A microtubule-dependent zone of active RhoA during cleavage plane specification

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Cytokinesis in animal cells results from the assembly and constriction of a circumferential array of actin filaments and myosin-2. Microtubules of the mitotic apparatus determine the position at which the cytokinetic actomyosin array forms, but the molecular mechanisms by which they do so remain unknown. The small GTPase RhoA has previously been implicated in cytokinesis. Using four-dimensional microscopy and a probe for active RhoA, we show that active RhoA concentrates in a precisely bounded zone before cytokinesis and is independent of actin assembly. Cytokinetic RhoA activity zones are common to four echinoderm species, the vertebrate Xenopus laevis, and the highly asymmetric cytokinesis accompanying meiosis. Microtubules direct the formation and placement of the RhoA activity zone, and the zone is repositioned after physical spindle displacement. We conclude that microtubules specify the cytokinetic apparatus via a dynamic zone of local RhoA activity.

Introduction

In animal cells, cytokinesis is accomplished by an array of actin filaments and myosin-2 that assembles and closes at the cell equator between the separating chromosomes. Nearly 50 yr ago, it was demonstrated that physical extirpation of the mitotic spindle prevents formation of the cytokinetic apparatus in echinoderm embryos (Hiramoto, 1956). In the years since then, a variety of physical (Rappaport and Conrad, 1963), pharmacological (Hamaguchi, 1975), and molecular genetic (Abraham et al., 1983) approaches have confirmed that microtubules direct cytokinetic array assembly and positioning and do so via a mechanism that is remarkably plastic. That is, the signal provided by microtubules for cytokinetic apparatus specification is operative during an incredibly broad range of biological variation, including equilateral, unilateral, and asymmetric cytokinesis, and spans several orders of magnitude in cell size (Rappaport, 1996). It is also operative in the face of experimental manipulations that drastically change the relationship between the spindle and cell surface (Rappaport, 1996). It is also operative in the face of experimental manipulations that drastically change the relationship between the spindle and cell surface (Rappaport, 1996; Alsop and Zhang, 2004). This plasticity befits the importance of cytokinesis. At present, however, the signal(s) provided by microtubules that direct cytokinetic apparatus specification remains mysterious, as does the basis of its plasticity.

RhoA is a small GTPase that positively regulates actomyosin contractility. Based on studies using RhoA inhibitors or molecular genetic manipulation, RhoA is thought to be required for cytokinesis in diverse organisms (Kishi et al., 1993; Mabuchi et al., 1993; Drechsel et al., 1997; Jantsch-Plunger et al., 2000). Furthermore, RhoA localizes to the furrow region in mammalian cells (Takaishi et al., 1995; Yonemura et al., 2004). In addition, Ect2 (also known as Pbl), a RhoA guanine nucleotide exchange factor that promotes RhoA activation, localizes to the cytokinetic furrow and is required for cytokinesis in cultured mammalian cells (Tatsumoto et al., 1999) and Drosophila melanogaster (Prokopenko et al., 1999).

However, simple localization of RhoA does not necessarily reflect high RhoA activity (Pertz and Hahn, 2004). Indeed, CYK-4 (also known as MgcRacGAP), a RhoA GTPase-activating protein (GAP) that inactivates RhoA (Jantsch-Plunger et al., 2000; Minoshima et al., 2003), forms a complex with Ect2 (Sowers and Saint, 2003) and likewise localizes to the furrow region (Hirose et al., 2001; Minoshima et al., 2003; Sowers and Saint, 2003). The GAP activity of CYK-4 is required for cytokinesis (Hirose et al., 2001; Somers and Saint, 2003; Lee et al., 2004). Moreover, the only studies to monitor local RhoA activity during cytokinesis have led to the conclusion that RhoA activation in the furrow region either occurs only after the onset of cytokinetic apparatus specification or not at all (Yoshizaki et al., 2003, 2004), leading to the proposal that local RhoA inactivation, rather than activation, directs cytokinetic apparatus assembly (Yoshizaki et al., 2003).
Thus, whether active RhoA represents a link between microtubules and cytokinetic apparatus assembly remains unclear. In this study, we use a fluorescent reporter for RhoA activity (Benink and Bement, 2005) and four-dimensional imaging to monitor the distribution of active RhoA in echinoderm and amphibian embryonic cells. These large cells provide excellent spatial and temporal resolution, whereas the application of four-dimensional imaging ensures that spatially or temporally localized signals are not missed. Furthermore, echinoderm embryos permit a number of physical manipulations that are difficult to conduct in other systems. By exploiting these advantages, we show that microtubules specify the cleavage plane by directing the formation and spatial extent of a highly localized zone of RhoA activity.

Results

A local zone of RhoA activity during cytokinesis

If RhoA represents a link between microtubules and the cytokinetic apparatus, active RhoA should concentrate in the furrow region. To test this, fertilized eggs of *Strongylocentrotus purpuratus* (purple urchins) or *S. droebachiensis* (green urchins) were microinjected with mRNA encoding eGFP fused to the Rho GTPase–binding domain (rGBD) of rhotekin (eGFP-rGBD). The rhotekin fragment binds specifically to RhoA-GTP (i.e., active RhoA) in biochemical pull-down assays, and eGFP-rGBD is a faithful reporter of local RhoA activity in living *X. laevis* oocytes (Benink and Bement, 2005).

Urchin embryos injected with mRNA encoding eGFP-rGBD showed sufficient expression to allow four-dimensional imaging by the two-to-four-cell stage. Four-dimensional image series showed that eGFP-rGBD consistently concentrated at the equator of purple (Fig. 1, A and B, and Video 1) and green (Fig. 1 C and Video 2, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1) urchin blastomeres in narrow zones, coinciding precisely with the sites of furrow formation (Fig. 1, A–C). The zones moved inward in concert with ingressing cleavage furrows and disappeared after the completion of cleavage. Before anaphase, RhoA activity was apparent at a lower level throughout the cortex. This ubiquitous activity, which was more prominent in green than in purple urchins (Fig. 1 C), disappeared abruptly at the onset of anaphase before the emergence of the equatorial RhoA zone.

To confirm that eGFP-rGBD specifically labels active RhoA, we injected C3 exotransferase, a specific inhibitor of RhoA in vertebrates and echinoderms (Kishi et al., 1993), into one blastomere of two-cell embryos that were previously injected with eGFP-rGBD. C3-injected cells failed to cleave and likewise failed to concentrate eGFP-rGBD at either the cell cortex or the equator (Fig. S1, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1). Furthermore, eGFP alone failed to concentrate at the cortex or cleavage furrow (Fig. S1).

Figure 1.  **A zone of RhoA activity in echinoderm and amphibian cytokinesis.** (A) Surface view of four-cell purple urchin embryo; projection of 18 1-μm sections. eGFP-rGBD begins to accumulate immediately before furrowing (arrowheads), brightens, and disappears once furrows are complete. (B) Surface view of eight-cell purple urchin embryo; projection of 18 1-μm sections. eGFP-rGBD accumulates before the furrow appears (arrowheads) at the site of the future furrow. (C) Sectional view through eight-cell green urchin embryo; projection of 16 1-μm sections. Before cleavage [00:00], eGFP-rGBD reveals uniform, cortical RhoA activity, which disappears [02:40] before localized activation of RhoA in the equator (arrowhead, 04:40), where the furrow will develop [06:40]. (D) Surface view of *X. laevis* embryo; projection of 12 sections. eGFP-rGBD appears in narrow stripes (arrowheads) that presage furrow formation. See online supplemental material for Videos corresponding to B–D [Videos 1–3, respectively, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1]. Times are given in minutes:seconds after filming began. Bars, 25 μm.
To explore the generality of RhoA activation in cytokinesis, eGFP-rGBD was microinjected into embryos of two additional echinoderms—sand dollars and starfish—and the vertebrate X. laevis. Four-dimensional imaging confirmed that in these organisms, RhoA activation at the equator presaged cytokinesis (Fig. 1 D; Video 3; and Fig. S2, A and B, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1). Local RhoA activation at the equator also preceded furrowing in the much smaller epithelial cells of the echinoderm and X. laevis blastulae and gastrulae (Fig. S2 C and not depicted).

Further analysis revealed additional features of the cytokinetic RhoA zones. First, the width of the RhoA zone remains nearly constant as furrowing progresses, as shown both by inspection (Fig. 2 A) and by signal intensity analysis of lines drawn along the plasma membrane at successive times during cytokinesis (Fig. 2, E and F). Second, the width of the RhoA zone varied linearly in relation to cell diameter over a range of 5–15 μm (Fig. 2 G) in both species of urchin and frog (Fig. 2 H). Third, a comparison of the timing of eGFP-rGBD accumulation to furrowing onset revealed that the RhoA zone preceded furrowing by 1–4 min (Fig. 2, I and J).

The eGFP-rGBD probe also appeared to label the spindle (Fig. 2, A and B) and centrosomes (Fig. 2 B). To distinguish between probe-specific versus nonspecific labeling, we coinjected TRITC dextran and subtracted it from the eGFP-rGBD signal. This showed that only the cortical and centrosomal accumulation is specific to the eGFP-rGBD probe, whereas the apparent spindle signal reflected the exclusion of organelles from the spindle region and the corresponding enrichment of cytoplasm (Fig. 2, C and D).

Figure 2. Characteristics of RhoA activity zones. [A] Single optical sections through a green urchin blastomere before, early, and late in furrowing showing zone in cross section. Bar, 25 μm. [B] Single optical sections through a blastomere from green urchin embryo showing eGFP-rGBD accumulation in spindle region. Chromosomes appear as a dark band (arrow, 15:12) that splits (arrows, 19:00) during anaphase. eGFP-rGBD highlights the centrosomes at all phases of mitosis (arrowhead, 26:00). Times are given in minutes:seconds after filming began. [C and D] Images of rGBD-eGFP (top), TRITC dextran (bottom), and difference images (middle) show that only the signal at the very cortex (C) and at the centrosome (D, arrowheads) is specific to eGFP-rGBD. Images in C are the mean of three successive frames and in D are the mean of 10 successive frames at 3-s intervals. [E and E’] eGFP-rGBD signal intensity measured along the cortex during division in green urchin. E shows raw data from single optical sections 2 min apart (from the cell shown in A), with time points ordered along the rainbow from red to violet. E’ shows curves obtained by fitting a weighted sum of a Gaussian and quadratic to the data in E. The Gaussian fits the furrow signal, whereas the quadratic fits the rest of the cortex. In this and five similar traces we performed, we note that the width of the fit Gaussian varies by 10% or less as the furrow ingresses despite the increasing curvature of the cortex. [F and F’] eGFP-rGBD signal intensity measured along the cortex during division in X. laevis embryo. F shows raw data from single optical sections 2 min apart (from the cell shown in A), with time points ordered along the rainbow from red to violet. F’ shows curves obtained by fitting a weighted sum of a Gaussian and quadratic to the data in E. The Gaussian fits the furrow signal, whereas the quadratic fits the rest of the cortex. In this and five similar traces we performed, we note that the width of the fit Gaussian varies by 10% or less as the furrow ingresses despite the increasing curvature of the cortex.
RhoA activity during asymmetric cytokinesis

All of the previous results depict divisions in which the cleavage furrow forms circumferentially between two equivalent mitotic asters deep in the cell. We also investigated RhoA activity in two specialized forms of cytokinesis: micromere formation in sea urchins and polar body formation in *X. laevis*. At the eight-cell stage in sea urchins, the four vegetal cells divide highly asymmetrically such that the vegetal-most daughter is 1/30 the volume of the other. In preparation for micromere formation, the mitotic spindle develops in an eccentric position with one aster flattened against the vegetal cortex and the other deep in the cytoplasm. During micromere formation, the RhoA zone was asymmetrically positioned toward the inner edge of the blastomeres, and both formed and focused first on the side of the blastomere, where the spindle was closest, corresponding to the site of furrow initiation (Fig. 3 A and Video 4, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1).

Polar body emission during *X. laevis* female meiosis represents the extreme of unequal cytokinesis in which the meiotic microtubule array is miniscule compared with the oocyte, and only one aster appears to interact intimately with the cortex. During polar body emission, the RhoA zone appeared as a circle at the animal pole (Fig. 3 B) and subsequently moved downward and inward in concert with the cytokinetic array that excises the forming polar body, as revealed by the four-dimensional imaging of oocytes injected with both rhodamine tubulin and eGFP-rGDI (Fig. 3 C and Video 5, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1). Thus, the RhoA activity zone is a feature of every variant of embryonic cytokinesis in the species we examined; in all instances, active RhoA appears in a narrow zone immediately prefiguring the site of cytokinetic furrowing.

**The cytokinetic RhoA activity zone forms in the absence of actin accumulation**

If the RhoA activity zone represents the link between microtubules and cytokinetic apparatus specification rather than a consequence of equatorial actin accumulation, the zone should form even under conditions in which actin cannot accumulate. We treated urchin embryos with cytochalasin D to prevent actin assembly. In purple urchin embryos, a 15–20-min treatment with cytochalasin dramatically reduced the F-actin level, and furrows failed to develop (Fig. S3, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1). Latrunculin B likewise prevented furrowing and deranged the cortex, yet did

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**Figure 3.** RhoA zones accompany divergent forms of cytokinesis. (A) Micromere formation in green urchin embryos. Projection of 12 1-μm sections of an eight-cell green urchin embryo. Dashed outlines in first frame show spindle position and orientation. Cell at top forms a circumferential furrow above the spindle midplane; in other cells, the asymmetric position of the spindle corresponds to asymmetric furrowing, and the region of concentrated eGFP-rGDI spreads around the circumference as furrowing proceeds. (B) Polar body formation in *X. laevis* oocytes. Projection of 13 optical sections showing that eGFP-rGDI becomes concentrated in a circular region at the animal pole and constricts inward. Arrowheads indicate edges of zone. (C) Dual-labelled images from projection of 13 optical planes showing tubulin (red) and eGFP-rGDI (green) during polar body emission. Top row shows facing view; circular region of concentrated eGFP-rGDI closes inward around microtubules of the first meiotic spindle. Bottom three rows show Z view in which eGFP-rGDI is seen to contract inward and downward in concert with the closure of the cytokinetic array, which pinches off the forming polar body. The microscope was refocused at 05:20 to allow the eGFP-rGDI ring to be followed deeper into the cytoplasm. See online supplemental material for videos corresponding to A (Video 4) and C (Video 5, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1). All times are in minutes:seconds after filming began. Bars, 25 μm.
not interfere with the formation of the equatorial RhoA zone (Fig. S3). When cytochalasin treatment begins shortly before cleavage, furrows may form and then regress. RhoA zones were maintained in regressing furrows (Fig. 4 B). Indeed, regressed zones persisted for 30 min or more in the presence of cytochalasin, which is more than three times as long as in control cells (Fig. 1), even when the cortex is obviously disrupted (Fig. 4 C). RhoA activity zones also formed in green urchin embryos that were treated with cytochalasin (Fig. 4 D). These results show that the equatorial activation of RhoA causally precedes F-actin accumulation.

Curiously, active RhoA was often observed to dart away from the equatorial zone inward on linear tracks that extended toward the spindle poles (unpublished data; Fig. 4 F). The inward extension of linear tracks that are rich in active RhoA could be seen in single optical sections and were particularly striking in green urchins (Fig. 4 E and Video 7, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1). These objects were not confined to the equator of cytochalasin-treated cells but were consistently brighter in the region where the furrow would have formed. Three-dimensional projections from single time points (unpublished data) showed clearly that the linear tracks point toward the spindle poles. The formation of linear extensions was nocodazole sensitive (see Fig. 5 A), indicating that they are microtubule dependent.

**Focusing on and maintenance of the RhoA zone depends on microtubule function**

If the RhoA activity zone is the link between microtubules and cytokinetic apparatus specification, microtubule disruption should interrupt RhoA zone formation. Treatment of embryos with high concentrations of nocodazole (10–40 μM) before furrowing prevented both zone formation and furrow ingression (unpublished data). Therefore, we treated purple sea urchin embryos with cytochalasin to permit anaphase onset and RhoA zone formation and treated embryos with 20 μM nocodazole. In contrast to embryos exposed to cytochalasin alone, wherein the zone persisted (Fig. 4, B and C), in those treated with cytochalasin and nocodazole, the RhoA activity zones dissipated within 5–10 min of nocodazole exposure and did so in the apparent absence of the inward translocation of active RhoA on linear tracks (Fig. 5 A).
cological disruption of microtubules disrupts both the RhoA activity into discrete zones and failed to furrow. Thus, pharmaceuticals treated with 5 nM nocodazole failed to focus RhoA with this dose of nocodazole. Similarly, green urchin embryos furrow broadening and regression (Fig. 5 B). In addition, RhoA highly unstable, with the RhoA zone expanding in concert with sional imaging showed that such zones and furrows were correspondingly broad furrows (Fig. 5, C–E). Four-dimen-

Figure 5. Microtubule disruption disrupts RhoA zone. (A) Projection of seven sections through a purple urchin embryo, which was first treated with 12 μM cytochalasin D immediately before furrowing, and then treated with 25 μM nocodazole at the time the furrows began to regress (00:00). Nocodazole causes rapid abolition of RhoA zones (arrowheads). Bar, 25 μm. (B) Projection of 18 sections through purple urchin embryo cultured in 5 nM nocodazole for 30 min before filming. Furrows in top two cells are associated with uneven, poorly bounded zones of RhoA activity (arrowheads, 00:00). Zones subsequently fragment, and fur-rows regress. (C) Projection of 18 sections through a control purple urchin embryo showing normal width and brightness of the RhoA zone during telophase. (D) Projection of 18 sections through a four-cell purple urchin embryo cultured in 5 nM nocodazole. The RhoA zone is much wider than controls [compare brackets in C and D]. (E) Scatter plot showing that RhoA zones are consistently wider in embryos treated with 5 nM nocodazole. Zones were measured at the point just after ingression begins (exemplified by the lower left furrows in C and D) in four untreated and six treated em-

As a second approach, purple urchin embryos were treated with 5 nM nocodazole in metaphase. This level of no-
codazole did not cause metaphase arrest in most blastomeres but consistently resulted in abnormally broad RhoA zones and correspondingly broad furrows (Fig. 5, C–E). Four-dimen-

The RhoA activity zone responds to physical manipulations of the spindle

We first tested whether isolating the cortex from the spindle would prevent formation of the zone. We flattened cells with a microneedle (Fig. 6 A and Video 8, available at http:// www.jcb.org/cgi/content/full/jcb.200501131/DC1) so as to im-

Next, we tested whether the RhoA activity zone, once formed, could respond dynamically to a perturbation of spindle position. We had observed occasional cells in which the spin-

dle shifted during cytokinesis and in which the RhoA zone appeared to follow (Fig. S4, available at http://www.jcb.org/ cgi/content/full/jcb.200501131/DC1). To mimic this naturally occurring experiment, spindles were displaced longitudinally after RhoA zone formation and the onset of furrowing. We placed a blunt microneedle into one end of a forming daughter blastomere (without penetrating the cell), which resulted in im-

We then conducted the converse experiment by displac-
ing a patch of nonequatorial cortex so that it came very close to the spindle midzone after furrowing was well underway. Within a short time, the displaced cortex exhibited intense, highly localized RhoA activity (Fig. 6 C). The activation of RhoA was not simply caused by stretching of the cell mem-

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Figure 6. Physical displacement of the cortex relative to the spindle midplane modifies the RhoA zone. All times in this figure are in minutes:seconds relative to the physical perturbation indicated in the diagrams on the left. In each case, the dashed outlines in the first frame show the position of the spindle and the glass needle. Blastomeres from green urchin embryos at the 32–64-cell stage were used for these experiments. (A) Projection of four sections through a cell upon which the needle was pressed slightly to one side of the spindle, distending a portion of the cell into a pouch ∼10 μm thick. The side nearer the spindle initiates a tightly focused RhoA activity-rich furrow that ingresses (arrows); the far side accumulates active RhoA (brackets) but fails to focus it, and a series of shallow, unstable furrows develop and regress. (B) Projection of nine sections through a blastomere in which the spindle was displaced along the polar axis after furrow initiation. In the first frame, the blunt-ended needle is parked against one pole of the cell, slightly denting it. At 00:00, the needle was advanced by ∼15 μm (without penetrating the cell membrane), shoving the spindle so that the midplane shifts up relative to the furrow. Arrow and bracket in 00:20 mark the position immediately after the shove of the furrow and the RhoA zone, respectively, and remain the same for comparison in subsequent frames. The RhoA zone climbs higher on the cortex after the spindle midplane is followed, in turn, by the furrow (second set of brackets and arrows in 03:00–06:40) such that the cell cleaves asymmetrically. (C) Projection of eight sections through a cell subjected to the converse of B: the cortex was displaced by a blunt needle toward the spindle midzone. In ∼00:20, the needle is parked slightly off center; at 00:00, the needle was advanced to bring a patch of nonequatorial cortex deep into the equatorial zone. At 06:20, needle tip shows accumulation of active RhoA (arrow). In addition, the original RhoA zone slides up the cortex (brackets in 04:00–08:40), apparently after half of the mitotic apparatus is broken by the needle. See online supplemental material for videos corresponding to A (Video 8) and B (Video 9, available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1). Bars, 25 μm.

Discussion

More than 50 yr of work has demonstrated that the geometry of the mitotic microtubule array, which interacts with the cell cortex, somehow provides the signal for cytokinetic apparatus specification in animal cells. The results of this study demonstrate that a focused region of active RhoA has all of the expected properties of the hypothetical microtubule-dependent signal for cytokinesis. First, active RhoA concentrates in a narrow zone that coincides with the furrow, and, in cases where furrowing occurs asymmetrically as a result of natural variability or physical manipulation, furrowing occurs first where active RhoA is most concentrated. Second, RhoA zone formation precedes furrowing by up to several minutes. Third, the RhoA zone is conserved in four different echinoderms and in the vertebrate X. laevis. Fourth, the RhoA zone not only forms during cytokinesis in blastomeres but also forms in the much smaller epithe-
Our results suggest a potential resolution to this paradox. First, we found that the RhoA activity zone either maintains a constant width (embryonic cytokinesis) or actually narrows...
(polar body formation) while both constraining circumferentially and increasing in intensity. RhoA, like many other small GTPases, has an extraordinarily low rate of intrinsic GTPase activity (Zhang et al., 2000). Consequently, if RhoA were simply activated locally throughout active furrowing, the width of the RhoA zone should increase as its intensity increases (assuming that GTP-bound RhoA experiences some diffusional mobility). We also showed that the RhoA activity zone is rapidly remodeled after spindle displacement. Altogether, these results indicate that zone formation does not simply reflect local RhoA activation but instead reflects continual activation balanced by continual inactivation (Maddox and Oegema, 2003). Therefore, we suggest that Ect2 and Cky-4 conspire to locally elevate the flux of RhoA through the GTPase cycle. Elevating the flux increases the availability of active RhoA without necessarily raising the standing crop and, therefore, without the risk of diffusional spread of the signal. If RhoA targets compete with Cky-4 to bind to free GTP-bound RhoA, each of the available targets diverts some of this flux in proportion to the target concentration. Assuming RhoA targets protect bound RhoA from inactivation by RhoGAP, the major role of RhoGAP would be to inactivate the “excess” active RhoA that fails to locally interact with RhoA targets. The advantage of such a mechanism for the cell is that the ultimate targets of RhoA, such as myosin-2, can be tightly and continually focused. The consequences of failed zone focusing are revealed by the results of low concentrations of nocodazole or displacement of the spindle away from one side of the blastomere; in both cases, RhoA activity fails to focus, and the furrows that form are highly unstable. Strikingly, the disruption of Cky-4 and p190RhoGAP, which is another RhoA GAP that localizes to the furrow region, also results in unstable and/or ectopic furrows (Su et al., 2003; Lee et al., 2004).

How, then, do microtubules of the mitotic apparatus direct the formation of the RhoA GTPase activity zone? Three general models, based on previous proposals, must be considered: (1) zone formation by delivery of the stimulus from the spindle midzone (Cao and Wang, 1996); (2) zone formation by delivery of the stimulus from overlapping, antiparallel microtubules at the equator (Devore et al., 1989; Harris and Gewalt, 1989; Somers and Saint, 2003); and (3) zone formation by delivery of the stimulus to regions of low microtubule density flanked by regions of high microtubule density (Mandato et al., 2000; Dechant and Glotzer, 2003). Ultimately, the answer to this question awaits simultaneous live cell imaging of active RhoA and microtubules as well as the development of approaches for the rapid local suppression of MKLP, Ect2, and Cky4.

However, we suggest that the following mechanism could work for all three general models: Ect2–Cky-4 complexes could be transported to microtubule plus ends and fall off, diffusing until they encounter another microtubule. Their transportation (when bound to microtubules) and diffusion in the cytoplasm would establish convective movement of the complex outward from astral centers. The spindle midplane would receive input from two convective sources, thereby increasing the local concentration of the Ect2–Cky4 complex and leading to the initiation of the RhoA activity zone. Close apposition of growing microtubule ends in this region would also act to locally muffle convection, thereby promoting rapid amplification of the zone. Then, once furrowing is underway, overlapping microtubules gathered by actomyosin-dependent ingression would sustain RhoA flux in the furrow by continually trapping the Ect2–Cky-4 complex (Somers and Saint, 2003). Such a mechanism would explain why the zone persists in the presence of cytochalasin but is sensitive to nocodazole, whereas in the absence of actin disruption, both the zone and furrowing are impervious to nocodazole.

This mechanism also has the virtue of explaining how a RhoA activity zone might form through converging mechanisms in all of the following cases: small cells in which overlap microtubules emerge in the midplane of the cortex before furrowing; large cells in which astral microtubules only begin overlapping after the onset of furrowing; and unequally cleaving cells in which the furrow forms at the margin of a single flattened astral microtubule array. It could also explain the failure of furrowing in large cells in which a local minimum of cortical microtubule density is prevented by suppression of anaphase B (Dechant and Glotzer, 2003) because both the local suppression of convection and trapping of the Ect2–Cky-4 complexes in a narrow region would presumably be prevented by having a broad region of microtubule overlap.

Intriguingly, results from this study exactly match the predictions of this model. That is, the width of the RhoA zone scales with the linear dimension of the cell. The angle of the wedge from the cell center to the margins of the RhoA zone is essentially constant regardless of the size of the cell in both echinoderms and X. laevis. Low doses of nocodazole, which limit aster growth, change this relationship, such that the zone is widened and diluted. The same result is achieved when contact between astral microtubules and the cortex is limited by physical manipulation of the blastomere. In other words, the reduction of contact between astral microtubules and the cortex by either pharmacological or physical means does not prevent RhoA activation but does prevent zone focusing and stabilization.

One of the most fascinating aspects of local RhoA activity during cytokinesis is its striking similarity to RhoA activity in X. laevis oocyte wound healing (Benink and Bement, 2005). That is, wounding elicits activation of RhoA in a broad region that rapidly focuses into a narrow zone around the site of plasma membrane damage and then moves inward in concert with a circular array of F-actin and myosin-2. Like the cytokinetic RhoA activity zone, the wound zone is tightly bounded and forms independently of cortical F-actin. It is also modulated by microtubules, though to a lesser degree than the cytokinetic RhoA zone (Benink and Bement, 2005). The striking similarity between the two systems supports the proposal that cytokinesis and single-cell wound healing have common evolutionary roots and that findings from the wound healing system may be extrapolated to cytokinesis (Mandato and Bement, 2001). Two features of the wound healing system are particularly noteworthy in this context. The first is the finding that the wound RhoA zone directs the local accumulation of phosphorylated (activated) myosin-2. Therefore, we suggest that the cytokinetic RhoA zone directs and maintains myosin-2 phosphorylation specifically at the furrow region, where it is needed.
The second feature of the wound healing system that may be relevant to cytokinesis is the formation of a complementary zone of Cdc42 activation that circumscribes the RhoA zone (Benink and Bement, 2005). Although we do not yet know if active Cdc42 forms a similar zone during cytokinesis, this possibility is consistent with the reported Cdc42 dependence of cytokinesis in X. laevis embryos (Drechsel et al., 1997) and the proposal that complementary regions of local Rho-class GTPase activation could explain many of the features of cytokinesis (Mandato et al., 2000; Yoshizaki et al., 2004). In particular, local activation of Cdc42 and/or Rac1 in regions flanking the RhoA zone could enhance furrowing by reducing contractility outside the RhoA zone. This is accomplished either by directly suppressing myosin-2 phosphorylation (Sanders et al., 1999) or by negative cross talk with RhoA itself (Benink and Bement, 2005), which is another potential mechanism for maintaining RhoA zone boundaries.

Materials and methods

Purple urchins (S. purpuratus) were collected intentionally and maintained in submerged cages. Green urchins (S. droebachiensis) were collected by dredging or by hand and were maintained in flowing seawater tanks. Starfish (Pisaster ochraceus) and sand dollars (Dendraster excentricus) were collected by hand, and sand dollars were maintained on a layer of sand in flowing seawater tanks. X. laevis embryos (provided by T. Gomez, University of Wisconsin-Madison, Madison, WI) were obtained as described in Gomez et al. (2003).

All urchin egg-handling procedures were performed next to a flowing seawater table to maintain eggs and embryo cultures at 10–12°C. Urchins and sand dollars were spawned by intracoelomic injection of 0.55 M KCl. Sperm were collected by gravity alone and were resuspended in fertilizing seawater (NSW); green urchin vitellines were dissolved with gentle pipetting. M 1-methyladenine and were fertilized after germinal activation could explain many of the features of cytokinesis (Mandato et al., 2000; Yoshizaki et al., 2004). In particular, local activation of Cdc42 and/or Rac1 in regions flanking the RhoA zone could enhance furrowing by reducing contractility outside the RhoA zone. This is accomplished either by directly suppressing myosin-2 phosphorylation (Sanders et al., 1999) or by negative cross talk with RhoA itself (Benink and Bement, 2005), which is another potential mechanism for maintaining RhoA zone boundaries.

For echinoderm microinjections, embryos were cultured in watch glasses and were transferred by mouth pipette (also spit rinsed) into NSW in the wells of glass-bottomed dishes (MatTek). Needles were pulled from silanized glass tubes, broken to a tip opening <5 μm wide, and mounted at ~45°C on a manual micromanipulator next to a stereomicroscope (model Falcon XRB; Choald Instraments). Embryos were maintained between 12 and 14°C during microinjection and thermoelectric cooling stage (Dagan). Needles were backfilled with the desired injected solution and coupled to a pneumatic microinjector (model Picospritzer III; Parker-Hannifin) calibrated to deliver 2–3% of the egg volume at one pulse. Most injected eggs routinely survived injections of this volume, developing into regular blastulas and gastrulas on a relatively normal schedule whether injected with M13 with probes, fluorescent dextran, labeled tubulin, or other probes.

In some cases, purple urchin eggs were dejellied, settled onto poly lysine or protamine sulfate-coated glass in a drop of seawater containing 1 mM 3-amino-triazole to slow hardening of the vitelline, and injected immediately after the addition of dilute sperm. In this approach, embryos retained their hyaline layer, which helped keep embryonic blastomeres together. Otherwise, early embryos tended not to maintain the typical arrangement of cells as they cleaved. The presence or absence of the hyaline layer made no difference in the sensitivity of embryos to cytochalasin D, latrunculin B, or nocodazole. Injected embryos were returned to the sea table for culture until they began to express the probe.

For frog embryos, microneedles were broken to a tip size of 10–20 μm, mounted on a picoinjector (model PL-100; Medical Systems, Inc.), suction filled, and calibrated by injecting them into an oil droplet. Embryos were injected into one blastomere of two-to-four-cell stages with a 5-nl vol of eGFP::GBD at 1 mg/ml.

Microscopy

Echinoderm embryos were imaged in the same dishes used for injection and were inserted into a thermoelectric cooling stage insert (Dagan) to maintain them at 10–12°C. All imaging of urchin, sand dollar, and starfish embryos was conducted using a PlanApo 60× water immersion objective (1.2 NA; Nikon) mounted on an inverted microscope (model TE2000; Nikon) and images were collected on a camera (model ORCA ER; Hamamatsu). The four-dimensional image series used shuttered illumination to protect embryos from light damage. Microscope automation and image analysis were performed using Metamorph v. 6. Selected images were subjected to deconvolution by using either AutoDeblur v. 10 (AutoQuant Imaging, Inc.) or Volocity v. 3 (Improvision). Images of echinoderm embryos were processed as follows: cropped and maximum projected using MetaMorph, contrast stretched, gamma adjusted, converted to eight-bit depth using ImageJ, and compressed using QuickTime. The rationale for contrast and gamma adjustment was as follows: because, for the most part, our probe is fluorescent throughout the cytoplasm and the spinning disk experiences some cross talk from adjacent pinholes, each image includes an unavoidable “glow” from far-from-focused regions of the embryo (this is not a problem with tightly localized probes or with thinner specimens such as isolated blastomeres). This glow is much dimmer than the in-focus regions, and, therefore, appears as a lower peak in the histogram of image intensities. Rather than trim off the entire background peak, we set the black level slightly below the modal value for the lower peak and used a mild gamma of 0.1 to 0.1% of pixels in the cell of interest were saturated. Frog embryos were mounted in a ring of high vacuum grease on a slide, covered with a coverslip 3–18 h after microinjection, and imaged on a microscope (model Axiovert; Carl Zeiss MicroImaging, Inc.) using a confocal system (model 1024; Bio-Rad Laboratories). Four-dimensional image series were processed using Velocity and converted to QuickTime videos as described in the previous paragraph.

Micromanipulations

Micromanipulations were conducted using a hanging joystick oil hydraulic micromanipulator (model MO-202D; Narishige). Glass needles were hand pulled to yield a long filament and were broken by striking if a blunt probe was required. Sharp edges were removed by briefly bringing the probe near an alcohol flame.

Online supplemental material

– Fig. S1 shows the specificity of the eGFP::GBD probe. Fig. S2 illustrates RhoA activity zones in two additional echinoderm species and in embryonic epithelial cells. Fig. S3 shows the effect of 12 mM cytochalasin D treatment on the F-actin content of the embryo and also shows that latruncu-
lin B (like cytochalasin) prevents furrowing without interfering with RhoA zone formation. Fig. S4 supplements Fig. 6 B by showing that RhoA activation in the furrow follows the spindle midplane in normally occurring cases in which the spindle moves relative to the cleavage furrow. Videos 1 and 2 show the accumulation of eGFP-rGBD in the urchim furrow and correspond to Fig. 1B and C, respectively. Video 3 shows the accumulation of eGFP-rGBD in X. laevis and corresponds to Fig. 1D. Video 4 shows RhoA activity during unequal cleavage (micromere formation) and corresponds to Fig. 2C. Video 5 shows that half spindles induce RhoA activation in the presence of cytochalasin D and corresponds to Fig. 4 E. Video 6 shows that the RhoA zone forms in the presence of cytochalasin D and corresponds to Fig. 4 F. Video 7 shows that isolation of the cortex from the spindle prevents focusing of the RhoA activity zone and corresponds to Fig. 6 A. Video 9 shows that the RhoA activity zone moves after displacement of the spindle and corresponds to Fig. 6 B. Video 10 shows that half spindles induce RhoA activation and corresponds to Video 7 B. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.200501131/DC1.

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