Asymmetric Distribution of Myosin IIB in Migrating Endothelial Cells Is Regulated by a rho-dependent Kinase and Contributes to Tail Retraction

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All vertebrates contain two nonmuscle myosin II heavy chains, A and B, which differ in tissue expression and subcellular distributions. To understand how these distinct distributions are controlled and what role they play in cell migration, myosin IIA and IIB were examined during wound healing by bovine aortic endothelial cells. Immunofluorescence showed that myosin IIA skewed toward the front of migrating cells, coincident with actin assembly at the leading edge, whereas myosin IIB accumulated in the rear 15–30 min later. Inhibition of myosin light-chain kinase, protein kinases A, C, and G, tyrosine kinase, MAP kinase, and PIP3 kinase did not affect this asymmetric redistribution of myosin isoforms. However, posterior accumulation of myosin IIB, but not anterior distribution of myosin IIA, was inhibited by dominant-negative rho and by the rho-kinase inhibitor, Y-27632, which also inhibited myosin light-chain phosphorylation. This inhibition was overcome by transfecting cells with constitutively active myosin light-chain kinase. These observations indicate that asymmetry of myosin IIB, but not IIA, is regulated by light-chain phosphorylation mediated by rho-dependent kinase. Blocking this pathway inhibited tail constriction and retraction, but did not affect protrusion, suggesting that myosin IIB functions in pulling the rear of the cell forward.

INTRODUCTION

Nonmuscle myosin II is a ubiquitous motor protein that can form bipolar filaments, enabling it to contract actin-filament networks. Such contractility drives cortical constriction that divides cells during cytokinesis (Satterwhite and Pollard, 1992), creates pulling forces exerted by fibroblasts rearranging extracellular matrix fibers (Ehrlich et al., 1991; Kolodney and Wysolmerski, 1992), causes cytoplasm retraction when endothelial barriers open during inflammation (Dudek and Garcia, 2001), and plays a major role in generating traction forces during cell migration (Elson et al., 1999). In Dictyostelium amoebae, myosin II is also essential in orienting cell migration, as null mutants extend protrusions in multiple directions and fail to migrate with persistent orientation (Wessels and Soll, 1990).

In all vertebrates examined to date, including human (Simons et al., 1991), cow (Murakami and Elzinga, 1992), rat (Choi et al., 1996), rabbit (Murakami et al., 1998), mouse (Tullio et al., 1997), frog (Kelley et al., 1996), and chicken (Kawamoto and Adelstein, 1991), two different genes encode heavy chains of nonmuscle myosin II. Northern blotting and histochemistry with isoform-specific antibodies have shown that the two different heavy chains, A and B, are expressed in different proportions in different tissues and at different times during development (Kawamoto and Adelstein, 1991; Murakami and Elzinga, 1992; Murakami et al., 1993; Maupin et al., 1994; Phillips et al., 1995; Choi et al., 1996; Bhatia-Dey et al., 1998). When A and B heavy chains are expressed in the same cell, they have different subcellular distributions (Maupin et al., 1994; Rochlin et al., 1995; Kelley et al., 1996, Saitoh et al., 2001), suggesting that they perform different functions.

Myosin containing A-type heavy chains (myosin IIA) and myosin containing B-type heavy chain (myosin IIB) have slightly different enzymatic and assembly properties in vitro. Both isoforms possess actin-activated ATPase that is stimulated when myosin's regulatory light chains are phosphorylated by myosin light-chain kinase (MLCK). Light chain phosphorylation also stimulates filament assembly for both isoforms. However, fully activated myosin IIA and IIB move actin filaments at different rates in a molecular motility assay (Kelley et al., 1996), and filament assembly by myosin IIB, but not myosin IIA, is inhibited when heavy chains are phosphorylated by protein kinase C or casein kinase II (Murakami et al., 2000). Conversely, filament assembly by myosin IIA, but not myosin IIB, is disrupted by metastasis-associated protein, mts1 (Murakami et al., 2000).

The significance of these differences in vivo is not known. Despite extensive evidence for myosin II playing an essential role in moving amoebae (Fukui and Yumura, 1986; Wessels and Soll, 1990; Wessels et al., 1996; Elson et al., 1999; Zhang et al., 2002), the function of myosin II during migration of vertebrate nonmuscle cells is not well understood. Myosin IIB knockout mice have recently been generated, and these animals have severe cardiovascular and brain abnormalities, indicating that myosin IIB has an important and specific role in determining tissue organization (Tullio et al., 1996, 1997, 2001). In addition, neurons cultured from myosin IIB–deficient mice extend more slowly than cells from normal mice (Bridgman et al., 2001), suggesting a role...
in cell migration. The contributions of myosin IIA and IIB have not been examined in endothelial cells, which form the initial foundation for vascular structures that are defective in myosin IIB–deficient mice. Nor is it known how the behaviors of myosin IIA and IIB are regulated so that they distribute differently in vivo. Experiments described below address how myosin IIA and IIB act during endothelial migration and how their distinct distributions arise. Changes in the distribution of the two isoforms were observed as cells began to migrate at the edge of a wound and indicated that myosin IIA and IIB are involved in different aspects of migration. Myosin IIA was closely associated with protrusive activity, whereas myosin IIB appeared to be responsible for retracting the tails of migrating cells. Moreover, inhibition of protein kinases and the small G-protein, rhoA, revealed that the distribution of myosin IIB can be regulated in living cells independently from myosin IIA via rho-kinase-dependent phosphorylation of its regulatory light chains.

MATERIALS AND METHODS

Cell Culture and Wounding

All experiments were performed on primary cultures of bovine aortic endothelial cells (BAECs) between passage 13 and 18 after isolation. Cells were maintained in DMEM supplemented with 10% fetal calf serum as described previously (Kolega, 1999). Wounds were made within 24–48 h after cells reached confluence by dragging a plastic comb across the surface of the culture, creating a series of uniform, parallel wounds ~0.5 µm wide and 0.5 µm apart.

Plasmids and Transfections

An expression vector for the dominant-negative form of rhoA, T91Nho, was provided by Dr. Klaus Hahn (Scripps Research Institute, La Jolla, CA; Subauste et al., 2000). This vector is a pcDNA3-plasmid (Invitrogen, Carlsbad, CA) with T91Nho CDNA inserted in tandem with a GFP S65T eDNA, which encodes enhanced green fluorescent protein (EGFP) as an indicator of expression levels. pcMV plasmids containing constitutively active and kinase-dead mutants of MLCK, each tagged with a FLAG epitope, were provided by Dr. Patricia Gallagher (Indiana University Purdue University at Indianapolis, IN). The kinase-dead MLCK consists of full-length rabbit smooth muscle MLCK (130 kDa) that has a deletion in the ATP-binding site, rendering it catalytically inactive. The kinase-dead MLCK consists of full-length rabbit smooth muscle MLCK (130 kDa) that has a deletion in the ATP-binding site, rendering it catalytically inactive while maintaining calmodulin and myosin light-chain binding activity (Gallagher et al., 1993). It has been shown to act as a dominant negative inhibitor of endogenous MLCK activity in fibroblasts (Klemke et al., 1997). In the constitutively active mutant, the N-terminal autoinhibitory domain has been deleted.

Adherent BAECs were transiently transfected with nonlinearized plasmids using TransIT-T1 polyamine transfection reagent (PanVera Corp., Madison, WI). To study plasmid-expressing cells at wound edges, cultures were transfected when they were ~70% confluent and then incubated for an additional 24–48 h to allow them to reach confluence before wounding.

Antibodies

Isoform-specific polyclonal rabbit antibodies against the A and B isoforms of myosin II heavy chain were supplied by Dr. Robert Adelstein (National Institutes of Health) or purchased from Covance (Richmond, CA). These antibodies do not cross-react with other myosin isoforms (Kelley et al., 1996) and recognize only myosin II on immunoblots of endothelial cell proteins (Kolega, 1998b). For staining both myosin heavy chain isoforms, polyclonal antibody against smooth- and nonmuscle myosin from Biomedical Technologies Inc. (Bedford, MA) was used. Antibodies against phosphorylated myosin regulatory light chains were obtained from Cell Signaling Technology (Beverly, MA). One antibody recognizes light chains that are phosphorylated at serine 19, and another recognizes light chains that are phosphorylated at both serine 19 and threonine 18. FLAG-tagged proteins were stained using M2 anti-FLAG mAb (Sigma, St. Louis, MO). All secondary antibodies and Fab fragments were from Jackson ImmunoResearch (West Grove, PA), except Alexa488-conjugated antibodies, which were from Molecular Probes (Eugene, OR).

Fluorescent Staining

Cells were fixed for 30 min in 3.7% freshly prepared formaldehyde in cytoskeletal buffer (CB; 137 mM NaCl, 5 mM KCl, 1.1 mM Na2HPO4, 0.4 mM KH2PO4, NaHCO3, MgCl2, 2 mM EGTA, 50 mM glucose, 5 mM PIPES, pH 6.0) and permeabilized for 5 min with 0.1% Triton X-100 in CB. Protein was stained by incubating cells for 30 min in CB containing a 1:100 dilution of Cdye, a lysine-reactive succinimidyl ester of cyst (Amsersham Life Science, Pittsfield, PA). Cells were washed three times with CB, and any remaining unreacted dye was blocked by treating the coverslips for 1 h with 10% goat serum in phosphate-buffered saline. Coverslips were then stained for F-actin, using rhodamine-conjugated phalloidin (Molecular Probes) and for myosin IIA and IIB by indirect immunofluorescence using Alexa488-conjugated secondary antibodies.

To stain myosin IIA and IIB in the same cell, specimens were prepared as described above except that phalloidin was omitted and a fluorescent Fab fragment was used for the secondary antibody. Specimens were then blocked for 1 h with 1 mg/ml unconjugated Fab fragments and subsequently stained with the second antmyosin II primary and another secondary Fab antibody fragment conjugated with a different fluorophore.

In some experiments, fluorescent dextran was used as an inert indicator of cytoplasmic volume. Dextran was introduced into cells by “scrape-loading”; i.e., including the dextran in the culture medium during wounding; scraping the monolayer produced sufficient transient damage to surviving cells at the wound edge that nearly all of them took up the dextran to permit fluorescence imaging. Lysine-derivatized dextran (Molecular Probes), which is fixed by formaldehyde, was used in order to preserve dextran distribution when permeabilizing cells for cytoskeletal staining.

Image Acquisition and Analysis

Fluorescence staining was observed through a Zeiss Axiosvert 135 microscope using a 100× Plan-NEOFLUAR oil-immersion objective (Carl Zeiss Microimaging, Thornwood, NY) and imaged with a Hamamatsu Orca-ER CCD camera (Hamamatsu, Shizuoka, Japan). Images were adjusted for contrast using Adobe Photoshop (San Jose, CA), and calliper measurements were performed using NIH Image (Wayne Rasband, National Institutes of Health) or ImageJ (rsb.info.nih.gov/ij). ImageJ was used to correct the registration of images taken through different excitation wavelengths.

RESULTS

Myosin IIA and Myosin IIB Distribute toward Opposite Ends of Migrating Endothelial Cells

In confluent monolayers of BAECs, the A and B isoforms of myosin II heavy chains were symmetrically distributed around the center of the cell and overlapped extensively. Some diffuse staining was observed throughout the cytoplasm for both isoforms, but most of the myosin IIA and myosin IIB was located in rows of dots that were coincident with actin stress fibers. These formed rings or polygons around the body of the cell a few micrometers proximal to the contacts between cells (Figure 1, C and E). When cells...
Figure 1. Asymmetric distribution of myosin IIA and myosin IIB in migrating endothelial cells. BAECs were fixed and stained 1 d after reaching confluence (A, C, and E) or 1 h after wounding the confluent monolayer (B, D, and F). The wound is at the right of the figure. Cells were stained with lysine-reactive cy5 to directly visualize total protein distribution (A and B) and with antibodies against myosin IIA (C and D) and myosin IIB (E and F), which were imaged by indirect immunofluorescence. Arrowheads in B, D, and F mark the location of the leading edges of one cell’s lamellipodia. Note that the lamellar protrusions are very flat and contain much less protein mass compared with the cytoplasm around the nucleus, so the strong myosin IIA staining in the protrusions represents local concentration of myosin IIA. Myosin IIB is much less abundant toward the front of migrating cells, but is concentrated in cytoplasm at their trailing edges (F; arrows).
were induced to migrate by wounding the monolayer, myosin IIA and myosin IIB moved to different parts of the cells. Both myosins were still found predominantly in linear arrays of dots, but myosin IIA, which constitutes 70–90% of the myosin II in BAECs (Kolega, 1998a), distributed throughout the broad lamellar protrusions that extended toward the wound, except at the extreme distal edge (Figure 1D, arrowheads). Staining for myosin IIA in the front of the cell was equal to that in the main body of the cell, even though the front of the cell was much flatter and contained much less protein. Thus, on a concentration basis, myosin IIA was strongly enriched toward the front of the cell. In contrast, myosin IIB, which makes up 10–30% of the cell’s myosin II, was largely excluded from the front of the cell and instead accumulated in large, dense bundles along the cell’s trailing edges (Figure 1F, arrows). In migrating cells, the distributions of myosin IIA and IIB did continue to overlap somewhat, especially in the largest myosin bundles, but as cells became more polarized the two isoforms became more distinctly skewed in opposite directions.

To determine if these opposite, asymmetric distributions might play a role in determining the polarity of protrusive activity, myosin asymmetries were compared with asymmetry in the assembly of actin filaments, which is responsible for formation of protrusions at a cell’s leading edge. Asymmetry was measured by determining the extent to which myosin II or F-actin mass was shifted away from the center of mass of the cell (Figure 2). In migrating cells, F-actin and myosin IIA were both strongly skewed toward the front of the cell, whereas myosin IIB skewed away from the front (Figure 2C). In contrast, a 40-kDa fluorescent dextran, which does not assemble or bind to specific structures in the cell and which was introduced into cells by scrape loading, did not distribute asymmetrically. This demonstrated that the asymmetries measured for actin and myosin II were not caused simply by changes in the shape of the cytoplasm. Actin and myosin must undergo specific changes that cause them to concentrate in particular regions relative to the direction of cell movement.

**Polarization of Protrusive Activity Precedes Polarization of Myosin IIB, But Not Myosin IIA**

Endothelial monolayers were fixed and stained at various times after wounding to examine the development of cy-
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Figure 3. Development of F-actin and myosin II asymmetry. Mean asymmetries of F-actin, myosin IIA, and myosin IIB were measured for cells along wound edges that were fixed at various times after wounding. To compare components more easily, values were normalized to the maximum mean asymmetry attained during the 2-h time course, which was observed at 120 min for F-actin and myosin IIA and at 60 min for myosin IIB. Each point represents the mean of 30–40 cells; error bars, 1 SD.

Figure 4. Development of F-actin and myosin II asymmetry. Mean asymmetries of F-actin, myosin IIA, and myosin IIB were measured for cells along wound edges that were fixed at various times after wounding. To compare components more easily, values were normalized to the maximum mean asymmetry attained during the 2-h time course, which was observed at 120 min for F-actin and myosin IIA and at 60 min for myosin IIB. Each point represents the mean of 30–40 cells; error bars, 1 SD.

Figure 5. Effect of various kinase inhibitors on myosin II asymmetry. Cells were treated with the indicated kinase inhibitor at 10 μM and a 24-h time course for F-actin, myosin IIA or myosin IIB, at concentrations well above their in vitro Ks. Likewise, inhibitors of MAP kinase (PD98059), tyrosine kinases (genistein), and PIP kinase (wortmannin and LY294002; Davies et al., 2000), all failed to disrupt the development of F-actin and myosin II asymmetry in migrating BAECs. Thus, only Y-27632 changed the direction of asymmetry so that myosin IIB became skewed toward—the rather than away from—the wound.
of rhoA (Pan et al., 1998), and for enhanced green fluorescence protein (EGFP), which serves as an indicator of plasmid expression. Fluorescence microscopy of cells expressing T19Nrho showed that myosin IIB did not accumulate along the trailing edge and was no longer excluded from anterior protrusions, even while immediately adjacent cells displayed normal polarization (Figure 6, A–C). Measurements of asymmetry confirmed that myosin IIB distributed toward the front of cells expressing T19Nrho (Figure 6D) and that this effect was apparent even at the minimum detectable levels of plasmid expression (Figure 6E). This occurred despite the fact that cells expressing dominant negative rhoA did not elongate as much as untransfected cells, possibly because rhoA is involved in regulating turnover of cell-substratum adhesions (Ridley, 2001). Myosin IIA asymmetry was reduced by dominant-negative rhoA (Figure 6, D and E), but the direction of asymmetry was unchanged, with myosin IIA always remaining skewed toward the wound. Thus, rhoA’s influence on the direction of asymmetry was specific to myosin IIB.

**Posterior Accumulation of Myosin IIB Is Induced by Myosin Light-chain Phosphorylation**

Rho-dependent kinase can regulate the activity of myosin II in vitro by phosphorylating the myosin II regulatory light chains at the same site that is recognized by myosin light-chain kinase (Amano et al., 1996). To determine if this is how myosin IIB behavior is regulated in migrating BAECs, the effect of Y-27632 on light-chain phosphorylation was examined. Western blots of endothelial cell extracts were probed with antibodies that recognize myosin II regulatory light chains that have been either singly phosphorylated at serine 19 or doubly phosphorylated at serine 19 and threonine 18. These sites can be phosphorylated by rho-dependent kinase and myosin light-chain kinase in vitro. In cells treated with 2 μM Y-27632, levels of both mono- and di-phosphorylated light chains were markedly reduced (Figure 7). Quantitative measurements of Western blot chemiluminescence indicated that Y-27632 reduced monophosphorylated light chains to 35 ± 8% (n = 5) of control levels and di-phosphorylated light chains to 34 ± 5% (n = 5) of controls. In contrast, the myosin light-chain kinase inhibitor, ML-7, which did not affect myosin II asymmetry, had little or no effect on phosphorylation at these sites (light-chain phosphorylation was 97 ± 15% and 110 ± 28% of controls for mono- and di-phosphorylated light chains, respectively).

The distribution of phosphorylated light chains in migrating cells was determined by immunofluorescence with the phosphorylation-specific antibodies. Like myosin IIB, both mono- and di-phosphorylated light chains were particularly concentrated along the posterior and lateral edges of migrating cells (Figure 8). This suggests that light chains were preferentially phosphorylated on myosin IIB over those on myosin IIA. However, some patches of light-chain phos-
phorylation were also detected toward the front of migrating cells, where there was very little myosin IIB, indicating that phosphorylated light chains were not exclusively associated with myosin IIB. It should be noted that when phosphorylated light chains were seen toward the front of a cell, they were found in regions where lamellipodia were absent or retracting and the cell margin had a concave contour (arrows in Figure 8, C and F). Thus, there was a strong correlation between light-chain phosphorylation and the absence of protrusion.

If phosphorylation of myosin IIB is indeed responsible for the normal distribution of myosin IIB in the tails of migrating cells, then artificially phosphorylating the regulatory light chains should cause posterior accumulation of myosin IIB even when rho-kinase activity is blocked. This was tested by transiently transfecting cells with a FLAG-tagged, constitutively active mutant of MLCK (Figure 9). In the presence of 2 μM Y-27632, staining of phosphorylated light chains was dramatically reduced (compare untransfected cells in Figure 8C with Figure 9C), but in cells expressing the mutant MLCK, phosphorylation of myosin regulatory light chains at serine 19 was restored (Figure 9C). A similar result was observed for di-phosphorylated light chains. Furthermore, myosin IIB accumulated in the tails of MLCK-transfected, Y-27632-treated cells, but not in untransfected cells in the same wound (Figure 10, A–C). Myosin IIB asymmetry was “rescued” in all cells that expressed high levels of constitutively active MLCK and in most cells expressing even minimally detectable amounts (Figure 10E, right). Note, however, that the magnitude of the asymmetry in highly expressing cells was not greater than in the cells with lower levels. Nor did constitutively active MLCK increase the posterior distribution of myosin IIB in control wounds (Figure 10D). This suggests that there is a threshold of kinase activity, above which myosin IIB is caused to accumulate posteriorly. A dominant-negative mutant of MLCK did not affect the loss of posterior accumulation of myosin IIB in Y-27632–treated wounds, nor did it disrupt the polarization of myosin IIB in control wounds (Figure 10D).

Constitutively active MLCK also affected myosin IIA. Low levels of expression inhibited the anterior polarization of
myosin IIA, but did not change the direction of asymmetry. However, at very high levels of MLCK expression, myosin IIA began to skew toward the posterior of the cell like myosin IIB (Figure 10E). Dominant-negative MLCK had no effect on myosin IIA distribution (our unpublished results). Thus, increasing phosphorylation of myosin II regulatory light chains generally promoted posterior accumulation of myosin II, with myosin IIA being more resistant to this effect than myosin IIB.

**Inhibition of Posterior Accumulation of Myosin IIB Affects Tail Retraction But Not the Forward Extension of Lamellipodia**

To understand better the function of myosin IIB accumulation in the tail, the morphology and dynamics of cell migration were examined in the presence and absence of Y-27632. Immediately after wounding, BAECs rapidly extended lamellipodia into the wound, with the cells’ leading edges advancing at \(-0.5 \mu\text{m/min}\). Y-27632 had little or no effect on the rate of protrusion during the first 30 min after wounding (Figure 11). This indicated that myosin IIB asymmetry was not necessary for the development of polarized protrusive activity. However, just when cells in control wounds became fully polarized 20–40 min after wounding, differences in behavior were seen in Y-27632–treated cells. In control cells, spreading of the leading edge slowed to about half of its original speed, and the trailing edge began to move forward. Thereafter, the leading and trailing edges advanced, on average, at the same rate (Figure 11, solid symbols). In contrast, the trailing edge did not begin to move until 50–60 min after wounding in Y-27632, even though the leading edge continued to spread until 90 min after wounding and did so more rapidly than controls (Figure 11, open symbols). Because of the long delay in moving the rear of the cell, Y-27632–treated cells became more elongated before the bodies of the cells began to translocate.

These observations suggested that Y-27632 might inhibit contractility in the rear of the cell. This idea was supported by the morphology of migrating cells. In control cells, the cytoplasm posterior to the nucleus was typically sharply constricted, so that the cells had tapering, phase-dense tails with concave contours (Figure 12A). Gaps developed not only behind cells as they moved into the wound, but also between adjacent cells along the edge, indicating that the...
cells contracted laterally as they elongated. The tails retracted rapidly toward the cell body when cell-substratum attachments broke, as if under contractile tension. But in Y-27632, the shapes of the trailing edges did not change much while the leading edges of the cells spread into the wound (Figure 12B). Gaps between cells were fewer, smaller, and developed later than in control cells. The cell bodies did narrow slightly when the cells were fully elongated, but even 60 min after wounding the tails of drug-treated cells were wider than their untreated counterparts (Figure 12C). In untransfected cells, the average width of the cell immediately posterior to the nucleus was 14 ± 3 μm in Y-27632 compared with 9 ± 2 μm in controls, which is significantly larger (n = 48; p > 95%). Similarly broad posteriors were observed for cells in which rho activity was inhibited by transient transfection with T19Nrho (see Figure 6). In contrast, the tails of Y-27632–treated cells that were transfected with constitutively active MLCK did constrict and taper (see Figures 9 and 10). Thus, tail morphology was regulated in parallel with myosin IIB asymmetry.

DISCUSSION

Because myosin IIA and IIB redistributed toward opposite ends of an endothelial cell as it began to migrate (Figure 1) and because they did so at different times (Figure 3), they must perform very different functions during cell migration. Saitoh et al. (2001) reported a similarly polarized distribution of myosin IIA and IIB in human fetal lung fibroblasts and proposed that myosin IIA was generally involved in cell migration, with myosin IIB playing a supporting role in the rear. In both endothelial cells and fibroblasts, the distribution of myosin IIB is very similar to myosin II in Dictostelium amoebae, where only a single myosin II isoform is present. Genetic knockouts of the Dictostelium myosin II indicate that it contributes to the formation of a contractile cortex around the tail: the tails of myosin II–deficient cells are less rigid (Pasternak et al., 1989), exert less traction force (Elson et al., 1999; Fukui et al., 2000), and produce less hydrostatic pressure for squeezing cytoplasm toward the front of the cell (Pasternak et al., 1989; Elson et al., 1999; Fukui et al., 2000). Myosin IIB appears to have a similar role in endothelial cells, because disruption of myosin IIB by inhibiting rhoA or rho-kinase resulted in delayed tail retraction and diminished constriction of the tail. Although inhibition of rho and rho-kinase undoubtedly affects other proteins in the cell besides myosin IIB, the posterior accumulation of myosin IIB, phosphorylation of myosin II regulatory light chains, and the narrow, tapered morphology characteristic of contracting tails were all specifically restored by constitutively active MLCK. This demonstrates that the altered tail contractility is specific to rho-kinase’s effects on phosphorylation of myosin II regulatory light chains. Bridgman and colleagues have also shown correlations between myosin IIB and cytoplasmic retraction: in cultured nerve growth cones, myosin IIB is concentrated behind edges that are retracting rather than extending (Rochlin et al., 1995), and neurons from myosin IIB–deficient mice exert less traction force on the substratum (Bridgman et al., 2001). Thus, the role of myosin IIB in migrating cells may be to contract the locomotive cytoskeleton after protrusions have extended. Such contractility can pull the rear of the cell forward (or retract a protrusion from the front or side of the cell), increase traction forces between the front and rear of the cell, and create hydrostatic pressure to drive flow of cytoplasm toward the front of the cell.

Contraction of the cortical cytoplasm by myosin IIB might also constrain protrusive activity in the tail, because myosin II–deficient amoebae display excessive protrusive activity from their posterior and lateral edges (Wessels et al., 1998). However, we did not observe any new protrusions along the rear or side edges of endothelial cells migrating without posterior accumulation of myosin IIB (i.e., in Y-27632 or after transfection with T19Nrho). Furthermore, myosin IIB was not asymmetrically distributed until >15 min after wounding, even though BAECs already had new protrusions restricted to the wound edge within 5 min of wounding. Thus, myosin IIB apparently does not dictate protrusive polarity at the beginning of wound healing. It is likely that inhibitory signals from cell-cell contacts prevent lateral and posterior protrusion in the wound-healing scenario, obviating a role for myosin IIB early on. However, myosin IIB and tail retraction may become more important when cell-cell contacts are absent. Experiments are underway to test the effects of disrupting myosin IIB on protrusive polarity and locomotive efficiency in isolated endothelial cells migrating toward a chemotactic signal or during random-walk migration.

The role of myosin IIA in endothelial migration remains unclear. The timing with which myosin IIA becomes asymmetrically redistributed so closely parallels that of F-actin that it is tempting to postulate a structural role for myosin IIA in forming protrusions. Although myosin II is initially excluded from the tips of new protrusions in fibroblasts and endothelial cells (DeBiasio et al., 1988; Kolega, 1998a) and is not required at all for protrusive activity in Dictostelium (Wessels et al., 1988), disrupting the assembly of myosin IIA with truncated fragments of the heavy chain caused retraction of protrusions and rounding up of HeLa cells (Wei and Adelstein, 2000). Verkhovsky et al. (1995) have shown that the myosin II toward the front of keratinocytes is organized
into short, bipolar ribbons that interconnect actin filaments and accumulate in large actin-myosin bundles, suggesting that myosin II acts as a cross-linker more than a contractile motor in this region. This is supported by the behavior of microinjected, fluorescently labeled, chicken-gizzard myosin II, which we have shown colocalizes with myosin IIA in endothelial cells (Kolega, 1998b). In fibroblasts and endothelial cells, this fluorescent myosin II analog accumulates into actin-containing bundles parallel to the leading edge, which associate with cell-substratum adhesions but do not contract in the direction of movement as the cell moves forward (DeBiasio et al., 1988, and our own unpublished observations). Thus, the function of myosin IIA may be to stabilize and organize the actin cytoskeleton in protrusions at the

**Figure 10.** Constitutively active MLCK restores myosin IIB polarity in Y-27632–treated cells. BAEC cultures that had been transiently transfected with plasmid encoding FLAG-tagged, constitutively active MLCK were fixed 1 h after wounding in 2 μM Y-27632 and then stained with lysine-reactive cy5 (A), antibody against the FLAG epitope on constitutively active MLCK (B), and antibody against myosin IIB (C). Arrowheads mark leading edges of migrating cells. In untransfected cells, myosin IIB extended far into the lamellar protrusions, but it was excluded from the front of the cell at the upper right, which contained high levels of constitutively active MLCK. Note the heavy accumulation of myosin IIB along the rear of this cell (C, arrow), whereas myosin IIB was more generally distributed through the cytoplasm of untransfected neighboring cells. (D) Transfected cultures were fixed and stained after cells had migrated for 1 h in the presence or absence of Y-27632. Myosin IIB asymmetries were then calculated for cells transfected with constitutively active MLCK (caMLCK), for cells transfected with dominant-negative MLCK (dnMLCK) and for untransfected cells. Mutant MLCKs did not affect asymmetry in control wounds, but constitutively active MLCK prevented the reversal of myosin IIB asymmetry caused by Y-27632. Error bars, 1 SD; n = 26 for each mean. (E) Asymmetries of myosin IIA (left) and myosin IIB (right) plotted as a function of the expression levels of constitutively active MLCK, as measured by the fluorescence intensity of FLAG staining. Dotted lines indicate the mean myosin II asymmetry in 20 untransfected cells in the same fields. At low levels of MLCK expression, myosin IIA asymmetry in transfected cells was less than the untransfected average, but it did not become negative in most cells until expression levels reached ~1 U. Myosin IIB asymmetry was negative; i.e., skewed toward the tail even at very low levels of MLCK expression (~0.2 U).
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Figure 11. Movements of the leading and trailing edges of migrating BAECs. Time-lapse movies were made of BAECs migrating at the edge of a wound in the presence (dotted lines, open symbols) or absence (solid lines, closed symbols) of 2 μM Y-27632. Each point represents the average distance moved toward the wound by the leading edges (circles) and trailing tails (triangles) of six cells migrating in the same experiment (error bars, 1 SD). The results shown are representative of three separate experiments. Note the constant distance between the leading and trailing edges of control cells after 50 min and the much larger separation between the front and rear of cells in Y-27632.

front, whereas myosin IIB contracts it in the rear. The present demonstration that the distributions of myosin IIA and IIB can be independently regulated may lead to agents that selectively disrupt myosin IIA, which will permit more definitive tests of its function in cell migration.

How are the distributions of myosin IIA and IIB controlled in the cell? The posterior accumulation of myosin IIB was blocked by inhibition of either rho-dependent kinase or rhoA itself and was restored by artificially activating MLCK, indicating a pathway in which rhoA activates rho-dependent kinase, leading to myosin light-chain phosphorylation. Because phosphorylation of myosin II by rho-kinase in vitro stimulates myosin II filament assembly and motor activity (Amano et al., 1997), direct phosphorylation of myosin IIB by rho-kinase could induce contraction of the cortical cytoskeleton in the tail. Rho-kinase also inhibits myosin phosphatase (Kimura et al., 1996), decreasing the rate of light-chain dephosphorylation, which could further enhance myosin II assembly and activation.

Surprisingly, it appears that MLCK is not the primary regulator of posterior accumulation of myosin IIB in BAECs, because neither the pharmacological inhibitor, ML-7, nor the dominant negative mutant, kinase-dead MLCK, had a significant effect on myosin IIB asymmetry. The ability of constitutively active MLCK to induce posterior accumulation of myosin IIB when rho-kinase is inhibited, suggests that endogenous MLCK could perform this function, but is not sufficiently active during the normal wound response or is not present in sufficient amounts in BAECs to produce myosin IIB rearrangement. The activity of rho-kinase, on the other hand, may be elevated after wounding, because loss of cell-cell contacts is accompanied by activation of rhoA in MDCK and HEK293 epithelial cells (Noren et al., 2001). A similar response in endothelial cells could provide the necessary cue for rho-kinase–mediated phosphorylation of myosin IIB.

The ability of constitutively active MLCK to produce posterior accumulation of myosin IIB in Y-27632–treated cells also indicates that the asymmetry in myosin IIB distribution does not require asymmetric distribution of the kinase. Myosin IIB may get phosphorylated throughout the cytoplasm, causing it to assemble and contract, so that it accumulates in the rear simply because it remains in place while the rest of the cell advances. However, the punctate, linear arrays of myosin IIB in Y-27632–treated cells (Figure 4F) indicate that myosin IIB remains assembled in some cytoskeletal framework even when rho-kinase is inhibited. This is further demonstrated by the skewing of myosin IIB toward the front during rho-kinase inhibition. Fumoto et al. (2003) showed that myosin II containing nonphosphorylatable light chains (in which serine 19 and threonine 18 are replaced with alanines) still distributes with F-actin networks in fibroblasts, demonstrating that assembly of actin-myosin structures can occur without light-chain phosphorylation. Therefore, the posterior accumulation of myosin IIB during normal migration must involve an active contractile event or motor activity that is turned on by light-chain phosphorylation. Contraction of actin cytoskeleton by myosin IIB would tend to pull both the actin and myosin IIB toward the cells’ strongest attachments, which early in migration are toward the rear. As new cell-substratum adhesions develop toward the leading edge and posterior attachments weaken, this contractility would also lead to tail retraction later in migration.

Why is myosin IIA not affected in the same way as myosin IIB? Several lines of evidence suggest that myosin IIA is not phosphorylated in the same manner as myosin IIB in
BAECs. First, regulatory light chains were most heavily phosphorylated in the posterior cytoplasm where myosin IIB accumulated (Figure 8). Second, little phosphorylation was detected in the anterior cytoplasm of migrating cells, where myosin IIA is abundant and myosin IIB is absent. Third, changes in light-chain phosphorylation (Figure 7) correlated with changes in asymmetry of myosin IIB, but not myosin IIA (Figure 5). Fourth, much higher levels of constitutively active MLCK were required to cause posterior accumulation of myosin IIB in Y-27632–treated cells than were required to skew myosin IIB rearward (Figure 10E). Two alternative mechanisms could account for different levels of light-chain phosphorylation between myosin IIA and IIB: In one scenario, the relevant kinase(s) could distinguish between myosin IIA and IIB. Little is known about the relative affinity of rho-dependent kinases for different isoforms of nonmuscle myosin II in vitro or in vivo. If a rho-dependent kinase preferentially phosphorylates myosin IIB over myosin IIA, it could cause myosin IIB to contract F-actin structures, pulling them toward stable anchor points that become the tail of the cell. Meanwhile, the less phosphorylated myosin IIA would be free to enter the cell’s newly formed protrusions and incorporate into the F-actin cytoskeleton at the leading edge. Alternatively, both myosin IIA and IIB may get phosphorylated, but myosin IIA may be preferentially dephosphorylated. We previously showed that the phosphate on myosin regulatory light chains turns over more rapidly in migrating BAECs than in unwounded monolayers (Kolega, 1999). If the responsible phosphatases had a preference for myosin IIA, myosin IIA would get dephosphorylated to a greater extent than myosin IIB, perhaps contributing to myosin IIA’s ability to move forward into actin networks in new protrusions, whereas myosin IIB lags behind in large contractile structures. Preferential dephosphorylation of myosin IIA could also explain why constitutively active MLCK more readily affects myosin IIB—more kinase activity would be required to outpace the phosphatase.

The preponderance of light-chain phosphorylation in the posterior cytoplasm in BAECs is somewhat different from what has been observed in fibroblasts, where phosphorylation of the regulatory light chains at serine 19 and/or threonine 18 is observed at both the front and the rear of migrating cells (Post et al., 1995; Matsumura et al., 1998; Saitoh et al., 2001; Fumoto et al., 2003). Because fibroblasts also display anterior skewing of myosin IIA and posterior accumulation of myosin IIB (Saitoh et al., 2001), such anterior phosphorylation of regulatory light chains most likely occurs on myosin IIA in fibroblasts. Why this was not observed in BAECs is not clear; however, BAECs were notably insensitive to the MLCK inhibitor, ML-7 (Figures 4, 5, and 7), suggesting that they may have lower MLCK activity or less MLCK than fibroblasts. A higher level of endogenous MLCK in fibroblasts might be sufficient to cause anterior phosphorylation of myosin IIA in fibroblasts, but not enough to induce posterior accumulation, much as moderate levels of constitutively active MLCK in BAECs decrease myosin IIA asymmetry but do not reverse it (Figure 10E, left panel). It would be interesting to determine if migrating BAECs exert less contractile tension in the anterior portions of the cell when compared with fibroblasts and whether constitutively active MLCK changes the distribution of traction forces along the anterior-posterior axis.

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REFERENCES

Myosin IIB Asymmetry in Migrating Cells


