetramethylrhodamine B isothiocyanate (TRITC)-lectin (stock of 5 mg/ml in dH2O, Sigma) for 10 min. Cells were then washed twice and resuspended in EMM. Cells were then diluted to OD600 = 0.2 in EMM and grown for 6 h before staining with calcofluor white from 200× stock (2 mg/ml in 100 mM Tris-HCl, pH 9.0). Actin staining was performed as described (Martin et al., 2005).

Measurement of acid phosphatase secretion

Acid phosphatase was assayed as previously described with minor modifications (Wang et al., 2002). Cells were grown overnight to OD600 = 0.6 to 0.8 in EMM at 25°C and washed twice with EMM. Cells were then diluted to OD600 = 0.3, and 500 μl was removed and designated 0 h. The 500-μl aliquot was centrifuged, and 350 μl of the supernatant was added to 350 μl of 2 mM p-nitrophenyl phosphate, 0.1 M sodium acetate, pH 4.1, prewarmed to 30°C. Reactions were incubated at 30°C for 10 min and then stopped by the addition of 350 μl 1 M NaOH. This was repeated every hour for each strain. Absorbance was read at 405 nm, and values were normalized by subtracting the value at 0 h.

ACKNOWLEDGMENTS

We thank M. Balasubramanian, M. Edamatsu, T. Kuno, H. Valdivieso, and J.C. Ribas for yeast strains; L. Lo Presti for strain generation; and R. Benton, N. Geldner, and members of S.G.M.’s laboratory for discussions and comments on the manuscript. F.O.B. was supported by a National Science Foundation postdoctoral fellowship (DBS2905). Research in the laboratory of S.G.M. is supported by a Swiss National Science Foundation Professorship grant (PP00A-114936) and a Human Frontiers Science Program Career Development Award (CDA0016/2008).
REFERENCES

Ayscough KR, Stryker J, Pokala N, Sanders M, Crews P, Drubin DG (1997). High rates of actin filament turnover in budding yeast and roles for actin in establishment and maintenance of cell polarity revealed using the actin inhibitor latrunculin-A. J Cell Biol 137, 399–416.

Balasubramanian MK, Helfman DM, Hemmingsen SM (1992). A new tropomyosin essential for cytokinesis in the fusogenic yeast S. pombe. Nature 360, 84–87.

Balasubramanian MK, Hirani BR, Burke JD, Gould KL (1994). The exocyst complex in fission yeast, is a component of the cell division ring and interacts with profilin. J Cell Biol 137, 169–182.

Cortes JC, Camero E, Ishiguro J, Sanchez Y, Duran A, Ribas JC (2005). Sec3p is a spatial landmark for myosin essential for cytokinesis in the fission yeast. Curr Biol 15, 6483–6494.

Deb S, Guo W (2009). The exocyst complex in polarized exocytosis. Curr Biol 19, 501–515.

Finger FP, Hughes TE, Novick P (1998). Sec3p is a spatial landmark for myosin essential for cytokinesis in fission yeast, is a component of the cell division ring and interacts with profilin. J Cell Biol 137, 169–182.

Cortes JC, Camero E, Ishiguro J, Sanchez Y, Duran A, Ribas JC (2005). Sec3p is a spatial landmark for myosin essential for cytokinesis in the fission yeast. Curr Biol 15, 6483–6494.

Cortes JC, Ishiguro J, Duran A, Ribas JC (2002). Localization of the (1,3)β-D-glucan synthase catalytic subunit Bgs4p is essential during both cytokinesis and polarized growth. J Cell Sci 115, 157–174.

Cortes JC, Ishiguro J, Duran A, Ribas JC (2002). Localization of the (1,3)β-D-glucan synthase catalytic subunit homologue Bgs1p/Cps1p from fission yeast suggests that it is involved in septation, polarized growth, mating, spore wall formation and spore germination. J Cell Sci 115, 4081–4096.

Desnos C, Huet S, Fang et al. (2007). Myosin Va mediates docking of secretory granules at the plasma membrane. J Neurosci 27, 10636–10645.

Dong Y, Pruneau D, Bretscher A (2003). Formin-dependent actin assembly is regulated by distinct modes of Rho signaling in yeast. J Cell Biol 161, 1081–1092.

Edamatsu M, Toyoshima YY (2003). Fission yeast synaptobrevin is involved in polarized growth and organelle segregation in yeast. Annu Rev Cell Dev Biol 20, 559–591.

Pruneau DW, Schott DH, Bretscher A (1998). Tropomyosin-containing actin cables direct the Myo2p-dependent polarized delivery of secretory vesicles in budding yeast. J Cell Biol 143, 1931–1945.

Rincon SA, Ye Y, Villar-Tajadura MA, Santos B, Martin SG, Perez P (2009). Pob1 participates in the Cdc42 regulation of fission yeast actin cytoskeleton. Mol Biol Cell 20, 4390–4399.

Roumanie O, Wu H, Molk JN, Rossi G, Bloom K, Brenwald P (2005). Exocyst complex in fission yeast is required for actin organization and membrane trafficking. J Cell Biol 170, 583–594.

Sahin A, Daignan-Fornier B, Sagot I (2008). Polarized growth in the absence of F-actin in Schizosaccharomyces pombe. Cell Motil Cytoskeleton 63, 149–161.

Martin SG, Berhelot-Grosjean M (2009). Polar gradients of the DYRK-family kinase Pdm1 couple cell length with the cell cycle. Nature 459, 852–856.

Martin SG, Chang F (2006). Dynamics of the formin for3p in actin cable assembly. Curr Biol 16, 1161–1170.

Martin SG, McDonald WH, Yates JR III, Chang F (2005). Teap4 links microtubule plus ends with the formin for3p in the establishment of cell polarity. Dev Cell 8, 479–491.

Martin SG, Rincon SA, Basu R, Perez P, Chang F (2007). Regulation of the formin for3p by cdc42p and bud4p. Mol Biol Cell 18, 4155–4167.

Martin-Cuadrado AB, Konomi M, Antia S, Osumi M, Balasubramanian M, Gould KL, Del Rey F, de Aldana CR (2005). Role of septins and the exocyst complex in the function of hydrolytic enzymes responsible for fission yeast cell separation. Mol Biol Cell 16, 4867–4881.

Motepe F, Arai R, Mabuchi I (2001). Identification of two type V myosins in fission yeast, one of which functions in polarized cell growth and moves rapidly in the cell. Mol Biol Cell 12, 1367–1380.

Mulvihill DP, Edwards SR, Hyams JS (2006). A critical role for the type V myosin, Myo52, in septation deposition and fission cytokinesis in Schizosaccharomyces pombe. Cell Motil Cytoskeleton 63, 149–161.

Murphy M, Garza D, Scheller RH, Schwarz TL (2003). Mutations in the exocyst component Sec5 disrupt neuronal membrane traffic, but not neurotransmitter release persists. Neuron 37, 433–447.

Nakano K, Imai J, Arai R, Toh EA, Matsu S, Mabuchi I (2002). The small GTPase Rho3 and the diaphanous/formin For3 function in polarized cell growth in fission yeast. J Cell Sci 115, 4629–4639.

Petersen J, Weilguny D, Egel R, Nielsen O (1995). Characterization of fus1p of Schizosaccharomyces pombe: a developmentally controlled function needed for conjugation. Mol Cell Biol 15, 3068–3077.

Pruneau D, Lefebvre Miller A, Gao L, Dong Y, Bretscher A (2004). Mechanisms of polarized growth and organelle segregation in yeast. Annu Rev Cell Dev Biol 20, 559–591.

Pruneau DW, Schott DH, Bretscher A (1998). Tropomyosin-containing actin cables direct the Myo2p-dependent polarized delivery of secretory vesicles in budding yeast. J Cell Biol 143, 1931–1945.

Rincon SA, Ye Y, Villar-Tajadura MA, Santos B, Martin SG, Perez P (2009). Pob1 participates in the Cdc42 regulation of fission yeast actin cytoskeleton. Mol Biol Cell 20, 4390–4399.

Roumanie O, Wu H, Molk JN, Rossi G, Bloom K, Brenwald P (2005). Rho GTPase regulation of exocytosis in yeast is independent of GTP hydrolysis and polarization of the exocyst complex. J Cell Biol 170, 582–594.

Sahin A, Daignan-Fornier B, Sagot I (2008). Polarized growth in the absence of F-actin in Schizosaccharomyces cerevisiae: a key role for the exocyst. PLoS One 3, e2556.

Sharifmoghadam MR, de Leon N, Hoya M, Curto MA, Valdivieso MH (2010). Different steps of sexual development are differentially regulated by the Sec63p and Exo70p exocyst subunits. FEBS Lett 580, 71–80.

Sudhoff TC, Rothman JE (2009). Membrane fusion: grappling with SNARE and SM proteins. Science 323, 474–477.

Takeda T, Chang F (2005). Role of fission yeast myosin I in organization of the actin stress-fiber-like networks in the cell. J Mol Biol 351, 326–337.

Tatebe H, Nakano K, Maximo R, Shizaki K (2008). Ppm1p DYRK regulates localization of the Rga4 GAP to ensure bipolar activation of Cdc42 in fission yeast. Curr Biol 18, 322–330.

TerBush DR, Maurice T, Rath D, Novick P (1996). The exocyst is a multi-protein complex required for exocytosis in Saccharomyces cerevisiae. EMBO J 15, 6483–6494.

Vidali L, van Gisbergen PA, Guerin C, Franco P, Li M, Burkart GM, Augustine RC, Blanchion L, Bezanilla M (2009). Rapid formin-mediated actin filament elongation is essential for polarized plant cell growth. Proc Natl Acad Sci USA 106, 13341–13346.

Wang H, Tang X, Liu J, Trautmann S, Balasundaram D, McCollum D, Balasubramanian MK (2002). The exocyst complex is essential for cell separation in Schizosaccharomyces pombe. Mol Biol Cell 13, 515–529.
Zhang X, Bi E, Novick P, Du L, Kozminska KG, Lipschutz JH, Guo W (2001). Cdc42 interacts with the exocyst and regulates polarized secretion. J Biol Chem 276, 46745–46750.

Zhang X, Orlando K, He B, Xi F, Zhang J, Zajac A, Guo W (2008). Membrane association and functional regulation of Sec3 by phospholipids and Cdc42. J Cell Biol 180, 145–158.

Zhang X, Zajac A, Zhang J, Wang P, Li M, Murray J, TerBush D, Guo W (2005). The critical role of Exo84p in the organization and polarized localization of the exocyst complex. J Biol Chem 280, 20356–20364.

Yamamoto T, Mochida J, Kadota J, Takeda M, Bi E, Tanaka K (2010). Initial polarized bud growth by endocytic recycling in the absence of actin cable-dependent vesicle transport in yeast. Mol Biol Cell 21, 1237–1252.

Zajac A, Sun X, Zhang J, Guo W (2005). Cyclical regulation of the exocyst and cell polarity determinants for polarized cell growth. Mol Biol Cell 16, 1500–1512.

Win TZ, Gachet Y, Mulvihill DP, May KM, Hyams JS (2001). Two type V myosins with non-overlapping functions in the fission yeast Schizosaccharomyces pombe: Myo52 is concerned with growth polarity and cytokinesis, Myo51 is a component of the cytokinetic actin ring. J Cell Sci 114, 69–79.

Wu H, Turner C, Gardner J, Temple B, Brennwald P (2010). The exo70 subunit of the exocyst is an effector for both cdc42 and rho3 function in polarized exocytosis. Mol Biol Cell 21, 430–442.

Yamamoto T, Mochida J, Kadota J, Takeda M, Bi E, Tanaka K (2010). Initial polarized bud growth by endocytic recycling in the absence of actin cable-dependent vesicle transport in yeast. Mol Biol Cell 21, 1237–1252.

Zajac A, Sun X, Zhang J, Guo W (2005). Cyclical regulation of the exocyst and cell polarity determinants for polarized cell growth. Mol Biol Cell 16, 1500–1512.

Zhang X, Bi E, Novick P, Du L, Kozminska KG, Lipschutz JH, Guo W (2001). Cdc42 interacts with the exocyst and regulates polarized secretion. J Biol Chem 276, 46745–46750.

Zhang X, Orlando K, He B, Xi F, Zhang J, Zajac A, Guo W (2008). Membrane association and functional regulation of Sec3 by phospholipids and Cdc42. J Cell Biol 180, 145–158.

Zhang X, Zajac A, Zhang J, Wang P, Li M, Murray J, TerBush D, Guo W (2005). The critical role of Exo84p in the organization and polarized localization of the exocyst complex. J Biol Chem 280, 20356–20364.

Zhang Y, Sugiura R, Lu Y, Asami M, Maeda T, Itoh T, Takenawa T, Shunoh H, Kuno T (2000). Phosphatidylinositol 4-phosphate 5-kinase Its3 and calcineurin Ppb1 coordinately regulate cytokinesis in fission yeast. J Biol Chem 275, 35600–35606.