cdc12p, a Protein Required for Cytokinesis in Fission Yeast, Is a Component of the Cell Division Ring and Interacts with Profilin

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Abstract. As in many other eukaryotic cells, cell division in fission yeast depends on the assembly of an actin ring that circumscribes the middle of the cell. Schizosaccharomyces pombe cdc12 is an essential gene necessary for actin ring assembly and septum formation. Here we show that cdc12p is a member of a family of proteins including Drosophila diaphanous, Saccharomyces cerevisiae BNI1, and S. pombe fus1, which are involved in cytokinesis or other actin-mediated processes. Using indirect immunofluorescence, we show that cdc12p is located in the cell division ring and not in other actin structures. When overexpressed, cdc12p is located at a medial spot in interphase that anticipates the future ring site. cdc12p localization is altered in actin ring mutants. cdc8 (tropomyosin homologue), cdc3 (profilin homologue), and cdc15 mutants exhibit no specific cdc12p staining during mitosis. cdc4 mutant cells exhibit a medial cortical cdc12p spot in place of a ring. mid1 mutant cells generally exhibit a cdc12p spot with a single cdc12p strand extending in a random direction. Based on these patterns, we present a model in which ring assembly originates from a single point on the cortex and in which a molecular pathway for the functions of cytokinesis proteins is suggested. Finally, we found that cdc12 and cdc3 mutants show a synthetic-lethal genetic interaction, and a proline-rich domain of cdc12p binds directly to profilin cdc3p in vitro, suggesting that one function of cdc12p in ring assembly is to bind profilin.

Cell division in many eukaryotic cells is accomplished through the action of an actin-based contractile ring (for reviews see Conrad and Schroeder, 1990; Satterwhite and Pollard, 1992; Fishkind and Wang, 1995). The positioning of this ring, which dictates the subsequent division plane, can determine cell size, shape, and orientation. Placement of the division plane is also critical during development, for instance, in the segregation of localized determinants (Rhyu and Knoblich, 1995; Horvitz and Herskowitz, 1992). Events in cell division must be coordinated with events in nuclear division to ensure that each daughter cell receives one intact genome. In animal cells, the coordination of cellular and nuclear division events appears to involve a mechanism in which the cleavage plane is determined by the mitotic asters (see Rappaport, 1986). It has been proposed that the mitotic asters send signals to the cell surface that induce contractile ring formation (Rappaport, 1986). Although a number of components of the contractile ring have been identified, little is known about the molecular mechanism of ring assembly at the plasma membrane and even less is known about the putative signals responsible for establishing the position of the ring.

The fission yeast Schizosaccharomyces pombe is an excellent organism for studying eukaryotic cell division at the molecular-genetic level (Fankhauser and Simanis, 1994; Chang and Nurse, 1996). Cell division in fission yeast requires an actin-based ring, which forms in early mitosis and shrinks in late mitosis as the septum cell wall material grows centripetally from the cell surface (Marks and Hyams, 1985). This ring may play two roles in cell division. First, it may mark the site of cell wall septum formation, and, second, it may play a contractile role in actively closing the plasma membrane. Although the ring clearly closes (Jochova et al., 1991; McCollum et al., 1995; this work), definitive evidence that the actin ring is contractile—that it exerts an active, contractile force—is still lacking. Alternatively, the actin ring may stabilize or guide the plasma membrane during septation. Conservation of ring components indicate that the S. pombe actin ring may be similar at a molecular level to the contractile ring in larger eukaryotes.

In fission yeast, it has been proposed that the actin ring and the subsequent division site are positioned in the middle of the cell by a signal from the premiotic nucleus.
(Chang and Nurse, 1996). The positions of the nucleus and subsequent division site always coincide, even in mutant cells with a displaced nucleus, multiple nuclei, or altered cell polarity (Toda, T., personal communication; Marks et al., 1987; Snell and Nurse, 1994; Verde et al., 1995). In contrast with animal cells (Rappaport, 1986), in fission yeast, ring assembly and placement are independent of the mitotic spindle (Chang et al., 1996). Indeed, assembly of a medial ring can be induced in certain circumstances in interphase cells (Fankhauser et al., 1995; Ohkura et al., 1995), suggesting that signals responsible for medial positioning may be present even before mitosis.

To study the molecular basis of actin ring assembly and placement, genetic screens have been used to identify six genes required for actin ring formation (cdc3, cdc4, cdc8, cdc12, cdc15, and rng2) and one gene required for ring placement (mid1) (Nurse et al., 1976; Marks et al., 1987; Chang et al., 1996). Temperature-sensitive mutations in these genes cause defects in cell division and actin organization at restrictive temperature. These mutants develop into large, multinucleate cells and ultimately die. Different aberrant patterns of actin distribution indicate that these gene products play different roles in actin ring assembly. cdc3 and cdc8 mutants display disorganized actin structures throughout the cell cycle, suggesting that cdc3 and cdc8, which encode profilin and tropomyosin, respectively, may organize actin in a general fashion (Marks et al., 1987; Balasubramanian et al., 1992, 1994; Chang et al., 1996). cdc12 and cdc15 mutants exhibit delocalized actin patches during mitosis but normal actin distributions during interphase (Fankhauser et al., 1995; Chang et al., 1996), suggesting that these gene products play specific roles in ring assembly during mitosis. cdc4 and rng2 mutants display disorganized actin cables instead of a ring, suggestive of a defect in a late step of ring assembly (McCollum et al., 1995; Chang et al., 1996). cdc4 encodes an EF hand–containing protein with properties of a myosin light chain (McCollum et al., 1995). mid1 is necessary for placement of the ring, since mid1 mutants exhibit rings and septa located at random positions and angles on the cell surface (Chang et al., 1996). cdc15p and the polo kinase homologue plo1p have been implicated as important regulators of ring assembly in the cell cycle, since overexpression of either one is sufficient to generate a ring at any stage of the cell cycle (Fankhauser et al., 1995; Ohkura et al., 1995).

Here we describe the cloning and molecular characterization of one of the actin ring genes, cdc12. The phenotype of cdc12 mutants suggests that cdc12 gene product is required specifically for actin ring assembly during mitosis and thus may be a target for cell cycle and spatial regulators of ring assembly (Chang et al., 1996). cdc12 is a member of a family of proteins that have been implicated in cytokinesis, suggesting that the function of cdc12p is conserved. cdc12p is the first member of this protein family to be localized to a cell division ring. Studies of cdc12p localization patterns upon overexpression and in mutant backgrounds reveal a medial cdc12p spot. This localization pattern may provide novel insights into mechanisms of ring formation and placement. Furthermore, we provide genetic and biochemical evidence suggesting that one function of cdc12p is to associate with another gene product required for ring formation, profilin cdc5p. Profilins are small actin-binding proteins that have been shown to bind monomeric actin, an actin-related protein complex, phospholipid PIP2, and proline-rich peptides such as poly-L-proline and VASP, and may regulate actin dynamics in the formation of F-actin structures (see Mach ery and Pollard, 1993; Pollard, 1995; Mach esky et al., 1994). These studies begin to address how protein–protein interactions build the actin ring.

## Materials and Methods

### Yeast Strains and Genetic Methods

Standard *S. pombe* genetic techniques and media were performed as previously described in Moreno et al. (1991). All *S. pombe* strains were isogenic to 972 (Leopold, 1970). *S. pombe* strains used are listed in Table I. FC20/ura4-D18 cdc12-112 h− was isolated in a cross between cdc12-112 h− and h+ ura4-D18 (P. Nurse lab collection). cdc4-377 homozygous diploid strain was isolated spontaneously from FCl23; this diploid was used because of the higher percentage of well-defined actin aster structures in the diploid, but the same structures were present in a haploid strain as well. Yeast transformations were performed by the lithium acetate method (Moreno et al., 1991) or by electroporation (Kelly et al., 1993).

### DNA Manipulations and Hybridizations

Standard DNA ligation and cloning procedures were used (Maniatis et al., 1982) with GeneClean from Bio101 (Vista, CA) and DNA prepared from Qiagen plasmid kits (Chatsworth, CA). Genomic yeast DNA was prepared as described (Moreno et al., 1991). Enhanced chemiluminescence (ECL) Southern hybridization was carried out as recommended (ECL southern blotting; Amersham Corp., Arlington Heights, IL). In colony hybridizations, 32P-labeled DNA probes were prepared using a Prime-It kit (Stratagene, La Jolla, CA).

### cdc12 Cloning

The cdc12 gene was cloned by complementation of the temperature-sensitive lethal phenotype of cdc12-112. A pUR19 (ura4+)–based *S. pombe* genomic library (Barbet et al., 1992) was transformed into ura4-D18 cdc12-112 (FC112), and 5 × 104 ura4+ transformant colonies were screened by replica printing onto YE5S with phloxin for growth at 36°C. Four colonies showed plasmid-dependent rescue. Isolation of plasmid DNA from two of these transformants identified two related plasmids, pFC103 and pFC104.

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1. Abbreviations used in this paper: DAPI, 4′,6-diamidino-2-phenylindole; ECL, enhanced chemiluminescence; GST, glutathione-S-transferase; PLP, poly-L-proline.
pFC104, pFC103 complemented a cdc12-112 strain upon retransformation and contained a 6-kb insert in pUR19. Deletion analysis showed that a central region was critical for activity (see Fig. 1 A). Three genetic criteria demonstrated that complementing activity was the cdc12 gene: first, hybridization to an ordered cosmids blot (Hoheisel et al., 1993) showed that pFC103 mapped to left tip of chromosome I, at the corresponding location to which cdc12 has been previously mapped genetically. Second, pFC110, which contains a 3-kb EcoRI cdc12 insert from pFC103 and a sup3-5 marker from pEFA1, was integrated into the genome by homologous recombination. Random spore analysis showed that the plasmid integrated at the cdc12 locus. Third, introduction of the COOH-terminal half of cdc12 gene into cdc12-112 does not confer rescue at 36°C in the majority of the cells, but confers rare stable gene conversion of the cdc12-112 allele, suggesting that the genetic defect of cdc12 resides in the COOH-terminal half of the protein.

cDNA and additional genomic DNA clones of cdc12 were isolated to delineate the ends of the transcript and to test the existence of possible introns. pFC125, which contains a partial 2.5-kb cdc12 cDNA that includes the 3′ half of the gene from the central EcoRI site, was identified by hybridization (Maniatis et al., 1982) from a S. pombe cDNA λYES library (generous gift from S. Elledge, Baylor University, Houston, TX). Elledge et al. (1991) using central 1.0- and 0.94-kb HindIII fragments as a probe. The insert in pFC125 was subcloned in T718R vector to produce pFC126 and pFC127, which were used in sequencing and further subcloning. pFC128, which contains a 2.4-kb cdc12 cDNA covering the 5′ end of cdc12, was obtained by a PCR approach 5′ RACE (Gibco BRL, Gaithersburg, MD). 109ext1 (GATCATTGGAGAATATCA) was used as an initial gene-specific oligonucleotide along with a 5′ anchor oligonucleotide. Two cycles of PCR with internal primers 109ext2 (GGAGGATCCGTGAGACAGTGAGG) and then 109ext3 (CAATTCCATCGTTTGACC) allowed the amplification of a 2.4-kb fragment that was cloned into a TA KS cloning vector (gift from J. Wuarin, Imperial Cancer Research Fund, London, UK). pFC163, which contains a 5-kb genomic cdc12 fragment covering the 5′ end and putative promoter region of the gene in pDB248, was cloned by hybridization from the Tamagawa and Noguchi S. pombe genomic DNA library (gift from T. Toda, Imperial Cancer Research Fund; Hirano et al., 1988).

**Deoxynucleotide Sequencing**

Deoxynucleotide sequencing was performed using an ALF automated sequence machine using a T4 polymerase sequencing kit from Pharmacia Biotech Inc. (Piscataway, NJ). Both cdc12 cDNA clones pFC127 and pFC128 and a 5.5-kb cdc12 genomic clone from Xhol to BamHI derived from pFC103 were sequenced, using subclones and primer walking. The pFC127 cDNA (3′ of EcoRI) and the pFC155 genomic DNA (5′ of cdc12 BamHI to EcoRI) were sequenced completely on both strands, and sequences from these were used when the cDNA and the genomic sequences did not agree; in particular, numerous single base pair changes were found in the pFC128 cDNA isolated by PCR, which were not incorporated. In addition, pFC163 was used to confirm sequences 5′ of the start site not included in pFC123 to delineate the start AUG. Sequences were aligned and analyzed using the DNA analysis programs Assemblign, DNA Strider, and DNA-Star.

**cdc12::ura4 Deletion**

A 5.5-kb BamHI-Xhol cdc12 DNA fragment from pFC103 containing the entire cdc12 open reading frame was ligated into the BamHI and Xhol sites of KS+ vector to produce pFC161. pFC162 (cdc12::ura4) was constructed by replacement of a 4.1 kb of PstI–SalI fragments in cdc12 in FC161 by a 1.8-kb PstI–SalI ura4 fragment. To replace the wild-type cdc12 gene with cdc12::ura4, pFC162 was cut with BamHI and Xhol, and the upper 3.6-kb band was gel purified and transformed into an ura4+ strain (see Table I) of appropriate dilution of cdc12 in PBS, 20 µl of ura4+ 45 kD, 20 µl of ura4+ 40 kD, and 20 µl of ura4+ 50 kD. Poly-t-proline (PLP, 1,000–10,000; average mol wt 5,600; n = 50, Sigma Chemical Co.) was diluted in PBS. In binding experiments, 20 µl of appropriate dilution of cdc12 in PBS, 20 µl of 50% beads in PBS

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containing appropriate dilutions of protein, and 140 μl of CB buffer (0.6 M sorbitol, 50 mM Tris, pH 7.5, 140 mM NaCl, 5 mM EDTA, 0.06% Triton X-100) were mixed and incubated in a 200 μl tube at room temperature with inversion for 1 h. In PLP inhibition experiments, 5 μl PLP or buffer alone was added to the binding reactions. Aliquots were taken for total sample. Supernatant and pellet fractions were collected upon centrifugation in a picofuge (Stratagene) for 30 s. Fractions were analyzed by SDS-PAGE gels and Coomassie staining. Densitometry of bands was performed with an IS-1000 gel documentation system (Alpha Innotech Corp., San Leandro, CA).

Results

cdc12 Encodes a Member of a Newly Recognized Family of Cytokinesis Proteins

The fission yeast cdc12-112 mutant is a recessive temperature-sensitive lethal mutant with a specific defect in actin ring formation and cell division (Nurse et al., 1976; Marks et al., 1987; Chang et al., 1996). We cloned the cdc12 gene by screening for a plasmid from a genomic DNA library that could rescue the temperature-sensitive lethality of cdc12-112 mutant. Multiple genetic criteria showed that the plasmid pFC103 contained the cdc12 gene (see Materials and Methods). Sequence analysis of the clone revealed one large open reading frame (Fig. 1 A). Deletion analysis (Fig. 1 A) showed this open reading frame is responsible for complementation of the cdc12-112 mutation. Comparison of nucleotide sequences from genomic and cDNA clones helped to delineate the ends of the mRNA transcript and demonstrated that cdc12 does not contain introns.

Conceptual translation of the nucleotide sequence predicts that cdc12 encodes a polypeptide of 1,841 amino acid residues. Features in the deduced polypeptide include two predicted coiled-coil domains (Lupas et al., 1991) and a central region containing two stretches of polyproline (Fig. 1 B). Database searches using the BLAST algorithm revealed that the cdc12 gene product is similar to an emerging family of proteins that include Bni1p from S. cerevisiae, diaphanous from Drosophila, fus1p from S. pombe, figA/sepA from Aspergillus nidulans, cappuccino from Drosophila, and formins from mouse, human, and chicken (Fares, H., and J. Pringle, personal communication; Petersen et al., 1995; Harris et al., 1997; Castrillon and Wasserman, 1994; Emmons et al., 1995; Woychik et al., 1990; Maas et al., 1991; Trumpp et al., 1992). Of these proteins, diaphanous, Bni1p, sepA, and cappuccino have been implicated in cytokinesis (Castrillon and Wasserman, 1994; Kohno et al., 1996; Harris et al., 1997; Manseau et al., 1996).

These proteins share several regions of homology, including two domains that have been termed FH1 and FH2 (formin homology domains) (Castrillon and Wasserman, 1994). The FH1 domain includes proline-rich sequences...
in the NH2-terminal half of the proteins (not shown). Deletion analysis of cdc12 suggests that the COOH-terminal two-thirds of the protein, which contains the conserved FH1 and FH2 domains, is essential and sufficient for activity (Fig. 1 A).

**cdc12 Is an Essential Gene Required for Actin Ring and Septum Formation**

To determine the function of cdc12, we examined the effects of a cdc12 deletion. A cdc12::ura4 deletion construct was made in which >70% of the open reading frame, including the conserved FH1 and FH2 domains, was replaced by the ura4 gene. This construct was transformed into a diploid strain, and multiple stable ura4+ diploids, which were confirmed to be heterozygous for a homologous replacement of the cdc12 gene, were sporulated and analyzed. Tetrad analysis showed that at least two of the four spores were dead and that there were no viable haploid ura4+ spores, demonstrating that the cdc12::ura4 haploid cells were not viable. Microscopic examination of individual spores showed that two inviable spores of each tetrad germinated and grew into a single large swollen dumbbell- or pear-shaped cell that did not divide. In random spore analysis, introduction of a plasmid containing the cdc12 gene rescued the lethality of the cdc12::ura4 spores, indicating that the lethal phenotype associated with the cdc12::ura4 was due to the disruption of the cdc12 gene. Thus, cdc12 is essential for viability.

Germinated cdc12::ura4 spores were examined for effects on actin and septum organization. Wild-type cells form cortical actin patches at the ends of cells during interphase and an actin ring during mitosis (Fig. 2, A and B; Marks and Hyams, 1985). cdc12::ura4 cells had normal interphase cortical actin patches (Fig. 2, C and E), but only delocalized actin patches instead of an actin ring during mitosis (Fig. 2, G and I). In some mitotic cells, actin dots were concentrated in the zones where the actin ring would have formed (Fig. 2 I). cdc12::ura4 cells became multinucleate (Fig. 2), indicating that nuclear division occurred in the absence of cytokinesis. This phenotype is identical to that seen in temperature-sensitive cdc12 alleles at restrictive temperature (Chang et al., 1996; Marks et al., 1987; Nurse et al., 1976). Thus, cdc12 is required for actin ring assembly during mitosis, but is not required for actin organization during interphase.

cdc12::ura4 cells had no depositions of septal material (Fig. 2, K and L). This is in contrast to all known temperature-sensitive alleles of cdc12, which display multiple aberrant patches of septal materials (Chang et al., 1996; Streiblova, 1984; Nurse et al., 1976). Thus, cdc12 is also necessary for septum formation.

**cdc12 Is a Component of the Cell Division Ring**

To localize the cdc12 gene product, we raised polyclonal rabbit antibodies against a cdc12 FH1 domain protein fragment expressed in E. coli. The affinity-purified antibody recognized on an immunoblot a single band of ~220 kD (Fig. 3 A), which is consistent with the size predicted from the nucleotide sequence. This 220-kD protein was confirmed to be cdc12p by showing that the level of this protein is increased ~10-20-fold in cells containing a plasmid.
that overexpresses cdc12p from the thiamine-regulated nmt promoter (Fig. 3 A). Measurements of cdc12p levels both from synchronized cells and from cells arrested in G2 (cdc25 block) and G1 phases (cdc10 block) showed that cdc12p is expressed throughout the cell cycle with no large fluctuations in protein levels or mobility shifts in different phases of the cell cycle (data not shown).

Immunofluorescence using this anti-cdc12p antibody revealed staining of the fission yeast cell division ring (Fig. 3). cdc12p was present in early mitotic cells as a thin, faint ring (Fig. 3 D). This ring was more intense during anaphase (Fig. 3 H) and, after completion of anaphase, appeared to contract to a single dot between the daughter cells during cytokinesis (Fig. 3 J). cdc12p staining was very similar to staining patterns of other components of the ring such as actin and cdc4p (Marks and Hyams, 1985; McCormum et al., 1995). cdc12p did not localize to other actin structures, such as interphase actin patches at the ends of cells or actin dots adjacent to the septum during septation (Marks and Hyams, 1985). The cdc12p staining was specific because there was no ring staining in cdc12-112 mutant cells (see Fig. 5 A), and, in addition, a green fluorescent protein–cdc12 fusion is located at similar structures (Chang, F., unpublished observations).

In interphase cells, only weak, diffuse cytoplasmic staining was detected (Fig. 3 B, see cell i). This may be largely nonspecific background staining, since similar weak cytoplasmic staining was also present in cdc12-112 (see Fig. 5 A) and cdc12::ura4 cells (data not shown).

Cells Overexpressing cdc12 Exhibit a cdc12p Spot

We also examined cdc12p localization in cells overexpressing cdc12p to attempt to visualize cdc12p structures that may be too small or stained too weakly in wild-type cells. A moderate strength thiamine-repressible nmt1 promoter (derived from pREP41x) was cloned 5′ of the cdc12 open reading frame (pmnt-cdc12; see Materials and Methods), and the construct was integrated in the chromosome. Cells carrying this construct expressed cdc12p at 10–20-fold higher than wild-type levels, but retained normal growth rate, cell morphology, cell division, and actin distribution after 20 h of induction (data not shown).

Overexpression of cdc12 revealed structures that were not previously observed in wild-type cells (Figs. 4 and 5; Table II). During interphase, the most common pattern (37% of the cells) was a discrete medial spot located between the nucleus and the cortex (Fig. 4, cell J; Table II). This dot was not associated with a similar dot of F-actin (data not shown). 18% of the cells exhibited a dot on the cell surface near the end of the cell, which is presumably a midbody remnant from a previous division (Fig. 4, cell C; Table II). 33% of the cells exhibited no specific staining, and other less frequent patterns such as multiple dots were also observed (Fig. 4, cell 6; Table II). Medial spot staining appeared to be cell cycle regulated, as almost all (96%) cells at the very beginning of interphase (very short cells) exhibited no medial spot staining, while most (76%) late interphase cells (long cells) exhibited a medial spot.

In early mitosis, cells exhibited a similar medial spot (17%; Fig. 5 C), a spot with an intersecting faint cdc12 ring and strand (31%; Fig. 5, B and C), or a ring similar to a wild-type cell (50%; Fig. 5 D). Examination of cells in different focal planes (Fig. 5) showed that the cdc12p spot is not, for instance, a ring seen in a particular focal plane (compare spot in cell A with ring in cell D). In cells where both a spot and a ring (or strand) are observed (Fig. 5, B and C), the two structures always coincided, suggesting...
that the spot may mark or give rise to the ring. In these cells, about half of the rings appeared discontinuous around one side of the spot (Fig. 5 C, top panel). In late mitosis, nearly all cells exhibited a cdc12p ring as seen in wild-type cells (Fig. 4, cells 3 and 4).

A corresponding medial spot was not readily detectable in wild-type cells that do not overexpress cdc12, and thus it is not known if cdc12p resides in such a spot in wild-type cells. A small faint dot in the proper location was occasionally seen, but it was usually not significantly more intense than other background cytoplasmic dots. However, we have observed cells in which cdc12p ring staining appears stronger at one side of the cell (see cell e in Fig. 3 B). Several explanations for the cdc12p spot are considered in the Discussion.

cdc12p Localization in Different Actin Ring Mutants

Next, we examined expression and localization of cdc12p in the different actin ring mutants. First, immunoblot analysis showed that expression of cdc12p was not altered in cdc3, cdc4, cdc8, cdc15, or mid1 mutants (data not shown). Second, we examined cdc12p localization in different mutant backgrounds. cdc3-213, cdc8-346, and cdc15-287 mutants generally showed no specific cdc12p staining during mitosis, much like a cdc12-299 mutant (Fig. 6, A–D, left panels). In addition, cdc15 mutant cells that overexpressed cdc12p did not exhibit any cdc12p spot or ring staining in either interphase or mitotic cells (data not shown). Thus, cdc3 (profilin homologue), cdc8 (tropomyosin homologue), and cdc15 genes are necessary for cdc12p localization at the ring, and at least cdc15 is also required for cdc12p spot formation.

In contrast, cdc12p was localized to a single medial cortical spot in cdc4-377 mutant cells during mitosis (Fig. 6 E; Table II). While most early mitotic cells (76%) exhibited no staining, most late mitotic cells (76%) exhibited this spot (Table II), suggesting that this spot is formed during mitosis. In addition, some cells (6% of late mitotic cells) possessed a spot with a faint intersecting ring. Thus in a cdc4 mutant, cdc12p accumulated in a medial spot in place of the ring. The relationship of cdc12p and actin was examined in cdc4-377 mutant cells. Instead of an actin ring, these cells form an asterlike array of actin cables organized around a single cortical point (Fig. 6 F; Chang et al., 1996). Double staining revealed that the cdc12p dot was located to the center of the larger actin aster (Fig. 6 F).

mid1-366 mutants exhibited highly variable patterns that reflect multiple defects in the spatial organization of the ring (Fig. 7; Table II). Generally, mid1 mutants had a medial
Figure 5. The positions of the cdc12p spot and the ring coincide. FC565 (pmnt-cdc12) cells were processed as described in Fig. 4. Shown are four representative cells in early mitosis, around the period of ring formation. Top three panels show three different focal planes of the same cell, and the bottom two panels show tubulin and DAPI staining as labeled. (A) Cell with a cdc12p spot. (B) Cell with a cdc12p associated with a complete ring. (C) Cell with a cdc12p spot with an incomplete ring. Note the discontinuity of the ring adjacent to the spot in the top panel. (D) Cell with a cdc12p ring but no spot. Bar, 10 μm.

cdc12p spot associated with single strand (Fig. 7, A–C). Over 90% of the strands were associated with the nucleus at some point along the strand, and some strands even wrapped around the nucleus (Fig. 7 C). Some cells only had a medial spot of cdc12p (Fig. 7 D) or no staining at all (not shown). 30% of the spots were positioned away from the cell middle and the nucleus (Fig. 7 E), indicating an apparent defect in placing the spot. Although few (<5%) com-

cdc12p staining; the cytoplasmic staining is nonspecific background staining. (E and F) Note the medial spot of cdc12p (arrow) in the cdc4 mutant, which localizes to the origin of an actin aster (F, middle panel, labeled a). Bar, 10 μm.

Figure 6. Localization of cdc12p in different actin ring mutants during mitosis. (A) cdc12-299 (FC127); (B) cdc3-313 (FC114); (C) cdc8-346 (FC131); (D) cdc15-287 (FC55); (E and F) cdc4-377 (FC361). Mutant cells were grown in YE5S at permissive temperature (25°C), and then shifted to restrictive temperature (35.5°C) for 4 h. Cells were fixed and processed for immunofluorescence with anti-cdc12 antibody, anti-tubulin antibody or anti-actin antibody, and DAPI. On the basis of spindle and nuclear morphology, cells pictured are in anaphase, the cell cycle period of maximum cdc12p ring staining in wild-type cells. (A–C) Cells are in mitosis in which two nuclei are dividing into four and thus exhibit double spindles; (E–F) cells exhibit single spindles. (A–C) Mutants exhibit no specific
Table II. cdc12p Localization Patterns in Wild-type and Mutant Cells

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Cells were fixed and stained with anti-cdc12 and anti-tubulin antibodies and DAPI. Individual cells were first screened by fluorescence microscopy for a particular cell cycle stage on the basis of tubulin staining, and were then examined for cdc12p localization. Cells with a short mitotic spindle before nuclear division were designated as being in early mitosis. Cells in anaphase or postanaphase were designated as being in late mitosis. Cells with an interphase microtubule array and a single nucleus were designated as being in interphase. Dots and lines indicate cdc12p localization, and the empty circle indicates the nucleus. OP (overproducing) cdc12: cells (FC566) that contain a chromosomal integrated copy of pmnt-cdc12 were induced in minimal media for 20 h at 30°C. cdc8-546 (FC131), cdc15-287 (FC55), and cdc4-377 (FC361) mutants were grown for 4 h at the restrictive temperature of 35.5°C. cdc12-366 (FC164) cells were grown for 2 h at 35.5°C. (a) Cells with no specific cdc12p staining. (b) Cells with a medial cdc12p spot. Interphase spots were adjacent to the nucleus. (c) Cells with a cdc12p spot near the end of the cell, which probably is a midbody remnant, left from a previous division. (d) Cells with multiple dots in overexpressing cells or dots not covered in b or e. Many cells in this category have a combination of patterns seen in b and e. (g) Cells with an intact but displaced ring. (h) Cells with a cdc12p strand. Many are associated with a dot, and >90% are associated with the nucleus. (i) In mid1 cells, dots are not always on the cortex, and some dots (~30%) are displaced away from the medial nucleus.

Figure 7. Localization of cdc12p in mid1 mutant cells during early mitosis. mid1-366 mutant cells were grown in YES at permissive temperature (25°C), and then shifted to restrictive temperature (35.5°C) for 2 h. Cells were processed for immunofluorescence with anti-cdc12 antibody, anti-tubulin antibody or anti-actin antibody, and DAPI. On the basis of spindle and nuclear morphology, cells pictured are in early mitosis, the cell cycle period around ring formation. Note different configurations of cdc12p dot and strand (arrows). Bar, 10 μm.

Evidence That cdc12p Interacts with Profilin cdc3p

The existence of proline-rich sequences in cdc12p suggests that cdc12p may bind to the profilin homologue cdc3p, since profilins are known to bind to proline-rich sequences (Tanaka and Shibata, 1985). In addition, evidence that cdc3 and cdc12 share similar mutant phenotypes (Chang et al., 1996) and that both gene products localize in the septum region during cell division (Balasubramanian et al., 1994; this work) suggests that these proteins may interact in vivo. Therefore, we tested for the interaction between these gene products using genetic and biochemical methods.

First, we tested whether cdc3 and cdc12 interact genetically by constructing cdc12 and cdc3 double mutants. Fig. 8 shows the phenotypes of wild-type, cdc3, cdc12, and cdc3 cdc12 mutants. The cdc3-313 cdc12-112 double mutants had a much more severe phenotype than either single mutant. cdc3 cdc12 mutant spores were either dead at 25°C or produced cells with very poor growth at 25°C and no growth at the intermediate temperature of 29°C. In comparison, single cdc3 and cdc12 mutants grew well at 25°C and 29°C. The single mutants and the double mutants did not grow at 36°C. Thus, cdc3 and cdc12 genes exhibit a...
Discussion

**cdc12p and Cell Division**

cdc12 encodes a member of an emerging family of proteins that function in cytokinesis or other actin-mediated processes. The mutant phenotype of cdc12 indicates that it is required for actin ring formation and septum formation in cell division: cdc12 mutants exhibit actin dots instead of an actin ring, do not form a septum, and accumulate as large, multinucleate cells. cdc12p localization at the ring indicates that it is likely to be a structural component of the cell division ring. In contrast with some actin-binding proteins that organize multiple actin structures (Balasubramanian et al., 1992), cdc12 may function specifically in ring formation during mitosis: cdc12 mutants are not affected in actin patch organization during interphase (Chang et al., 1996; Fig. 2), and cdc12p is not located with other actin structures such as actin patches. cdc12p also has a role in directing septum cell wall formation outside the plasma membrane proximal to the ring and may be involved in targeting cell wall synthetases to the ring site.

**Interaction between cdc12p and Profilin**

We imagine that cdc12p is a component of a multiprotein complex that organizes actin at the plasma membrane. Here we have found evidence that cdc12p binds directly to the actin-binding protein, profilin cdc3p. Since profilin will bind to eight to ten sequential prolines (Machesky and Pollard, 1993; Perelroizen et al., 1994), it is likely that the sequential stretches of nine and six prolines in the FH1 domain of cdc12 contribute to this interaction.

Four in vivo observations support the in vitro interaction data. First, cdc3 and cdc12 mutants have very similar phenotypes: both mutants are defective in actin ring assembly and display disorganized actin dots in place of a ring during mitosis (Chang et al., 1996; Marks et al., 1985; Balasubramanian et al., 1994). Second, cdc3p and cdc12p are located in the same regions of the cell: cdc3 is located during mitosis in a band at the cell middle that overlaps but is broader than the narrow ring of cdc12p (Balasubramanian et al., 1994). Third, cdc3 is required for the localization of cdc12p at the ring, since cdc12p is not localized in a cdc3 mutant (Fig. 6 B). Fourth, cdc3 and cdc12 mutants exhibit a synthetic-lethal genetic interaction. Together, the genetic and biochemical data support the idea that cdc12p and profilin interact physically and function together in actin ring assembly.

Though profilin has been intensely studied, its role in regulating actin in vivo is still not well understood. In vitro, profilin has the potential both to inhibit actin polymerization by binding to actin monomers as well as to drive actin polymerization, possibly by affecting the nucleotide-binding state of actin and by lowering the critical concentration for actin polymerization (Pantaloni and Carlier, 1993; Theriot and Mitchison, 1993). In vivo, profilin is often located at sites of active actin assembly, for instance, at the end of *Listeria* motile bacterium, where it may promote actin polymerization (Theriot et al., 1994). In *S. pombe*, profilin appears to have an active role in actin ring assembly (Balasubramanian et al., 1994). Therefore, cdc12p may influ-
ence actin assembly during ring formation through this interaction with profilin.

There is evidence that other members of the cdc12p family also interact with profilin. In Drosophila, cappuccino and profilin mutants possess similar phenotypes in oogenesis, and an interaction has been demonstrated in the two hybrid system (Manseau et al., 1996). Two-hybrid, genetic, and biochemical data also suggest that S. cerevisiae BNI1 interacts with profilin (Evangelista et al., 1997). Recently, two other proline-rich proteins have also been implicated as profilin ligands: VASP and Mena are related proteins that appear to regulate actin assembly at focal adhesions and at the actin tail of the motile bacteria Listeria (Reinhard et al., 1992, 1995; Chakraborty et al., 1995; Gertler et al., 1996). Since profilin and VASP are associated with a nucleating center for the actin tail of Listeria, one possibility is that cdc12p and profilin are associated with a nucleating center for the ring.

cdc12p may possess additional binding partners. BNI1p has been found to interact with rho GTPases (Kohno et al., 1996; Evangelista et al., 1997). The cdc12p FH1 domain contains proline-rich consensus sequences for binding to SH3-binding domains. The two coiled-coil domains of cdc12p are potential sites for intramolecular or intermolecular interactions with other cdc12p protein molecules or with other coiled-coil proteins such as cdc15p, myosin, or septins. A large protein with multiple domains, cdc12p may act as a scaffold that brings together multiple ligands.

Evidence for a Pathway in Ring Formation

Analysis of cdc12p localization in different cell types revealed intriguing novel patterns that suggest that the site of ring assembly is initiated from a single point (Fig. 10). In cdc12p-overexpressing cells, the cdc12p was localized at a single medial spot between the nucleus and cortex during late interphase and early mitosis (Figs. 4, 5, and 7). This cdc12p spot was located precisely at the future site of Figure 9. cdc12p fragment binds to profilin cdc3p in vitro. (A) Purified proteins used in these studies. (Lane 1) Purified GST-cdc3. (Lane 2) Purified GST. (Lane 3) Purified His-tagged cdc12p fragment. (B and C) cdc12p binds to GST-cdc3 but not to GST. In each 180-μl reaction, cdc12p (1.6 μM final concentration) and 20-μl 50% slurries of glutathione agarose beads containing indicated concentrations of GST-cdc3 or GST were added to each reaction. Reactions were incubated at room temperature for 1 h, and the beads were pelleted. (B) Coomassie-stained gel of total proteins before pelleting (lane 1) and pellet fractions (lanes 2–10) at equivalent volumes. Bands were quantitated by densitometry relative to total protein in lane 1 and plotted in C. (D and E) Poly-l-proline inhibits binding. Varying amounts of poly-l-proline were added to the binding reactions similar to ones described above except cdc12p was 0.8 μM. (D) Coomassie-stained gel of the pellet fractions. (E) cdc12p in the pellets was quantitated by densitometry relative to supernatant fractions (not shown).
Numerous aspects of this model remain to be tested. For instance, since a cdc12p spot was not readily visualized in wild-type cells without overexpression, it is not known if a cdc12p spot is present in interphase wild-type cells, or if cdc12p has an affinity for an as yet unidentified medial structure that does not contain cdc12p normally. An alternate model is that the cdc12p spots represent aberrant aggregates of cdc12p. For instance, overexpression of cdc12p during interphase may induce the formation of an aggregate of ring proteins including myosin that contracts into a single tight ball. However, in any of these models, the fact that the cdc12p spot anticipates the ring site suggests that spatial signals that position the ring are present during interphase and that cdc12p or associated proteins are capable of responding to these spatial cues. Thus, the cdc12p spot may be regarded as a marker that reveals the activity of spatial regulators that position the division site.

**Roles of Ring Genes in Ring Formation**

Analysis of different ring mutants suggests that the different ring genes play different roles in ring formation. cdc12, cdc15, cdc3 (profilin homologue), and cdc8 (tropomyosin homologue) appear to be involved in an early step in ring formation, possibly in nucleation of the ring. cdc12p is not localized in cdc15, cdc3, and cdc8 mutants, suggesting that one role of these gene products is to localize cdc12p. cdc15p, an SH3 domain–containing protein, is an important regulator of ring formation in the cell cycle (Fankhauser et al., 1995) and is a candidate partner for binding an SH3-binding domain of cdc12p. cdc8p is a homologue of tropomyosin, a small actin-binding protein (Balasubramanian et al., 1992). Studies with the antiactin drug Latrunculin A show that F-actin is also necessary for cdc12p localization (Engqvist, A., and F. Chang, unpublished observations). As proposed for bud site determination in S. cerevisiae (Yang et al., 1997), F-actin organized by actin-binding proteins may be required as a cortical scaffold that binds cdc12p at the cortex. At the cortex, cdc12p with profilin may then organize ring components, including F-actin, at the site. As demonstrated in Thyone sperm (Tilney et al., 1983), F-actin may also be used as a nucleation seed for cdc12p and profilin-dependent actin assembly. Finally, cdc12p and these ring components may be required altogether for ring assembly, and loss of one of these essential components may cause delocalization of the other components.

In contrast, cdc4 and mid1 may not be necessary to localize cdc12p per se, but they may be required in a later step in ring formation. cdc4p is a putative myosin light chain, suggesting that a myosin-related protein is important in ring formation (McCollum et al., 1995). The mid1 gene product is necessary for the spatial regulation of at least two aspects of ring formation: guiding a cdc12p strand around the circumference, and placing the initial spatial cue in the middle of the cell. mid1p (dmf1) encodes a novel protein with a pleckstrin homology domain, PEST sequences, and a nuclear localization signal (Sohrmann et al., 1996). Intriguingly, the mid1 gene product is located in the nucleus during interphase and in a medial ring in early mitosis, suggesting that it may link the positions of the nucleus and ring. However, our analysis shows that, in most cases, cdc12p...
still appears associated with the nucleus in the earliest stages of ring formation in the mid1-366 mutant.

Role of cdc12-like Proteins in Cytokinesis and Spatial Organization

cdc12p is member of a family of proteins involved in cytokinesis or other actin-related processes such as cell fusion. Although the overall amino acid sequence homology between these proteins is low (<30%), similarity in their domain structure, conservation of certain small domains such as the formin homology domains (Castrillon and Wasserman, 1994), and their roles in related cellular processes suggest that the function of these proteins is conserved. Many of these proteins are required in cytokinesis: like cdc12, diaphanous in Drosophila is necessary for cytokinesis (Castrillon and Wasserman, 1994), and sep1/figA in Aspergillus is required for septation (Harris et al., 1997). BNI1p in S. cerevisiae has a role in the placement of the division site (bud site placement in the bipolar pattern) (Zahner et al., 1996), displays genetic interaction with a septin, and is located at the division ring and at the site of polarized growth at the bud tip (Fares, H., M. Longtine, and J. Pringle, personal communication).

Other members of the cdc12p family have related roles in localizing other proteins or determinants at certain regions of the cell cortex. cappuccino is required both for cytokinesis and the establishment of polarity during Drosophila oogenesis and is potentially involved in the signaling events between the nucleus and cortex that establish polarity axes (Emmons et al., 1995; Roth et al., 1995). cdc12, cdc3, and cdc8 may play analogous roles to cappuccino, profilin (chickadee), and tropomyosin II, which are required in the localization of posterior determinants in the Drosophila oocyte (Emmons et al., 1995; Erdelyi et al., 1995; Manseau et al., 1996). In S. cerevisiae, BNI1 also is required for the proper localization of a determinant (Ash1p) in the daughter bud (Bobola et al., 1996). cdc12p is also similar to S. pombe fus1p, which is required for cell fusion and nuclear migration during mating and localized to patches at the projection tip (Petersen et al., 1995). fus1 may be necessary to localize fusogenic proteins to the projection tip during the mating process. Candidate vertebrate homologues of cdc12p are the formins, which have been implicated in limb morphogenesis (Woychik et al., 1996). However, the cellular role of the formins has not been determined. Further study of cdc12p and its homologues may add a role of the formins in localizing other proteins or determinants at certain regions of the cell cortex.

We are grateful to past and present members of the Nurse laboratory and Drubin laboratory for help, advice, and reagents. We thank Bruce Goode for advice in binding studies; Jaime Correa-Bordes for gift of cell cycle extracts; Elmar Maier for assistance in cosmid mapping; and Charles Boone, Steve Wasserman, Lynn Manseau, John Pringle, Hana Fares, Steven Harris, and Takashi Toda for communication of results before publication. We also thank T. Toda, K. Ayscough, J. Thorner, K. Kozminski, and reviewers for helpful comments on the manuscript.

F. Chang was supported by the Helen Hay Whitney Foundation and a University of California CRCC grant.

Received for publication 30 April 1996 and in revised form 14 February 1997.

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