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Review

Dynamin and Cytokinesis

Catherine A. Konopka[1], Justin B. Schleede[2], Ahna R. Skop[2]* and Sebastian Y. Bednarek[1]*

[1]*Department of Biochemistry and Program in Cellular and Molecular Biology, University of Wisconsin – Madison, Madison, WI 53706, USA*
[2]*Department of Genetics and Medical Genetics, University of Wisconsin – Madison, Madison, WI 53706, USA*
**Corresponding author: Ahna R. Skop, skop@wisc.edu; Sebastian Y. Bednarek, bednarek@biochem.wisc.edu*

Animal and plant cytokineses appear morphologically distinct. Recent studies, however, have revealed that these cellular processes have many things in common, including the requirement of co-ordinated membrane trafficking and cytoskeletal dynamics. At the intersection of these two processes are the members of the dynamin family of ubiquitous eukaryotic GTPases. In this review, we highlight the conserved contribution of classical dynamin and dynamin-related proteins during cytokinesis in both animal and plant systems.

Key words: cell division, cell plate, cytokinesis, dynamin, mitosis, membrane trafficking

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Cytokinesis is the final stage of the cell cycle in which a single cell is physically separated into individual daughter cells. In eukaryotes, this process leads to the division and partitioning of chromatin, organelles, cytoplasmic components and the construction of new membrane between daughter cells. Animal cells divide by constricting plasma membrane and targeting membrane along the newly formed cleavage furrow. The cleavage furrow compacts and bundles the microtubules (MTs) found in the spindle midzone into a structure called the midbody (1). On the other hand, cells of higher plants divide by constructing a unique cytoskeletal apparatus, the phragmoplast, across the division plane and targeting new plasma membrane and cell wall components to the center of the cell creating an intermediate membranous network called the cell plate (2). It has long been thought that the mechanisms of cytokinesis in animals and plants were quite different. Recent work, however, has uncovered highly conserved roles for several membrane trafficking and cytoskeletal-associated proteins in these seemingly different modes of cytokinesis (1). Dynamin and dynamin-related proteins have been shown to play essential roles in cell division in plants (3), animals (4,5) and the protist, *Dictyostelium discoideum* (6). The phylogenetic relationship of *Dictyostelium* to plant and animal species (7) likely suggests that there is an ancestral role for dynamin in cytokinesis. In this review, we highlight several studies that suggest that dynamin and dynamin-related proteins (DRPs) have conserved functions in a variety of cell division events.

Animal Cytokinesis

Animal cells require the orchestration of both the cytoskeletal and membrane trafficking machinery to complete cytokinesis (8,9). Animal cells rely on the mitotic spindle to specify the position of the cleavage plane (10). The mitotic spindle contains two populations of MTs, asters and the spindle midzone, both of which have been implicated in specifying the position of the cleavage furrow (11,12). As animal cells enter into mitosis, various processes lead to the disassembly of the Golgi (16) and the release of Golgi associated proteins, including myosin II and Cdc42. Once the cleavage furrow is specified, the actin-based contractile ring assembles on the inner surface of the plasma membrane. Ring assembly is mediated by the formins and profilins that act to initiate actin filament formation (13), whereas Cdc42, a highly conserved Rho-type small GTPase, is involved in actin ring organization (14). Non-muscle myosin II drives the constriction of the contractile ring and subsequent ingression of the plasma membrane results in the formation of a cleavage furrow (15).

Membrane trafficking pathways regulate the addition of new membrane along the ingressing cleavage furrow (8), which culminates with the compression of the spindle midzone into a protein-rich structure called the midbody. Using FM1-43, a fluorescent, styryl dye, local membrane accumulation at the late furrow apices has been observed in both *Caenorhabditis elegans* and *Xenopus* embryos (17,18). Membrane trafficking to the cleavage furrow is sensitive to Brefeldin A (18,19) and is likely mediated by MTs found in the midzone or along the furrow cortex (17). These data suggest that the local accumulation of membrane is required to separate daughter cells. Endocytosis and membrane recycling are also crucial to cytokinesis, as drugs that inhibit endocytosis, such as chlorpromazine or methyl-beta-cyclodextrin (20), block daughter cell separation. Proteins such as clathrin, syntaxin, endobrevin and dynamin II/DYN-1 are also thought to play an integral role in furrow-specific endocytosis and fusion events during

daughter cell separation (8,21). Golgi and Endoplasmic Reticulum (ER) membranes also concentrate along the spindle midzone MTs and within the midbody during late telophase (4,22,23), suggesting that the interaction of these organelles and associated proteins may play a significant role during cytokinesis.

Plant Cytokinesis

Plants also co-ordinate cytoskeletal and membrane trafficking machinery to initiate and complete cytokinesis. Cytokinesis in pollen, somatic cells and endosperm syncytia has been visualized in detail and appears morphologically similar in many respects (24–27). During late anaphase in somatic cells, the phragmoplast, a plant-specific cytoskeletal array, composed of interdigitating MTs and actin microfilaments, is formed from the remnants of the spindle. MTs within the barrel-like phragmoplast are organized with their plus ends oriented toward the division plane. The cell plate is presumed to form from Golgi-derived vesicles carrying membrane, protein and cell wall precursors that are transported along MTs to the division plane where they fuse (26). Multiple rounds of vesicle fusion occur until a tubular-vesicular network (TVN) is formed. The polysaccharide 1,3-β-glucan (callose) is synthesized and deposited in the lumen of the tubules at the end of this stage by callose synthases, which are delivered by Golgi-derived vesicles (28). Spreading of the callose deposits is thought to increase the volume of the TVN (24,26), causing it to flatten into a more planar structure (26). The TVN continues to grow outward as the central region of the cell plate matures into a tubular network (TN) and then a fenestrated sheet (FS) as more membrane and callose are deposited at the cell plate. Callose synthesis decreases and the synthesis of the major cell wall polysaccharide 1,4-β-glucan (cellulose) increases (26), as the TVN–TN–FS maturation continues outward toward the parental plasma membrane. The completed membrane system then fuses with the parental plasma membrane separating the two daughter cells. A few components of the molecular fusion machinery required for cytokinesis in plants have been identified. Genetic and biochemical studies have demonstrated that KNOLLE, a syntaxin (29), KUELE, a Sec1 protein (30), SNAP33, a t-SNARE (31), and NSPNII, a v-SNARE (32) interact to promote cell plate vesicle and tubule fusion. KNOLLE, SNAP33 and NSPNII have been localized to the division plane (31–33), and mutant plants deficient in KNOLLE and SNAP33 have characteristic cytokinetic defects with cell wall stubs and large multinucleate cells (29–31,34).

Actin dynamics also plays a significant role in plant cytokinesis (1). Microinjection of profilin causes a delay or an abortion of cytokinesis (35), and an *Arabidopsis* mutant lacking the formin FH5 has cellularization defects in the endosperm (36). It is thought that an actin–myosin-dependent process directs the growing cell plate to the cortical division site on the parental plasma membrane (37).

Similar to the process of vesicle trafficking to the plasma membrane, bi-directional membrane trafficking processes must be functional for cell plate formation to progress. It has been estimated that 70% of the membrane that is transported to the growing cell plate is removed during the process of cytokinesis (24). Morphological evidence suggests that the excess membrane is recycled by clathrin-dependent endocytosis (27). In tobacco-cultured cells and *Arabidopsis* meristematic cells, clathrin-coated structures and multivesicular bodies were seen during the TVN and FS stages, respectively (26,27). However, the process of membrane recycling during earlier stages of cell plate formation remains to be defined.

The Dynamin Superfamily

The dynamin superfamily, which is composed of conventional dynamin and DRPs, is conserved throughout eukaryotes. Dynamin I was originally identified as MT-binding protein (38), and since then, a number of dynamin and DRPs have been implicated in various processes such as endocytosis, actin nucleation and dynamics, mitochondrial and chloroplast biogenesis and cytokinesis (39). Despite the participation of dynamin in such broad activities, *in vitro* studies have characterized the ability of dynamin to bind directly to lipids, oligomerize into spiral structures around lipid bilayers, modulate lipid bilayers into narrow tubules and fragment the tubules in a GTPase-dependent manner (40). The domain structure of all dynamins consists of an N-terminal GTPase domain, a conserved middle domain and a C-terminal GTPase effector domain (GED) (Figure 1). The interaction of the three conserved domains allows for the oligomerization of dynamin (41). Subsequent GTP hydrolysis causes a conformational change of the dynamin rings and spirals (42). Most dynamins contain additional domains, which may account for the great diversity of cellular activities (43). For instance, mammalian dynamins I, II and III contain a plexstrin homology (PH) domain, which allows for phospholipid binding and a proline-rich domain (PRD) that interacts with the SRC-Homology-3 (SH3) domains of various proteins (43).

Plants have homologs to most dynamin and DRPs (Figure 1) found in animals [see (44) for dynamin nomenclature in plants]. *Arabidopsis* DRP2A and DRP2B are most similar in domain structure to dynamins I and II from mammals and are involved in vesicular trafficking from the Golgi to the vacuole (45). Plants also have a specific dynamin subfamily (DRP1). *Arabidopsis* has five genes that encode DRP1 isoforms A–E, three of which appear to have roles in cytokinesis and polar cell growth (3,46). Budding yeast has three DRPs, of which one, Vps1p, functions in actin dynamics and vacuolar fusion (47,48). It is not

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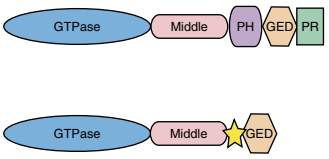

Domain structure	Name	Organism	Other cellular functions
	Dynamin II	*H. sapians*	Actin dynamics; endocytosis, membrane trafficking
	DYN-1	*C. elegans*	Membrane trafficking
	DRP2	*A. thaliana*	Golgi to vacuole transport
	Shibire	*D. melanogaster*	Clathrin-dependent endocytosis
	DymA	*D. discoideum*	Membrane trafficking
	DRP1	*A. thaliana*	Polar cell expansion
	Vps1	*S. cerevisae*	Actin dynamics; vacuolar fusion
	Vps1	*S. cerevisae*	Unknown

Figure 1: Domain structure of cytokinesis-associated dynamins. Listed are dynamins that have putative roles during cytokinesis along with their domain structure and other cellular functions. All dynamins contain an N-terminal GTPase domain followed by a conserved middle region and a C-terminal GTPase effector domain (GED). The region between the middle and GED domains has low homology within the superfamily, ranging from a large defined plexstrin homology (PH) domain in *bona fide* dynamins to a 25–50 undefined amino acid stretch in DRP1 and Vps1 (yellow star). Domains are represented by different shapes and colors. PR = proline rich. See References in text.

known whether Vps1p participates in cytokinesis; however, with its dual role in actin and membrane dynamics, a function in cytokinesis is likely.

Cellular Roles of Animal Dynamin

Membrane trafficking and endocytosis

Dynamin's best-defined role is its involvement in clathrin-mediated endocytosis in mammalian cells (49–51). Dynamin was first identified as having a role in endocytosis when it was shown to be the mammalian homolog of the Shibire protein in *Drosophila* (52). Initial analysis indicated that a temperature shift in *shibire-ts* animals gave rise to a rapid and reversible paralysis and accumulation of clathrin-coated pits at the plasma membrane (52–54). The necks of the coated pits were decorated with electron-dense collars composed primarily of dynamin. Subsequently, purified dynamin was shown to self-assemble into rings and spirals in low ionic strength buffers (55). The self-assembly of dynamin around the necks of coated pits and other lipid bilayers also stimulates its GTPase activity promoting its function as a mechanoenzyme during the late stages of scission (56–59). Besides its membrane fission activity, dynamin also promotes membrane remodeling through a direct interaction with acidic phospholipids such as $PI(4,5)P_2$ and the lipid bilayer via the PH domain. Interaction with acidic phospholipids also directly stimulates GTPase activity (59,60).

Over the last decade and a half, dynamin has been implicated in numerous membrane trafficking events including phagocytosis (61), trafficking to/from late endosomes and *trans*-Golgi membranes (62–65) and endocytic mediated pathogen entry into human cells (66). Despite this large amount of work, very little is known about the *in vivo* function of dynamin during mitosis. In addition, it remains to be determined whether dynamin-dependent endocytosis during cytokinesis uses well-characterized mechanisms such as cytoskeleton clathrin-mediated endocytosis or whether undiscovered processes facilitate the rapid membrane recycling that is needed for cleavage furrow ingression. It is attractive to speculate that dynamin might participate in multiple membrane trafficking events during mitosis, either along the cleavage furrow or during late cytokinesis events. It is also likely that dynamin's function in mitosis is dependent on its interaction with multiple cytoskeletal structures.

Actin nucleation

Dynamin plays a significant role in regulating actin assembly and organization via an interaction between F-actin-containing structures and the PRD domain (67). Dynamin, for example, can regulate actin reorganization via its interaction with cortactin and the Arp2/3 complex (68). Dynamin also interacts directly with two scaffolding proteins Intersectin-1 and Tuba that have been proposed to link dynamin with the actin cytoskeleton (69,70). Both Intersectin-1 and Tuba contain specific domains that catalyze Cdc42 guanine nucleotide exchange. Cdc42 has been implicated in a number of biological processes such as cytokinesis, cell polarity, actin polymerization and endocytosis (71). Most notably, in *Xenopus* embryos, inhibition or constitutive activation of the GTPase activity of Cdc42 inhibited furrow ingression (72). Lastly, profilins are small actin-binding proteins that regulate actin assembly and dynamics during a variety of cellular processes specifically cell motility, membrane trafficking and cytokinesis (73,74). In mouse brain extracts, profilin I and profilin II bound to a number of proteins required for actin assembly and endocytosis, including dynamin I, clathrin and synapsin (75). Interestingly, profilins were shown to co-localize with dynamin I and synapsin in axonal and dendritic processes (75). The *Drosophila* profilin homolog *chickadee* and the *C. elegans* homolog *pfn-1* are required for the stable maintenance of myosin II at the cleavage furrow, and protein depletion results in multinucleated cells (76,77).

Actin is one of the major constituents of the contractile ring in dividing animal cells, yet little is known about how this structure is established. Given recent data, one possibility is that dynamin regulates furrow-specific actin polymerization via interaction with profilin, whereas another possibility is that dynamin interacts with Intersectin-1 and

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Tuba to regulate Cdc42-specific GTPase activity and actin polymerization associated with the cell cycle. The dynamin –cortactin–Arp2/3 complex may also play a crucial role in remodeling cortical microfilaments outside the cleavage furrow. Future work will shed light on these interesting possibilities.

MT dynamics

Dynamin was originally identified as an MT-binding protein (38); however, there is very little evidence that dynamin and MTs interact *in vivo* (78). Recent proteomic analyses of mammalian midbodies show significant enrichment for dynamin II, whereas electron microscopy experiments localize dynamin II along MTs in the spindle midzone and midbody (4,5), suggesting that the dynamin and tubulin interaction might be significant. In rat hepatocytes, distinct labeling of dynamin is observed during metaphase along the mitotic spindle (Figure 2, blue) (5). Localization is enhanced at the spindle midzone during the transition from early to late anaphase. At the end of telophase, dynamin II localizes into two distinct areas within the intercellular bridge on each side of the midbody matrix (5). Experiments using glutathione *S*-transferase-tagged dynamin II identified a protein complex containing actin, alpha-tubulin and gamma-tubulin from rat liver homogenate. Further analysis revealed that gamma-tubulin and dynamin II interact directly (79). Dynamin II localized to the pericentriolar material and centrioles (Figure 2, blue), and the reduction of dynamin II by siRNAi displayed defects in centrosome splitting, suggesting a novel role for dynamin II in centrosome cohesion (79). Dynamin is likely to be involved in the regulation of MT dynamics during cell division, but the mechanisms have yet to be elucidated.

One possibility is that dynamin is required to stabilize and prevent the collapse of the spindle midzone by bundling MTs. Another possibility is that dynamin mediates and stabilizes interactions between MTs, actin and the plasma membrane at the end of telophase. Dynamin is also likely to participate in membrane fission and fusion events that facilitate the separation of the two daughter cells. The ability to interact with the cytoskeleton and the plasma membrane during the late stages of cytokinesis bestows dynamin with the potential to mediate signals to and from the cell surface to and from the spindle.

Dynamin Is Required for Cytokinesis in Animal Cells

Dynamin localizes to cleavage furrow membranes and is required for cytokinesis in a number of organisms (5,6,20,80). The *Drosophila* dynamin homolog, *Shibire*, localizes to the sites of membrane invagination while mutations in the GTPase domain disrupt cellularization, an alternate form of cytokinesis in which the cleavage furrow does not complete (80). Like its *Drosophila* counterpart, the *C. elegans* dynamin homolog, *dyn-1-ts*, was isolated in a mutagenesis screen designed to identify genes required for synapse function (81). When shifted to the restrictive temperature, animals displayed a rapid and reversible locomotion defect as well as increased embryonic lethality and sterility (81). Analysis of the *C. elegans*, *dyn-1-ts* embryos revealed late cytokinesis failures in which the furrow ingressed but failed to complete cell division. The *dyn-1-ts* mutants also displayed cellularization defects in the hermaphrodite germline similar to

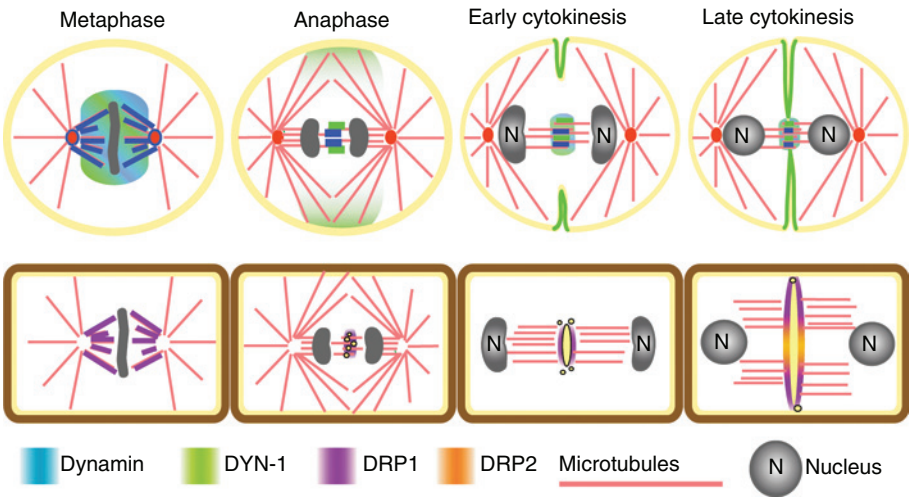

Figure 2: Localization of dynamin and dynamin-related proteins (DRPs) during mitosis and cytokinesis. Dynamin and DRPs have functional roles throughout the cell cycle but relocalize during mitosis and cytokinesis. In each stage above, the localization of dynamin is presented. In the case of animal cells, the localization was demonstrated by immunofluorescence microscopy (5). The localization of dynamin and DYN-1 differs. Both are found on microtubules, around the chromatin at metaphase and in the midbody in late cytokinesis. However, only DYN-1 is on the ingressing furrow and at the equitorial cortex. In plant cells, DRP1A–DRP1C were found at the cell plate by immunofluorescence and live-cell fluorescence microscopy (3,46,82,84,88) and DRP1A-positive rings were imaged with high-resolution electron tomography (24). DRP2 was localized using live-cell fluorescence microscopy (84).

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defects observed in *Drosophila* embryos (5,80). DYN-1 localization is similar to mammalian dynamin II both during metaphase and at the midbody prior to cell separation (Figure 2, green and blue). Interestingly, DYN-1 localization shifts in anaphase from the metaphase plate to the equatorial cortex and then specifically to the areas of new membrane formation along the cleavage furrow (Figure 2, green) (5). The work presented in both *Drosophila* and *C. elegans* embryos suggests that dynamin is involved in membrane trafficking during both phases of cytokinesis. How dynamin regulates these events is unclear, but future work will likely uncover a significant role for dynamin during furrow ingression and completion.

DRPs Are Required for Plant Cytokinesis

The soybean DRP1 homolog, phragmoplastin, was the first dynamin shown to be involved in cytokinesis in any organism (82,83). Subsequent work in the model plant *Arabidopsis* revealed two subfamilies of dynamins that localize to the division plane during cytokinesis. DRP2A, which is most closely related to mammalian dynamin I (Figure 1), localizes to the cell plate when expressed in dividing tobacco suspension-cultured cells (Figure 2, orange) (84). Of the two isoforms of DRP2, DRP2A has been studied more extensively. DRP2A is thought to be involved in clathrin-dependent (85) trafficking of vesicles between the *trans*-Golgi network and the vacuole (45). Although DRP2A does not seem to be required for trafficking vesicles to the plasma membrane (45), this does not rule out a possible role in cell plate membrane trafficking. One possible role of DRP2 at the cell plate is recycling of membrane via clathrin-dependent endocytosis during the formation of the TVN, TN and FS.

The function of the plant-specific DRP1 subfamily in cytokinesis has been studied in more detail than DRP2. Members of the DRP1 subfamily are very early markers of the cell plate, appearing at the division plane prior to TVN establishment (Figure 2, violet) (3,84). Live-cell imaging of DRP1A-GFP in roots and leaves indicates that DRP1A localizes to the cell plate before nuclear reassembly (3). In tobacco suspension-cultured cells, GFP-tagged DRP1A and DRP1C also localized to the spindle and phragmoplast (Figure 2, violet) (84); however, localization to these structures has not been observed in other cell types by immunofluorescence microscopy and in cells expressing DRP1-GFP under native conditions (3,46). As the cell plate grows toward the parental plasma membrane, soybean DRP1 and GFP-tagged DRP1A, DRP1C and DRP1E are most strongly associated with the leading edge of the structure, but the proteins also remain associated, albeit at lower levels, with the mature regions of the cell plate (Figure 2, violet) (3,83,84). These localization studies suggest that DRP1s function at several stages of cytokinesis, including the early phases of cell plate formation.

The presence of cell plate-associated dynamin-like proteins has also been observed using high-resolution electron tomography and immunoelectron microscopy (24,27). In syncytial-type cell plates, DRP1A-positive rings are present at sites of tubule constriction where fused vesicles and tubules form dumbbell shapes (24). The tubules in the TVN are initially 50 nm in diameter and, once constricted, are only 20 nm in diameter (24). If DRP1A is involved in generating the constrictions, then DRP1A may not be operating via the canonical dynamin action cycle in which dynamin I severs the tubules (58,86). The rings and spirals are likely transient structures, as there are numerous approximately 20 nm constrictions without the presence of the DRP1A rings (24). Dynamin-like rings and spirals also appear in somatic cell plates at sites of constriction of the fused vesicles before the TVN is formed and around tubules before the FS develops (27). Dynamin-like rings were also seen in association with clathrin-coated structures in the TN and FS. It remains to be determined whether the DRP1 and/or DRP2 proteins are components of these ring-like structures potentially assisting in early cell plate membrane fusion.

In addition to the microscopic and biochemical approaches, genetic studies have provided the most definitive role for DRP1s in plant cytokinesis. *drp1a/drp1e* double-mutant embryos display defects in cell expansion and cytokinesis and fail to complete embryogenesis (3). The *drp1a/drp1e* embryos can undergo several rounds of cell division before cytokinetic defects are manifested, which may be due to the presence of another functionally redundant DRP1 or maternal/paternal pools of DRP1 proteins. In the cytokinetic defective cells, cell walls are only partially formed, resulting in cell wall stubs (3). This cytokinetic defective phenotype is very similar to that of *knolle* and *kuele* mutants which affect cell plate membrane fusion (29,30). In contrast to *drp1A/drp1E* double mutants, *drp1A* plants do not show defects in cytokinesis but have polar expansion defects only in select cell types (3). As both plant cytokinesis and anisotropic cell expansion require highly polarized membrane trafficking (87), DRP1A may have a more general role in polar membrane trafficking as well as a specialized role in the cell plate formation and maturation.

Less is known about the roles of the DRP1 isoforms DRP1C and DRP1E during cell plate formation and whether they have similar functions as DRP1A. *drp1C* mutants display defects in pollen maturation; however, there are no defects in pollen cytokinesis (88). Likewise, *drp1E* single-mutant plants do not have cytokinetic defects (3). Each DRP1 has a highly variable region between the middle and GED domains, the site of the lipid-interacting PH domain in dynamin I (Figure 1). DRP1A, DRP1C and DRP1E have been shown to interact with soybean DRP1 in a yeast two-hybrid assay. However, as only DRP1A has been verified as a component of the rings and spirals around syncytial-type cell plate tubules

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(24), it is not known whether the DRP1s can form homo- or hetero-rings and spirals *in vivo*.

Roles of DRPs in plant cytokinesis?

Members of the DRP1 and DRP2 protein subfamilies appear to function throughout the process of cell plate biogenesis; however, their exact biochemical roles remain to be determined. Based on their similarity to other dynamins, DRP1 and DRP2 could function in the formation of Golgi-derived vesicles and/or recycling of the membrane from the nascent cell plate. DRP1s may also be involved in the construction of the intermediate, callose-containing cell wall. Soybean DRP1 was shown to directly interact with components of the cell plate-specific callose–synthase machinery by yeast two-hybrid and *in vitro* affinity chromatography assays (89). It is hypothesized that callose–synthase complexes are recruited by DRP1 to the cell plate and that the deposition of callose within the initial cell plate tubules leads to the flattening and consolidation of the TVN. In contrast to somatic and syncytial endosperm cytokinesis, callose is not present in the postmeiotic cell plate of developing pollen grains prior to fusion with the parental plasma membrane, and it is interesting that dynamin-like rings or spirals appear to be absent during the formation of this type of cell plate (25).

Another potential function for DRP1 and DRP2 during cytokinesis is that they play a role in the formation and stabilization of dumbbell-shaped intermediates that have been observed on the initial fusion of cell plate vesicles. Dynamin rings have been postulated to constrict the fusing vesicles into tubules (24,27), thereby reducing the enclosed volume that would promote dehydration and gelling of lumenal cell wall polysaccharides (27). The mechanochemical activity of cell plate-associated DRPs could also facilitate the concentration of fusion factors at the ends of the tubules and the formation of the TVN (27).

Interestingly, recent data have revealed that the yeast DRP, Vps1p, has a role in vacuolar fusion in yeast. Vps1p physically interacts with the t-SNARE, Vam3p, on vacuolar membranes (47). This interaction has been suggested to concentrate SNAREs and other membrane fusion components, creating membrane fusion 'hot spots'. Dynamins could play a similar role during plant cytokinesis in regulating membrane fusions at distinct regions necessary for the formation of the mature cell plate. DRP oligomers may constrict membrane tubules concentrating KNOLLE and other cell plate membrane fusion components at the end of the tubules, whereas another DRP could bind directly to them, limiting their mobility in the membrane. The interaction between DRPs and any of the cell plate membrane fusion machinery remains to be tested.

The interaction of plant dynamins with MTs and actin microfilaments also remains to be fully characterized. DRP2 shares a similar domain structure to mammalian dynamin II (Figure 1), which interacts with actin-binding proteins, suggesting that DRP2 could also modulate the actin cytoskeleton during cytokinesis. In contrast to DRP2, DRP1 isoforms and Vps1p lack the C-terminal proline-rich protein–protein interaction domain of the classical animal dynamins, which is required for cytoskeletal-associated protein interactions (90, see Figure 1). Vps1p has also been shown to help organize the actin cytoskeleton through interaction with Sla1p, an actin- regulatory protein (48). The Sla1-interacting region of Vps1p was mapped to a 50-amino acid region upstream of the GED domain (48), which shares little amino acid homology with the corresponding region of the DRP1 isoforms (Figure 1, star). Interestingly, the localization of DRP1A is altered on treatment of roots with the membrane trafficking inhibitor Brefeldin A and actin cytoskeletal inhibitors cytochalasin D and latrunculin B (CAK and SYB, unpublished results). Thus, DRP1A may interact with actin during polarized expansion and/or cytokinesis.

Conclusions

The essential function for dynamin in a variety of cellular processes that involve both membrane trafficking and actin dynamics is becoming more apparent. These events may require dynamin to oligomerize around lipid bilayers altering membrane morphology or to activate downstream effectors through GTP binding and hydrolysis. These dual functions place dynamin at key positions in cytokinesis where actin dynamics and membrane trafficking are necessary at multiple steps in both plant and animal systems. Membrane addition and actin dynamics are required to initiate and constrict the ingressing cleavage furrow and to align and drive cell plate expansion. In addition, the possible MT-bundling properties of dynamin may play a role at the midbody in animal cells and on phragmoplast MTs in plant cells.

The number of known dynamin-interacting proteins has risen in recent years, as the roles of dynamin and DRPs have been elucidated. This number will most likely grow, as more is known about the roles dynamins play in cytokinesis. In turn, the dynamin-interacting proteins will give us clues as to how dynamin is functioning in cytokinesis: a scaffold for cell wall synthases, a tubulator of cell plate intermediates, a nucleator of actin, a bundler for MTs and/or a recycler of excess membrane at the division plane. The regulatory network of dynamin function in each of these molecular events remains to be determined. There is much to learn about the protein interactions and mechanisms that promote cytokinesis and separate newly formed daughter cells. By elucidating the function of key players in cytokinesis, dynamin and DRPs, we will determine the interplay and relationships between the fundamental events that occur during cytokinesis in higher eukaryotes.

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