Nuf, a Rab11 Effector, Maintains Cytokinetic Furrow Integrity by Promoting Local Actin Polymerization

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Nuf, a Rab11 effector, maintains cytokinetic furrow integrity by promoting local actin polymerization

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Plasma membrane ingression during cytokinesis involves both actin remodeling and vesicle-mediated membrane addition. Vesicle-based membrane delivery from the recycling endosome (RE) has an essential but ill-defined involvement in cytokinesis. In the Drosophila melanogaster early embryo, Nuf (Nuclear-fallout), a Rab11 effector which is essential for RE function, is required for F-actin and membrane integrity during furrow ingression. We find that in nuf mutant embryos, an initial loss of F-actin at the furrow is followed by loss of the associated furrow membrane. Wild-type embryos treated with Latrunculin A or Rho inhibitor display similar defects. Drug- or Rho-GTP–induced increase of actin polymerization or genetically mediated decrease of actin depolymerization suppresses the nuf mutant F-actin and membrane defects. We also find that RhoGEF2 does not properly localize at the furrow in nuf mutant embryos and that RhoGEF2–Rho1 pathway components show strong specific genetic interactions with Nuf. We propose a model in which RE-derived vesicles promote furrow integrity by regulating the rate of actin polymerization through the RhoGEF2–Rho1 pathway.

Introduction

Cytokinesis, the physical separation of daughter cells after mitotic exit, requires the assembly of an actomyosin-based contractile ring that drives plasma membrane constriction and furrow ingression. The contractile ring forms perpendicular and midway to the anaphase spindle. Once the contractile ring forms, ingression of the cleavage furrow begins. Ingression of the animal cleavage furrow involves vesicle-mediated membrane addition as well as actomyosin-based contraction (Albertson et al., 2005; D’Avino et al., 2005; Glotzer, 2005). Thus, successful cytokinesis requires precise coordination between contraction and membrane addition.

Vesicle-based membrane delivery from both the Golgi and the recycling endosome (RE) is necessary for furrow ingression during cytokinesis (Lecuit and Wieschaus, 2000; Sisson et al., 2000; Skop et al., 2001, 2004; Xu et al., 2002; Farkas et al., 2003; Pelissier et al., 2003; Riggs et al., 2003; Fielding et al., 2005; Wilson et al., 2005; Giansanti et al., 2007). The RE, which is often found closely associated with microtubules, mediates vesicle transport directly to the plasma membrane (Ullrich et al., 1996). These properties make it especially well suited for regulating vesicle-mediated delivery to the cytokinesis furrows. Functional studies demonstrating a role for the RE in cytokinesis have relied extensively on rab11 mutants. Rab11 is a small GTPase that preferentially localizes to the RE and is required for proper RE formation (Maxfield and McGraw, 2004). Consequently, rab11 mutants render the RE nonfunctional and disrupt vesicle recycling to the plasma membrane. Mutations of rab11 in Caenorhabditis elegans, Drosophila melanogaster, and mammalian cells all result in a failure to complete cleavage furrow ingression (Skop et al., 2001; Pelissier et al., 2003; Riggs et al., 2003; Wilson et al., 2005; Giansanti et al., 2007).

Additional support for a specific role of the RE in vesicle-mediated membrane delivery during cytokinesis comes from analysis of the Rab11 effector protein Nuf/FIP3/Arfophilin2. Genetic studies in D. melanogaster identified the centrosome-associated protein Nuf (Nuclear-fallout) as being essential for proper furrow formation in the early embryo (Sullivan et al., 1993; Rothwell et al., 1998; Riggs et al., 2003). Nuf is a homologue of mammalian FIP3/Arfophilin2 and both share a conserved 20-aa C-terminal Rab11 binding domain (Hickson et al., 2003; Riggs et al., 2003). GST pulldowns demonstrate that Nuf

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Figure 1. F-actin is rapidly turned over in the furrow through depolymerization and repolymerization. The schematic illustrates the focal plane relative to the furrow. Blue, nuclei; green, membrane. (A) Rhodamine-actin (red) was rapidly incorporated into preexisting (arrows) and newly forming (arrowheads) furrows marked by GFP-Moesin (green) at cycle-12 prophase. (B) GFP-Moesin and Rhodamine-actin showed a dramatic signal decrease at the furrow within 4 min after LatA but not DMSO injection. (C) Areas measured to calculate net furrow signal decrease at the furrow within 4 min after LatA but not (B) GFP-Moesin and Rhodamine-actin showed a dramatic furrows marked by GFP-Moesin (green) at cycle-12 prophase. (D) White box indicates photobleached area. Yellow boxes indicate an example of a furrow region used for quantifications in E. See Video 1 (available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). (E) Relative fluorescence intensities of GFP-Moesin and Rhodamine-actin at the furrows (y axis) after photobleaching (from D; n = 10 embryos). Bars, 10 μm.

and Rab11 physically associate and functional studies demonstrate that Nuf and Rab11 are mutually required for their localization to the RE (Riggs et al., 2003). Mutational analysis reveals that Nuf and Rab11 are involved in proper membrane and actin organization at the invaginating furrows (Rothwell et al., 1998, 1999; Riggs et al., 2003). In nuf embryos, regions of the furrow are devoid of F-actin but not of other core furrow components (Rothwell et al., 1998). In addition, extensive gaps in the membrane are observed in the furrows of nuf and rabi1 embryos (Rothwell et al., 1999; Riggs et al., 2003). Associated with these gaps is an extensive accumulation of vesicles in the cortex, suggesting that these mutations disrupt RE-based vesicle-mediated delivery to the invaginating furrows (Rothwell et al., 1999; Riggs et al., 2003).

The fact that disrupting RE function through the nuf and rabi1 mutants produces defects in both membrane and F-actin organization suggests that these processes are closely linked (Riggs et al., 2003). To explore this linkage, we examined the relationship between F-actin turnover and stability of the metaphase and cellularization furrows in the early D. melanogaster embryo. Although actin turnover at the cytokinetic furrow has been well documented in other systems (Pelham and Chang, 2002; Guha et al., 2005; Murthy and Wadsworth, 2005), the functional significance remains unclear and the relationship between turnover and membrane stability has not been specifically explored. An advantage of studying this issue in the early D. melanogaster embryo is that furrow formation does not rely on actomyosin-based contraction (Royou et al., 2004). Surprisingly, disrupting myosin II function through mutations, antibody injection, or small molecule inhibitors has little effect on furrow progression (Royou et al., 2004). The same experiments performed in tissue culture cells undergoing conventional cytokinesis produced profound disruptions in furrow progression (Somma et al., 2002; Echard et al., 2004; Eggert et al., 2004). Furrow invagination in the early D. melanogaster embryos is driven primarily by vesicle-mediated membrane addition (Lecuit and Wieschaus, 2000; Sisson et al., 2000; Pelissier et al., 2003; Riggs et al., 2003). This enables us to explore functions of F-actin turnover that are independent of its role in actomyosin-based contraction.

In this paper, we describe a set of experiments that demonstrate that F-actin is required for the stability of the furrow membrane and actin turnover is required for normal furrow elongation. We also propose a model in which Nuf, a Rab11 effector, regulates furrow maintenance by regulating the rate of F-actin polymerization through the RhoGEF2–Rho1 pathway.

Results

F-actin is rapidly turned over at the furrow through depolymerization and repolymerization

To investigate actin dynamics at the metaphase furrows, we injected Rhodamine-labeled monomeric actin into embryos expressing the F-actin–specific label GFP-Moesin. The specificity for F-actin labeling (Edwards et al., 1997) was confirmed by colocalization of GFP-Moesin with phalloidin staining (Fig. S1, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). Monomeric Rhodamine actin was incorporated into newly forming furrow tips (Fig. 1 A, arrowheads). Interestingly, within 15 s after injection, Rhodamine-actin was rapidly incorporated into preexisting furrows and its fluorescence continued to increase for at least 2 min after injection (Fig. 1 A, arrows). The observation that actin polymerization occurred within existing cytokinetic furrows reveals that furrows are dynamic rather than static structures.

To determine whether furrow actin undergoes both polymerization and depolymerization, we used LatA (Latrunculin A), a small molecule that inhibits actin polymerization by sequestering actin monomers. LatA was injected into GFP-Moesin–expressing embryos during furrow invagination at cycle 13. These embryos had also been previously injected with Rhodamine-labeled monomeric actin, and time was provided for the monomeric actin to fully incorporate into furrows. At 1 min 20 s after Latrunculin injection, the levels of exogenous actin and GFP-Moesin were clearly diminished (Fig. 1 B), indicating loss of F-actin from the furrow. Quantification of the signal intensities at furrows areas indicated that 4 min after injection, the Rhodamine-actin and GFP-Moesin signals were reduced by 74.4 ± 6.6% (n = 3 embryos) and 78.8 ± 2.3% (n = 3 embryos), respectively (Fig. 1 C, furrow intensity calculation). In contrast, the fluorescence signals 4 min after injection in DMSO-injected...
F-actin turnover is required for furrow invagination

To investigate the functional impact of actin turnover on furrow dynamics, we inhibited actin turnover by injecting Jasp (Jasplakinolide) or LatA into living embryos. The efficacy of Jasp was demonstrated by excess F-actin accumulation at the invaginating furrows when it was injected during cycle 13 in wild-type (WT) embryos expressing a GFP-Dlg (Discs-Large) transgene (Fig. S2, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1; Quinones-Coello et al., 2007). Dlg has previously been used as a marker for cellularization membrane in D. melanogaster (Lee et al., 2003; Grosshans et al., 2005). Both furrow invagination, determined by the length of the furrow, and furrow integrity, indicated by the furrow ring structure behind the invaginating leading edge, were analyzed using this marker. Although furrow integrity was not perturbed, furrow invagination was blocked after Jasp injection (Fig. 2, A–C). In contrast, LatA injection permitted furrow invagination but caused gaps in the furrow ring structure (Fig. 2 A), which is reminiscent of a previous study demonstrating that the free ends of incomplete metaphase furrows in nuf mutant embryos extend normally (Rothwell et al., 1999). These results indicate that depolymerization or destabilization of F-actin at the furrow is required for furrow invagination, whereas actin polymerization is required for maintaining furrow integrity.

F-actin turnover is required for furrow invagination

To better understand actin dynamics at the furrow, we quantified turnover rates of F-actin at metaphase furrows using FRAP. Previous FRAP analyses on cleavage furrows could not differentiate the actin turnover rates at the preexisting furrow and at the ingressing furrow tips (Pelham and Chang, 2002; Guha et al., 2005; Murthy and Wadsworth, 2005). Our system enables viewing of preexisting furrows and furrow tips separately at defined z depths below the embryo surface, allowing examination of actin turnover exclusively in preexisting furrows and furrow tips, respectively. Monomeric Rhodamine-actin was injected into GFP-Moesin–expressing embryos and allowed to fully incorporate into existing furrows, and then these labels were photobleached. This experiment revealed that F-actin turnover is rapid in preexisting furrows, with a fluorescence recovery t_{1/2} of 25.9 ± 1.8 s (n = 10 embryos) for GFP-Moesin and 17.9 ± 1.3 s (n = 10 embryos) for Rhodamine-actin (Fig. 1, D and E; and Video 1, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). Furthermore, the respective fluorescence labels returned to 83.8 ± 2.9% (n = 10 embryos) and 86.3 ± 3.5% (n = 10 embryos) of their prebleached intensities 80 s after photobleaching, indicating that most of the F-actin in the furrow turned over within that time period. Similar fluorescence recovery results were obtained when furrow tips were photobleached, with a t_{1/2} of 24.2 ± 2.3 s (n = 11 embryos) for GFP-Moesin and 21.6 ± 1.6 s (n = 11 embryos) for Rhodamine-actin. Accordingly, 88.7 ± 5.7% (n = 11 embryos) of the GFP-Moesin and 92.3 ± 5.3% (n = 11 embryos) of the Rhodamine-actin intensities were recovered at the furrow tips 80 s after photobleaching. Collectively, with our experiments demonstrating actin polymerization and depolymerization activities at the metaphase furrows, these results indicate that metaphase and conventional cytokinesis furrows share the property of rapid F-actin turnover.

F-actin is required for maintaining membrane integrity during furrow invagination

To further investigate the relationship between F-actin stability and membrane integrity, we injected LatA into embryos that were previously injected with Rhodamine-labeled actin and also expressed GFP-Dlg. As shown in Fig. 3 A, GFP-Dlg–marked controls were reduced only by 0.9 ± 0.4% (Rhodamine-actin; n = 3 embryos) and 0.8 ± 0.3% (GFP-Moesin; n = 3 embryos).

Figure 2. F-actin turnover is required for furrow invagination. (A) 1 mM Jasp, 2 mM LatA, or DMSO control were injected into GFP-Dlg embryos at cycle-13 early prophase (when furrow is ~3 μm in length), and furrow invagination was followed over time at depths from ~2 μm to ~8 μm below the embryo surface. (B) The lengths of invaginating furrows (y axis) over time (x axis) after 1 mM Jasp or DMSO injections in A. (C) Quantification of results in A. Increases in furrow lengths [in micrometers] 8 min after Jasp (n = 5 embryos) or DMSO (n = 5 embryos) injections were analyzed. ***, P < 0.001. Error bars represent SEM. Bar, 10 μm.
brane integrity. To further verify these results, we analyzed the effect of LatA with a different plasma membrane marker, Spider-GFP, a casein kinase I which is associated with the plasma membrane (Frescas et al., 2006). As with the GFP-Dlg, LatA injection led to breaks in the previously contiguous Spider-GFP signal (Fig. S3 B). These data demonstrate that F-actin is required for maintaining membrane integrity at the invaginating furrow.

To examine the functional consequences of disrupted plasma membrane integrity after loss of F-actin, we injected LatA into living embryos carrying Rhodamine-labeled tubulin and GFP-Dlg to monitor the mitotic spindles and furrow membrane. As expected, LatA injection led to the formation of large gaps in the furrow membrane within 4 min after injection (Fig. 3 C and Video 2, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). Interestingly, mitotic spindles adjacent to those membrane gaps began fusing 4 min after LatA injection (Fig. 3 C, asterisks; and Video 2). However, mitotic spindles adjacent to partial or intact furrow membranes remained independent of one another (Fig. 3 C and Video 2). As most of F-actin was no longer associated with the remaining furrow membrane 4 min after LatA injection (Figs. 3 B and 1 B), these data indicate that plasma membrane, not F-actin, serves as the primary barrier separating neighboring spindles from one another.

Nuf is required to maintain furrow integrity

Previous studies have shown that the RE component Nuf is required for actin and membrane recruitment to the invaginating furrow (Rothwell et al., 1998; Riggs et al., 2003). To address why nuf mutant embryos exhibit actin as well as membrane defects, we examined furrow formation in living nuf1 (the strongest nuf allele; see Materials and methods) embryos expressing GFP-Moesin. In WT control embryos expressing GFP-Moesin, no breaks were seen at furrows during furrow invagination (Fig. 4 A). In contrast, it appears that the F-actin loss initially occurs basally and progresses apically at the furrows in nuf embryos (Fig. 4 B, arrowheads). Additionally, F-actin loss expands laterally (Fig. 4 B, arrows; and Video 3, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). At metaphase, when furrows have invaginated to their maximal length, breaks were seen throughout the entire length of the furrow resulting in spindle fusions (Fig. 4 B, asterisks; and Video 3). Loss of F-actin stability was also seen in Rab11 embryos during metaphase furrow invagination (Fig. 4 C) and in nuf embryos during cellularization (Fig. S4 A, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). Given that Rab11 is required for RE integrity, these results together indicated that the RE is required to maintain F-actin stability at the invaginating furrows.

Previous work has shown membrane breaks at the furrows in nuf and Rab11 mutant embryos (Rothwell et al., 1998; Riggs et al., 2003). Our live analysis of membrane dynamics using GFP-Dlg in nuf embryos showed a loss of membrane over time (Fig. 4 D, arrowheads). This indicates that, similar to F-actin, furrow membrane is not stably maintained. To investigate if membrane integrity is dependent on F-actin stability, we injected nuf embryos expressing GFP-Dlg with Rhodamine-actin. This live analysis indicated
membrane defects in the egg chambers that prevented them from undergoing embryonic development (unpublished data). When the hypomorphic \( \text{tsr}^1 \) allele (Gunsalus et al., 1995) was introduced into the \( \text{nuf}^1 \) background, the ovaries exhibited milder membrane defects, and a portion of eggs was able to develop after fertilization: 21% (\( n = 1,551 \) eggs) of the total eggs laid by \( \text{tsr}^1 /\text{Cy}; \text{nuf}^1 /\text{nuf}^1 \) females hatched and of these larvae, 75% (\( n = 331 \) larvae) developed into adult flies, compared with a 0% (\( n = 547 \) eggs) hatch rate of eggs laid by \( \text{nuf}^1 \) females. Moreover, these \( \text{tsr}^1 /\text{Cy}; \text{nuf}^1 /\text{nuf}^1 \) embryos displayed much less severe defects than \( \text{nuf}^1 \) embryos, with fewer furrow breaks and spindle fusions in metaphase and cellularizing furrows (Fig. 5, A and B; Video 5, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1; and not depicted). The suppression of \( \text{nuf} \) phenotype by reducing Twinstar dosage supports a role for Nuf in promoting actin polymerization at the furrow.

Drug-induced actin polymerization and stabilization suppresses the furrow defects exhibited by \( \text{nuf} \) embryos

To further test the possibility that Nuf promotes furrow integrity by promoting actin polymerization, we artificially enhanced actin nucleation and polymerization by injecting Jasp into \( \text{nuf} \) embryos and monitored furrow membrane dynamics with GFP-Dlg. In contrast to \( \text{nuf} \) control embryos (Fig. 5 C, top row; and Video 6, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1), \( \text{nuf} \) embryos injected with Jasp during nuclear cycle-13 early prophase (when furrow integrity is

Genetically reducing actin depolymerization rescues the furrow defects observed in \( \text{nuf} \) embryos

The striking reduction of furrow F-actin in \( \text{nuf} \) mutant embryos raises the question: does Nuf promote actin polymerization or stabilization at the furrow? If Nuf has such a function, one prediction would be that reducing actin depolymerization should suppress furrow defects in \( \text{nuf} \) embryos. Cofilin is a well-known actin depolymerizer in a variety of processes that require remodeling of the actin cytoskeleton including cell migration and cytokinesis (Ono, 2007). Homozygous mutations for \( \text{tsr} \) (twinstar), the \( \text{D. melanogaster} \) Cofilin homologue, are zygotic lethal and cause cytokinesis defects in contractile ring disassembly (Gunsalus et al., 1995). To test whether \( \text{tsr} \) can rescue the \( \text{nuf} \) phenotype, we collected eggs laid by female flies homozygous for \( \text{nuf} \) and heterozygous for \( \text{tsr} \) and then examined them for furrow and spindle morphology during cycle 13 in early embryogenesis. When twinstar-null alleles \( \text{tsr}^{N96A} \) and \( \text{tsr}^{N121} \) (Ng and Luo, 2004) were crossed into the homozygous \( \text{nuf}^1 \) background (e.g., \( \text{tsr}^{N96A}/\text{Cy}; \text{nuf}^1/\text{nuf}^1 \)), all the female ovaries had strong membrane defects in the egg chambers that prevented them from undergoing embryonic development (unpublished data). When the hypomorphic \( \text{tsr}^1 \) allele (Gunsalus et al., 1995) was introduced into the \( \text{nuf}^1 \) background, the ovaries exhibited milder membrane defects, and a portion of eggs was able to develop after fertilization: 21% (\( n = 1,551 \) eggs) of the total eggs laid by \( \text{tsr}^1/\text{Cy}; \text{nuf}^1/\text{nuf}^1 \) females hatched and of these larvae, 75% (\( n = 331 \) larvae) developed into adult flies, compared with a 0% (\( n = 547 \) eggs) hatch rate of eggs laid by \( \text{nuf}^1 \) females. Moreover, these \( \text{tsr}^1/\text{Cy}; \text{nuf}^1/\text{nuf}^1 \) embryos displayed much less severe defects than \( \text{nuf}^1 \) embryos, with fewer furrow breaks and spindle fusions in metaphase and cellularizing furrows (Fig. 5, A and B; Video 5, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1; and not depicted). The suppression of \( \text{nuf} \) phenotype by reducing Twinstar dosage supports a role for Nuf in promoting actin polymerization at the furrow.

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still relatively normal) showed almost no further loss of membrane (Fig. 5, B and C [bottom row]; and Video 7) or F-actin (Fig. S4 B) at the metaphase furrows. In regions where furrow membrane was already lost before injection, Jasp did not induce new membrane growth to fill the furrow gaps (Fig. 5 D), which is consistent with our finding that Jasp functions to stabilize actin cytoskeleton and its associated plasma membrane (Fig. 2, A – C). Jasp also disrupted spindle formation (Fig. S4 B), and thus spindle fusion was not pursued in these Jasp-treated embryos. In conclusion, actin assembly and stabilization driven by Jasp suppresses the reduced Rho signaling in the eye (Gregory et al., 2005). We examined if RhoA and Nuf share a common function in promoting furrow polymerization at the furrow, which in turn stabilizes furrow membrane.

**Up-regulating RhoA activities compensates the furrow defects observed in nuf embryos**

Insight into the mechanism by which Nuf promotes actin polymerization comes from the observation that overexpression of Nuf suppresses the reduced Rho signaling in the eye (Gregory et al., 2007). In addition, both RhoA and Nuf are crucial in actin remodeling at the furrows (Crawford et al., 1998; Prokopenko et al., 1999; Riggs et al., 2003; Padash Barmchi et al., 2005; Piekný et al., 2005). We examined if RhoA and Nuf share a common function in promoting furrow maintenance by testing if reduced RhoA activity produces the nuf phenotype. The Rho inhibitor C3 extransfere was injected into cycle-13 prophase embryos expressing GFP-Dlg. C3 transfere has been widely used to block Rho signaling in different systems including cellularization and conventional cytokinesis (Crawford et al., 1998; Bement et al., 2005). Similar to embryos deficient for Nuf or injected with LatA, C3-treated embryos induced membrane loss over time, which eventually led to neighboring spindle fusions (Fig. 6 A and Video 8, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). Importantly, loss of F-actin also precedes loss of membrane at the furrows after C3 injection (Fig. 6 B). This indicates that, similar to nuf embryos, blocking Rho activity induces loss of F-actin stability at the furrow, which results in loss of membrane integrity. The phenotypes of reducing Rho or Nuf function are strikingly similar, suggesting that Nuf functions within a Rho pathway to promote furrow integrity.

To test if RhoA and Nuf function in the same pathway for furrow maintenance, a constitutively active mammalian RhoA(Q63L) protein was injected into nuf embryos. *D. melanogaster* RhoA is highly related to its mammalian counterpart (Hariharan et al., 1995) and studies have shown that mammalian RhoA constructs are effective tools to inhibit the *D. melanogaster* RhoA pathway. Injection or expression of the constitutively active or dominant-negative mammalian RhoA in the *D. melanogaster* embryo specifically disrupts endogenous RhoA signaling (Crawford et al., 1998; Harden et al., 1999). RhoA(Q63L) injection into nuf embryos suppressed the nuf phenotype near the site of injection, where furrows were formed and maintained normally (Fig. 6 C, arrow; and Video 9, available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). In regions distant from the injection site, typical nuf-induced furrow defects were observed (Fig. 6 C, arrowheads; and Video 9). To verify the localized RhoA-GTP rescue, we performed injections in different embryonic regions. Rescue always correlated with site of injection during both cycle 13 (n = 6, 5, and 6 embryos for anterior, posterior, and central injection, respectively) and cellularization.
Nuf functions within the RhoA pathway to promote furrow integrity. (A and B) 1 mg/ml C3 transferase was injected at cycle-13 early prophase. (A) GFP-Dlg–marked furrow membrane (green) was progressively lost and eventually led to spindle fusions (red, asterisks). See Video 8 (available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). (B) 2 min after C3 injection, most of the F-actin has been lost from the furrow (bottom). In contrast, membrane loss has just started (top). (C) 1 mg/ml RhoA(Q63L) was injected into nuf embryos at cycle-13 early interphase. Green, GFP-Moesin; red, tubulin. At metaphase (18:00), normal furrow structures were maintained in the region close to injection site (arrow); however, loss of F-actin at the furrows is evident further away from the site of injection (arrowheads). See Video 9 (available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1). Bars: [A] 10 μm; [B] 5 μm; [C] 20 μm.

Figure 6. Nuf functions within the RhoA pathway to promote furrow integrity.
row defects in combination with nuf. The Arp2/3 complex has also been shown to drive actin polymerization for metaphase furrow assembly (Stevenson et al., 2002). Genetic interactions were tested between Arpc1 (Hudson and Cooley, 2002), which encodes the p40 subunit of Arp2/3, and nuf; however, no obvious furrow defects were observed (Fig. 7G and Table I). Among several possible interpretations, the strong dominant genetic interactions between Nuf, RhoGEF2, and Rho1 support a model in which these proteins cooperate in a common pathway to promote actin polymerization and furrow maintenance.
Discussion

F-actin rapidly turns over during myosin II-independent furrow invagination

Although the composition and dynamics of the cortical cytoskeleton associated with metaphase and cellularization furrows invagination have been well characterized (Foe et al., 1993, 2000), much remains unknown about the mechanisms driving actin dynamics and distribution at these furrows. To address this issue, we determined the turnover rates of F-actin by performing FRAP analysis on the furrow-associated F-actin located at the tip and 1–2 μm behind the leading edge of the furrow. These studies demonstrate that GFP-Moesin, an F-actin binding protein, and injected Rhodamine-labeled actin are rapidly turned over. The turnover rates are comparable with turnover rates observed in LLCPK1 epithelial cell contractile ring (26 s; Murthy and Wadsworth, 2005), normal rat kidney cell equatorial cortex (12–15 s; Guha et al., 2005) and fission yeast contractile ring (~25 s; Pelham and Chang, 2002). Furthermore, rapid incorporation of G-actin into preexisting furrow-actin filaments and rapid disappearance of F-actin from preexisting furrows after LatA treatment indicate that both actin polymerization and depolymerization contribute to F-actin turnover at the furrow. These studies are in accord with previous work demonstrating rapid turnover of actin at the cleavage furrows (Pelham and Chang, 2002; Guha et al., 2005; Murthy and Wadsworth, 2005). Although previous work focused on F-actin turnover specifically at the contractile ring, our studies demonstrate that F-actin also turns over in a myosin-free zone well behind the leading edge of the ingressing furrow (Royou et al., 2004).

Actin turnover coordinates furrow invagination with furrow integrity

Although it is likely that rapid actin turnover will prove to be a conserved feature of cytokinetic furrows, its functional significance remains unclear. F-actin turnover may be required for proper actomyosin-based constriction of the contractile ring, as this structure decreases in volume as constriction proceeds (Schroeder, 1972). However, the F-actin turnover observed behind the leading edge of D. melanogaster metaphase and cellularization furrows is likely to have additional function, as furrow ingression is not dependent on actomyosin-based contraction (Royou et al., 2004). Rather, ingression of these furrows relies largely on vesicle-mediated membrane addition (Lecuit and Wieschaus, 2000; Sisson et al., 2000; Pelissier et al., 2003; Riggs et al., 2003). Consequently, we analyzed the relationship between F-actin turnover, furrow membrane stability, and ingression by simultaneously monitoring plasma membrane and F-actin dynamics. We find that LatA injection results in an immediate loss of F-actin. In addition, the loss of F-actin after LatA treatment always precedes loss of furrow membrane integrity. These results indicate that cortical F-actin is critical for maintaining furrow membrane integrity. Previous studies demonstrated that LatA-induced disruption of F-actin results in relaxation of the cleavage furrow (Murthy and Wadsworth, 2005). Our studies suggest that this relaxation may be in part caused by loss of furrow membrane integrity. Our finding also provides a possible explanation for the observation that mutants in Anillin, an F-actin bundling protein, produce large gaps in the plasma membrane of the cellularization furrow (Field et al., 2005). These gaps may also be a direct consequence of F-actin loss.

To understand the functional significance of F-actin turnover at the furrow, we injected Jasp, a drug that stabilizes F-actin by inhibiting F-actin turnover (Bubb et al., 2000; Murthy and Wadsworth, 2005). Jasp resulted in a robust accumulation of F-actin at the furrows but did not disrupt furrow integrity. However, it prevented both furrow progression and regression, indicating an increase in furrow stability. This result is consistent with studies in other systems demonstrating that excess accumulation or stabilization of F-actin significantly slowed or blocked progression of the cleavage furrows (O’Connell et al., 2001; Murthy and Wadsworth, 2005; Mukhina et al., 2007). Those studies were performed in cells in which furrow advancement requires actomyosin-based contraction at the contractile ring and, thus, it remained unclear if the block of furrow

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<th>Maternal genotypes</th>
<th>Weak furrow</th>
<th>Very weak furrow</th>
<th>With breaks in furrow</th>
<th>Normal furrow morphology</th>
<th>Total embryos examined</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>35 (100%)</td>
<td>35</td>
</tr>
<tr>
<td>nuf1/+</td>
<td>3 (11%)</td>
<td>1 (4%)</td>
<td>0</td>
<td>23 (85%)</td>
<td>26</td>
</tr>
<tr>
<td>RhoGEF241/+</td>
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<td>0</td>
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<td>12</td>
</tr>
<tr>
<td>Rho1720/+</td>
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<td>0</td>
<td>7 (87%)</td>
<td>8</td>
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<tr>
<td>chic21/+</td>
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<td>0</td>
<td>0</td>
<td>12 (100%)</td>
<td>12</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
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</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>12 (100%)</td>
<td>12</td>
</tr>
<tr>
<td>RhoGEF241/Rho1720</td>
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<td>3 (23%)</td>
<td>7 (54%)</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>RhoGEF241/+; nuf1/+</td>
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<td>7 (39%)</td>
<td>0</td>
<td>4 (22%)</td>
<td>18</td>
</tr>
<tr>
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<td>1 (8%)</td>
<td>5 (42%)</td>
<td>3 (25%)</td>
<td>12</td>
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<tr>
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<td>2 (15%)</td>
<td>3 (23%)</td>
<td>4 (31%)</td>
<td>13</td>
</tr>
<tr>
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<td>0</td>
<td>5 (50%)</td>
<td>2 (20%)</td>
<td>10</td>
</tr>
<tr>
<td>Arpc1235sd/+; nuf1/+</td>
<td>2 (18%)</td>
<td>0</td>
<td>9 (82%)</td>
<td></td>
<td>11</td>
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</tbody>
</table>

Table I. Summary of furrow phenotypic frequencies in Fig. 7 G.

The number of embryos exhibiting the phenotype under each group is shown and the frequency is also indicated.
progression was solely caused by inhibition of contractile ring constriction. Because furrow invagination in the early D. melanogaster embryo is primarily the result of vesicle-mediated membrane addition and it does not require actomyosin-based constriction, the Jasp-induced block of metaphase furrow progression is likely caused by inhibition of processes other than actomyosin-based constriction.

One explanation for these results comes from studies demonstrating that cortical F-actin acts as a barrier preventing vesicles from gaining access to docking and fusion sites at the plasma membrane. Studies suggest that transient depolymerization of F-actin at the membrane–actin cytoskeleton interface facilitates membrane addition to the furrow (Eitzen, 2003). The recent realization that vesicle-mediated membrane addition plays an important role in ingress of the cytokinetic furrow (Albertson et al., 2005) raises the possibility that the defects in F-actin organization precede and cause the membrane defects observed in nuf and Rab11 mutant embryos. Support for this idea comes from our finding that the initial defect in nuf embryos is the formation of large gaps in the invaginating furrow-associated F-actin. Shortly after loss of F-actin, we observed loss of membrane integrity in the same region. This phenotype is strikingly similar to that observed in LatA-treated embryos: an immediate loss of F-actin followed by a loss of membrane integrity. These results suggest that a primary function of Nuf during furrow invagination is to maintain high levels of F-actin along the length of the furrows. In addition, we conclude that at least some of the observed membrane defects in nuf embryos are a direct consequence of the defects in F-actin organization (Fig. 8).

Because F-actin is rapidly turning over, the abundance of F-actin in any given region of the furrow depends on the relative polymerization and depolymerization rates. Thus, one explanation for the failure to maintain F-actin at thefurrows in nuf embryos is a disruption in the relative rates of polymerization and depolymerization. To test this idea, we artificially increased the rate of actin polymerization in nuf embryos by injecting Jas. The Jas injections prevented loss of furrow-associated F-actin in nuf embryos. Significantly, in addition to maintaining F-actin integrity, the Jas injections also maintained furrow membrane integrity in nuf embryos. We confirmed this result by genetically reducing the dosage of Twinstar/Coﬁlin in nuf embryos. Coﬁlin is known to sever and depolymerize F-actin during cell migration and cytokinesis (Ono, 2007). Thus, reducing Coﬁlin dosage is likely to reduce the rate of actin depolymerization and increase cortical F-actin levels. In accord with this reasoning, we find that reducing the dosage of Twinstar, the D. melanogaster homologue of coﬁlin, dramatically suppresses both the F-actin and membrane defects observed in nuf embryos. In contrast to embryos carrying the
normal dosage of twinstar, nuf embryos with reduced dosage of twinstar exhibited relatively normal metaphase and cellularization furrows. Normally, none of the eggs hatch from nuf embryos. However, in nuf embryos with reduced levels of Twinstar, significant egg hatch was observed and a large proportion of these gave rise to adults. These findings strongly support the idea that the primary defect in nuf embryos is a failure to maintain sufficient levels of F-actin at the plasma membrane during furrow invagination. The loss of F-actin ultimately results in loss of integrity in the plasma membrane.

**RE-derived vesicles deliver actin polymerization activity to the invaginating furrows**

Our studies raise the issue of the mechanism by which Nuf promotes F-actin stability during furrow invagination. Previous studies demonstrated that vesicles near the invaginating furrow are often associated with F-actin, raising the possibility that F-actin and vesicles are delivered as a unit to the invaginating furrows (Rothwell et al., 1999). It may be that as F-actin is depolymerized at the furrow, new F-actin is directly supplied by vesicle-mediated delivery. Support for this idea comes from studies in cultured animal cells demonstrating that F-actin is transported along the cortex to the ingressing furrow (Cao and Wang, 1990). It may be that, like in the D. melanogaster embryo, this cortically transported F-actin is vesicle associated.

An alternative explanation is based on the idea that RE-derived vesicles destined for invaginating furrows may carry potent actin remodelers (Riggs et al., 2003). Support for this model is provided by several studies demonstrating that RhoGEF2 and its downstream effectors Rho1 and Diaphanous are required for proper actin remodeling at the metaphase and cellularization furrows (Crawford et al., 1998; Afshar et al., 2000; Grosshans et al., 2005; Padash Barmchi et al., 2005). Analysis of RhoGEF2 mutants was particularly intriguing because the resulting gaps in the furrow-associated F-actin were strikingly similar to those observed in nuf and Rab11 embryos. In addition, RhoGEF2 was observed not only at the invaginating membrane but also in puncta throughout the cortex, raising the possibility that it is delivered through vesicles (Padash Barmchi et al., 2005).

In this paper, we find that RhoGEF2 delivery and localization at the metaphase furrows require Nuf and Rab11. In nuf embryos, although Rho1 and Diaphanous were mislocalized only in the region where furrow was disrupted, RhoGEF2 was globally diffuse around the furrow, implying a specific role for the RE in delivering RhoGEF2. We also find that treating embryos with the Rho inhibitor C3 exotransferase produces phenotypes similar to nuf, in which loss of F-actin at the furrow precedes membrane loss. Conversely, injecting constitutively active RhoA into nuf embryos rescues the nuf-induced furrow defects specifically at the injection site.

Synthetic genetic interactions between Nuf and the RhoGEF2–Rho1 pathway further support the model that vesicles derived from RE ferry both membrane and actin-remodeling activity to the invaginating furrow. This model emphasizes an important role for the RE in linking membrane addition to actin remodeling at the invaginating metaphase furrow, which may also be true for conventional cytokinesis. Further, because membrane addition requires transient actin depolymerization (Eitzen, 2003), by promoting actin polymerization at the site of membrane addition, this pathway compensates for the transient loss of F-actin during vesicle delivery.

**Materials and methods**

**Fly strains and genetics**

Experiments involving all nuf or Rab11 mutants were performed using the nuf-null allele or Rab11D102D1/Rab11D102D1 transheterozygous combination (Rothwell et al., 1998; 1999; Riggs et al., 2003). Germline clones of RhoGEF2 were generated using the FlpDF technique (Chou and Perrimon, 1996). The following stocks were obtained from the Bloomington Drosophila Stock Center (Indiana) and are reported as null [N] or hypomorphic alleles [H] according to Flybase: Rab1L102D1 [H], Rab1D102D1 [H], RhoGEF2-1 [N], RhoGEF2-2 [N], RhoGEF2-3 [N], RhoGEF2-4 [N]. These gave rise to adults. These findings strongly support the model that vesicles near the invaginating furrow are delivered through vesicles (Padash Barmchi et al., 2005). Other stocks used were: Nuf[tsr 1]N96A; Sop2Q22sd [N], tsr[tsr 1]N96A [N], and tsr[tsr 2D1]N96A [N]. For live embryo imaging, we used the following stocks: GFP-Moesin (gift from D. Kiehart, Duke University, Durham, NC; Edwards et al., 1997), GFP-Dlg (FlyTrap Project; Quinones-Coello et al., 2007), and Spider-GFP (created by A. Debec, Université Pierre et Marie Curie, Observatoire Océanologique, Villefranche-sur-mer, France), provided by J. Lippincott-Schwartz (National Institutes of Health, Bethesda, MD). Oregon R flies served as the WT control for all immunostained samples. All stocks were raised at 25°C on standard maize meal/molasses media.

**Embryo fixation and immunostaining**

Embryos were dechorionated in 50% Clorex bleach solution pretreated with 1:1 PBS/heptane solution for 45 s before adding an equal volume of 16.5% formaldehyde + 18% PFA (EM Sciences). The embryos were fixed for 22–25 min at 25°C and devitellinized by hand with a needle under a dissecting microscope. Immunofluorescence analysis was performed as previously described (Rothwell and Sullivan, 2000; Siisson et al., 2000). Alexa 488–conjugated, Rhodamine-conjugated, or Alexa 647–conjugated phallolidin (Invitrogen) was used to stain F-actin, and propidium iodide was used to stain DNA. The primary antibodies used include the following: rabbit anti-RhoGEF2 [1:500; provided by S. Rogers, University of North Carolina, Chapel Hill, NC; Rogers et al., 2004], mouse anti-Rho1 [1:10; Developmental Studies Hybridoma Bank], rabbit anti-Diaphanous [1:1,000; provided by S. Wasserman, University of California, San Diego, La Jolla, CA; Afshar et al., 2000], mouse anti-Dlg [1:100; provided by C. Doe, University of Oregon, Eugene, OR; Zito et al., 1997], and CyS-conjugated anti-Anillin [1:200; Field and Alberts, 1995]. Secondary Alexa 488–conjugated antibodies were used at 1:300 [Invitrogen].

**Live embryo analysis**

Embryos were prepared for microinjection and time-lapse scanning confocal microscopy as previously described (Tram et al., 2001). Except in Figs. 6C and 5D, all the reagents were injected at the 50% egg length and were diluted to 100-fold in the embryos [Foe and Alberts, 1983]. Except for the experiment after actin incorporation into the furrow, 10 mg/ml Rhodamine-conjugated actin [Cytoskeleton, Inc.] and 10 mg/ml Rhodamine-conjugated tubulin [Cytoskeleton, Inc.] were injected into the embryos one cycle before drug injections and imaging. The following drugs were injected either at early cycle-13 prophase or early cellularization: DMSO alone (Sigma-Aldrich), 2 mM Latrunculin A (in DMSO; Sigma-Aldrich), 1 mM Jasp (in DMSO; EMD and provided by P. Crews, University of California, Santa Cruz, Santa Cruz, CA), and 1 mg/ml C3 exotransferase [Cytoskeleton, Inc.]. C3 transferase is an ADP ribosyl transferase that selectively ribosylates and inactivates Rho-GTP with high specificity (Aktories et al., 1989; Sekine et al., 1989). 1 mg/ml of the constitutively active form of human recombinant RhoA protein [Q63L; Cytoskeleton Inc.] was injected at either early cycle-13 interphase or early cellularization. RhoA [Q63L] has a glutamine-to-leucine substitution at residue 63, preventing GTP hydrolysis, and maintains the protein in the active GTP-bound state (Gallos et al., 2002; Zhang et al., 2003). As described previously (Siisson et al., 2000), DMSO injection alone caused nuclei to move slightly away from the embryo cortex, but it had little effect on membrane and actin dynamics at the furrow.

**Confocal microscopy, image quantifications, and statistics**

Confocal microscope images were captured on an inverted photoscope (DMIRE2; Leitz) equipped with a laser confocal imaging system (TCS SP2; Leica Microsystems), and were processed using MetaMorph Imaging Software. ImageJ (Wayne Rasband, National Institutes of Health) was used for analysis of confocal images. Two-tailed t-tests (Statview software, SAS Institute) were used to determine if differences were statistically significant.
Leica) using an HCX PL APO 1.4 NA 63× oil objective (Leica) at room temperature. Except in FRAP experiments, ImageJ software (National Institutes of Health) was used to quantify the confocal images. For LatA injection experiments (Fig. 1 B), fluorescence intensities of GFP-Moesin and Rhodamine-actin at the furrows were subtracted from the background intensities measured from the nucleus regions. At least eight furrows and eight nuclear regions were analyzed in each embryo. In Table I and Fig. 7 G, based on the furrow morphology, embryos were classified into different groups: weak furrow (>10% of the furrows within an embryo showing uneven F-actin distribution), very weak furrow (>10% of the furrows within an embryo showing very uneven F-actin distribution), with breaks in furrow (>5% of the furrows within an embryo are broken), and normal furrow morphology. Student’s t test (two-tailed, equal variance) was performed to analyze the data for furrow invagination, furrow-break index, and spindle-fusion index. Error bars represent the SEM from at least three independent experiments. For videos, image series collected over time were cropped in ImageReady (v9.0; Adobe) and converted to QuickTime (Apple) videos using PNG lossless compression.

FRAP analysis

Imaging was controlled by the Leica Confocal Software Microlab. After five prebleach scans of an entire image, 10 bleaching scans (0.7 s each) with 100% intensity of 488 nm for GFP-Moesin or 100% intensity of 488 and 543 nm for Rhodamine-labeled actin) over the region of interest (10 × 10 μm) were performed. After photobleaching, the fluorescence recovery was monitored 10 times every 0.7 s and 60 times every 2 s. The recovery of fluorescence intensities, specifically at the furrow region, was monitored with Microlab. This software only measures a fixed x-y region. Thus, in a few cases where furrow structures showed slight drifts during fluorescence recovery, the FRAP image series were quantified using ImageJ software. The intensity of the bleached furrow area was normalized to the background nonbleached area. Recovery percentage was calculated as the final plateau intensity (I0) minus the first intensity after photobleaching (I stimulated by the inabolition of rho activity and the activation of Cdc42 function. Dev. Biol. 204:151–164.

**Online supplemental material**

Fig. S1 shows that GFP-Moesin marks F-actin cap and furrow. Fig. S2 shows that Jasp induces excess actin polymerization around the furrow. Fig. S3 shows that LatA injection results in disruption of GFP-Dlg and Spider-GFP–marked furrow plasma membrane integrity. Fig. S4 shows suppression of nuf phenotypes. Fig. S5 shows localization of RhoGEF2 and F-actin in nuf and Rab7½ embryos. Video 1 shows that F-actin signal is rapidly recovered at the furrow after photobleaching. Video 2 shows that LatA injection results in loss of membrane integrity and spindle fusions. Video 3 shows that F-actin is not stably maintained in nuf embryos. Video 4 shows that F-actin loss precedes membrane loss in nuf embryos. Video 5 shows that reducing the dosage of Tweakstabilizes F-actin at the furrow in nuf embryos. Video 6 shows that GFP-Dlg–marked furrow membrane is not stably maintained in nuf embryos treated with DMGQ. Video 7 shows that Jasp injection stabilizes membrane at the furrow in nuf embryos. Video 8 shows that C3 extracellular injection results in loss of membrane integrity and spindle fusions. Video 9 shows that RhoA(Q63J) suppresses the nuf furrow defects local to the injection site. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.200712036/DC1.

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References


