Differential Effect of Rac and Cdc42 on p38 Kinase Activity and Cell Cycle Progression of Nonadherent Primary Mouse Fibroblasts*

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The Rho GTPases play an important role in transducing signals linking plasma membrane receptors to the organization of the cytoskeleton and also regulate gene transcription. Here, we show that expression of constitutively active Ras or Cdc42, but not RhoA, RhoG, and Rac1, is sufficient to cause anchorage-independent cell cycle progression of mouse embryonic fibroblasts. However, in anchorage free conditions, whereas activation of either Cdc42 or Ras results in cyclin A transcription and cell cycle progression, Cdc42 is not required for Ras-mediated cyclin A induction, and the two proteins act in a synergistic manner in this process. Surprisingly, the ability of Cdc42 to induce p38 MAPK activity in suspended mouse embryonic fibroblast was impaired. Moreover, inhibition of p38 activity allowed Rac1 to induce anchorage-independent cyclin A transcription, indicating that p38 MAPK has an inhibitory function on cell cycle progression of primary fibroblasts. Finally, a Rac mutant, which is unable to induce lamellipodia and focal complex formation, promoted cyclin A transcription in the presence of SB203580, suggesting that the organization of the cytoskeleton is not required for anchorage-independent proliferation. This demonstrates a novel function for Cdc42, distinct from that of Rac1, in the control of cell proliferation.

The mechanisms by which anchorage-mediated cues are integrated at the level of the cell division cycle remain elusive. Constitutively active Ras mutants are frequently detected in human tumors and expression of mutated, oncogenic Ras in cultured rodent fibroblast cell lines induces alterations in cell morphology, loss of contact inhibition, changes in gene expression, decreased dependence on serum growth factors, and proliferation which is independent of adhesion to a substratum. Data accumulated during the past decade have shown that many of these Ras-promoted cellular transactions are mediated by Ras effectors, among which Ras family members play an important role, linking plasma membrane receptors to the organization of the actin cytoskeleton, cell adhesion, aggregation, motility, and proliferation (3).

The Rho family of small GTPases include various isoforms of Rac (1–3), Rho (A, B, C), RhoD, RhoE, RhoL, RhoH, RhoG, TC10, and Cdc42Hs. Like Ras, these GTPases oscillate between an active GTP-bound and inactive GDP-bound forms (4).

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1 The abbreviations used are: JNK, c-Jun NH2-terminal kinase; ERK, extracellular signal-regulated kinase; MEK, mouse embryonic fibroblasts; BrdUrd, bromodeoxyuridine; MAPK, mitogen-activated protein kinase; WASP, Wiskott-Aldrich syndrome protein; HA, hemagglutinin.
p63 proliferation of primary mouse embryonic fibroblasts (MEF) in liquid medium.

Expression of cyclin A is required for fibroblast proliferation. Through its association with cyclin-dependent protein kinases cdc2/cdk1 and cdk2, cyclin A controls the normal progression through the S phase and the G2/M transition. Even in the presence of growth factors, fibroblasts cultured without substrate contact fail to express cyclin A and, as a consequence, do not enter S phase. However, this situation can be overcome by ectopic expression of cyclin A. Since cyclin A expression is a marker of cell competence for proliferation, we assessed the role of the Rho GTPases in mediating proliferation in the absence of adhesion, through activation of cyclin A transcriptional activity. In the experiments reported here, we show that the anchorage requirement for cyclin A expression and subsequent cell cycle progression of MEF are alleviated by ectopic expression of the activated forms of either Ras or Cdc42, but not by Rac1, RhoA, or RhoG. Anchorage-independent proliferation is promoted by a synergy between Ras and Cdc42, thereby delineating two distinct signaling pathways. Finally, the level of p38 kinase activity seems to be a key regulator of anchorage-independent proliferation.

MATERIALS AND METHODS

Cell Culture and Transient Transfection Experiments—Early primary MEF were grown in Dulbecco’s modified Eagle’s medium containing 10% heat-inactivated fetal calf serum. Cells were transfected using the calcium phosphate procedure, cultured for 24 h in the presence of serum on agar-coated dishes, and processed for luciferase activity as described previously (1). Normalization was performed using the dual-luciferase reporter assay system from Promega. When required, cells were analyzed according to their DNA content with a FACScan (Becton Dickinson) after labeling with propidium iodide. The following plasmids were used: pCycA-luc is a pGL2-Basic vector containing murine cyclin A promoter sequences spanning nucleotides −177 to +100 relative to the 3’ most transcription initiation site; pDCR-Ras (Val-12) is pDCR-based vector containing the Ras mutant under the control of the early Ras promoter sequences; pDCR-K-Ras (Val-12), pDCR-H-Ras (Val-12), pDCR-N-Ras (Val-12), pDCR-K-Rac1, and pDCR-N-Rac1 are expression vectors for dominant-negative forms of the indicated GTPase; pDCR-CDR-Cdc42 (Val-12) is pDCR-based vector containing the Cdc42 mutant under the control of the early Cdc42 promoter sequences, pCSR3-Myr-RhoA (Val-14) is an expression vector for a myristoylated form of RhoA. As a result, the Cdc42-interacting domain of pWASP containing amino acids 179 to 223 is replaced by an N-terminal 31-residue non-activating insertion (pWASPΔ). Expression vectors for wild-type and dominant-negative forms of the indicated MAP kinases (pSR91A-JNK1 and pSR91A-p38 MAPK) were gifts from A. Debant and B. Derijard. Wild type HA-p38 MAPK and its dominant negative form, HA-p38 MAPK-TA-YF, were expressed in a PEBE-based expression vector (gift from A. Brunet). pCMV-WASP-GBD was constructed by insertion of an EcoRI-Xho1 fragment of pGEX-RG-WASP (gift from A. Hall) into the same sites of pCMV-β-galactosidase (gift from C. Sardet). As a result, the Cdc42-interacting domain of pWASP extending from amino acid 201 to 321, is cloned in-frame with an upstream Myc-tag located between the NcoI and EcoR1 sites of pcDNA3. 5 µg of total DNA was used for 106 cells per 3.5-cm diameter Petri dishes (0.5 µg of pCycA-luc, 0.1 µg of pRL-TK, expression vector as indicated in each figure legend and Bluescript SK1 for a total of 5 µg). To label cells with BrdUrd, MEF were cultured for 12 h in suspension and BrdUrd was then added for an additional 12 h. Cells were collected and fixed on glass slides before BrdUrd staining was monitored.

Protein Analysis and MAP Kinase Assays—After co-transfection of vectors expressing the various tagged MAP kinases and the small GTPases together with pCycA-luc, MEF were cultured for 24 h in the absence of adhesion. Cells were then lysed in Triton lysis buffer (TLB) containing 20 mM Tris-HCl (pH 7.5), 137 mM NaCl, 2 mM EDTA, 1% Triton X-100, 1 mM β-glycerophosphate, 1 mM Na3VO4, 10% glycerol, 1 mM phenylmethylsulfonyl fluoride, and 10 µg/ml leupeptin as described (21). Soluble extracts were prepared by centrifugation at 15,000 rpm for 30 min at 4 °C and split into two fractions. The first one was used to test the expression of the tagged proteins, and the second to assay for ERK2, JNK1, or p38 activities. Extracts were incubated with 5 µl of the 12CA5 anti-HA monoclonal antibody pre-bound to 20 µl of protein-Sepharose G (Amersham Pharmacia Biotech). After a 2-h incubation at 4 °C, immunoprecipitates were washed three times with TLB and twice with kinase buffer containing 25 mM Hepes (pH 7.5), 25 mM MgCl2, 25 mM β-glycerophosphate, 2 mM dithiothreitol, and 0.1 mM Na3VO4. Immunocomplex kinase assays were performed at 30 °C for 30 min in the presence of 50 µM ATP and 2 µCi of [γ-32P]ATP in 20 µl of kinase buffer using 4 µg of myelin basic protein (Sigma), GST-ε6-jun (amino acids 1–79), and GST-ATP2 (amino acids 1–110) as substrates for ERK2, JNK1, and p38 kinase activities, respectively. Reactions were stopped with Laemmli sample buffer and the products resolved by gel electrophoresis through 10% (JNK1 and p38) or 15% (ERK2) polyacrylamide SDS-containing gels. Dried gels were exposed on imaging plates for 1 h, and signals were quantified with a PhosphorImager (Molecular Dynamics). Western blot analysis was carried out on total cellular extracts after transfer onto nitrocellulose filters, and ECL detection was performed with the following primary antibodies: cyclin A CY-A1, Myc 9E10 (Sigma), and HA12CA5 (Cold Spring Harbor Laboratory) mouse monoclonals, as well as an anti-glyceraldehyde-3-phosphate dehydrogenase polyclonal rabbit IgG (1).

RESULTS

Activation of the Cdc42Hs-mediated Pathway Promotes Anchorage-independent Cyclin A Expression and S-phase Entry of Nonadherent MEF—Fibroblasts lacking contact with the extracellular matrix are arrested in the G1 phase of the cell cycle, as can be judged by most of the cells having a 2N DNA content and expressing cyclin D1 to a high level (data not shown) (25). It is well established that Rho family proteins play an essential role both in organizing the actin cytoskeleton (26) and in promoting cell cycle progression in adherent cells (14). We have investigated the effects of four Rho family members (RhoA, RhoG, Rac1, and Cdc42Hs) on cyclin A expression and S phase entry of nonadherent fibroblasts. The activated Myc-tagged mutants of the GTPases were co-expressed in transient transfection experiments with a transfected cyclin A promoter-driven luciferase reporter (pCycA-luc). In nonadherent MEFs, a constitutively activated form of Cdc42Hs (Cdc42Hs (Val-12) or Cdc42Hs (Leu-61) activated pCycA-luc (Fig. 1A). In contrast, RhoA (Val-14), RhoG (Val-12), and Rac1 (Val-12) failed to stimulate the cyclin A-promoter (Fig. 1A). However, in parallel experiments, Cdc42Hs, and to a lesser extent RhoA (Val-14) and Rac1 (Val-12), activated serum responsive element-driven transcription (Fig. 1B). We next investigated whether activated Rho proteins modulated the endogenous cyclin A expression in nonadherent MEF. We therefore analyzed endogenous cyclin A expression in nonadherent cells transfected with activated
forms of Cdc42Hs, Rac1, and RhoG. The different mutants were expressed at the same level as monitored by Western blot analysis performed with a monoclonal antibody directed against the Myc epitope (Fig. 2A). Nevertheless, activation of Cdc42Hs, but not RhoG nor Rac1, resulted in a significant expression of endogenous cyclin A in nonadherent MEF. Consistent with these data, BrdUrd labeling (Fig. 2B) indicative of S phase entry, were detected only in cells expressing activated Cdc42Hs. Moreover, using fluorescence-activated cell sorter analysis, we confirmed that these nonadherent MEF cells were competent for cell cycle progression since they accumulated in the S and G2/M phases of the cell cycle (data not shown).

**Cdc42Hs and Ras Promote Anchorage-independent Proliferation of MEF through Synergistic Signaling Pathways—**Experiments aimed at determining whether Cdc42Hs is a key downstream mediator of Ras signaling have led to conflicting results. Thus we investigated in primary fibroblasts whether Ras was necessary for the resumption of cell proliferation as measured by cyclin A expression. MEF were transfected with cytomegalovirus-driven plasmid expressing the HA-tagged mutant of Ras which contains the activating Val-12 mutation. As shown in Fig. 3A, Ras (Val-12) gave rise to a 5-fold increase in cyclin A promoter activity. We next investigated the effect of Ras (Val-12) on endogenous cyclin A expression. Whereas cyclin A was not expressed in nonadherent cells transfected with the empty vector (pDCR) following exposure to serum, introduction of Ras (Val-12) resulted in the accumulation of endogenous cyclin A protein (Fig. 3B). As a consequence, cells entered S phase as monitored by BrdUrd staining (Fig. 3C) and progressed through cell cycle as observed using fluorescence-activated cell sorter analysis (data not shown). We next examined whether Cdc42Hs and Ras stimulate cyclin A expression through activation of the same signaling cascade. The dominant negative Asn-17 mutant form of Cdc42Hs did not block Ras (Val-12) induced cyclin A promoter activity in nonadherent MEF (Fig. 4A). Importantly, the dominant negative Asn-17 Rac mutant inhibited the Ras effect by 50% but did not alter the Cdc42Hs response (Fig. 4A). The latter result is consistent with previous data suggesting that pathways downstream of Rac1 are required for full Ras signaling (18–21). To address whether Cdc42Hs mediates Ras-induced cyclin A transcription in nonadherent MEF, we used the Cdc42Hs-interacting domain of the Wiskott-Aldrich syndrome protein (WASP), a specific effector for Cdc42Hs involved in actin polymerization (27, 28). This fragment inhibits Cdc42Hs activity through competition with its effector binding site. Cdc42Hs, but not Ras (Val-12), induced cyclin A transcription was strongly inhibited upon expression of the WASP fragment (Fig. 4A). These results suggest that Ras and Cdc42Hs govern different pathways leading to adhesion-independent cyclin A induction. To determine whether Ras and Cdc42Hs activate co-operative pathways, we concomitantly expressed activated forms of Ras and Cdc42Hs, in nonadherent MEF cells. Separately, Ras (Val-12) and Cdc42Hs (Leu-61) activated cyclin A reporter activity to approximately the same extent (5-fold), whereas their co-expression affected cyclin A in a synergistic manner (15-fold) (Fig. 4B). In conclusion, these data suggest that Cdc42Hs and Ras cooperate to control anchorage-independent proliferation of MEF through parallel pathways.

**JNK Is Not Required for Cdc42-mediated Anchorage-independent Proliferation of MEF—**Activation of Cdc42Hs and Rac1 in adherent cells has previously been reported to activate the JNK and p38 stress kinases without any effect on the ERK pathway (12, 13, 29). We therefore assessed whether adhesion-independent cyclin A induction required the activation of any of these MAP kinases. MEF were transiently co-transfected with different combinations of HA-tagged versions of ERK2, p38, or JNK1 together with Ras (Val-12), Cdc42Hs (Leu-61), or Rac1 (Leu-61). As shown in Fig. 5A, Rac (Val-12) activated ERK and, to a much lesser extent, JNK1 in adherent cells. P38 activity was not induced by Ras (Val-12). In contrast, both Cdc42Hs (Leu-61) and Rac1 (Leu-61) had negligible effects on ERK activity whereas they activated p38 and JNK kinases. When the same
experiment was carried out on nonadherent cells, Ras (Val-12) still activated ERK, albeit to a lower extent and had negligible effects on JNK. Interestingly, in a nonadherent context, the basal level of p38 activity was inhibited by Ras (Val-12) (Fig. 5B) and Cdc42Hs (Leu-61) or Rac1 (Leu-61)-induced ERK and JNK activities were equivalent in adherent and nonadherent cells. Importantly, the Cdc42Hs-induced activation of p38 was significantly decreased in nonadherent cells as compared with adherent MEF (Fig. 5A).

In an attempt to identify the effector(s) involved, we used previously described Cdc42Hs and Rac1 variants, mutated in their effector domains, which are impaired in binding to specific effectors (30). Based on the work carried on Ras, single amino acids substitutions were introduced within the effector loops of the constitutively active Cdc42Hs (Leu-61) and Rac1 (Leu-61) (30). The resulting Cdc42Hs (Q61L/Y40C) and Rac1 (Q61L/Y40C) mutants no longer interact with some Cdc42Hs or Rac1-interactive binding motif-containing proteins such as the Ser/Thr protein kinase p65PAK or WASP (30). In contrast, the F37A substitution in Cdc42Hs (Q61L/F37A) and Rac1 (Q61L/F37A) does not affect the interactions with Cdc42Hs or Rac1-interactive binding domain-containing proteins, but Cdc42Hs (Q61L/F37A) lacks the ability to activate Rac1 (30). The experiments described above were repeated with these two Cdc42Hs (Leu-61) effector loop mutants. As expected, the Cdc42Hs (Q61L/Y40C) mutant did not induce JNK while the Cdc42Hs (Q61L/F37A) mutant was almost as potent as Ras (Val-12) or Cdc42Hs (Leu-61) in inducting cyclin A promoter activity after transient expression in nonadherent cells (Fig. 6C). Moreover, Cdc42Hs (Q61L/F37A) cooperated with Ras (Val-12) to the same level as Cdc42Hs (Leu-61).

One interpretation of these results is that Cdc42Hs induced JNK activity is required for cell cycle progression. To test this hypothesis, the dominant negative mutant of JNK (APF-JNK) was expressed in nonadherent cells. Although this dominant negative mutant abolished Cdc42Hs (Leu-61)-induced JNK activity (Fig. 7A), it did not inhibit Cdc42Hs-induced cyclin A expression (Fig. 7B). These data clearly demonstrate that JNK is not involved in Cdc42Hs-induced anchorage-independent proliferation.

**Anchorage-independent Proliferation of MEF Is Associated with the Down-regulation of p38 Kinase Activity**—Whereas Rac1 (Leu-61) was as potent as Cdc42Hs (Leu-61) in activating JNK, it did not induce cyclin A expression in nonadherent MEF. Interestingly, in contrast with Rac1 (Leu-61), Cdc42Hs did not activate p38 kinase in nonadherent cells (Fig. 5). Moreover, Ras (Val-12), which induced cyclin A expression in nonadherent MEF, strongly down-regulated p38 activity (Fig. 5). We therefore investigated whether the absence of p38 kinase activation was necessary for cyclin A expression in nonadherent MEF, and in particular, whether the ability of Rac1 to activate the p38 pathway could explain its inability to promote cyclin A expression. To test this hypothesis, Rac1 (Leu-61) effector loop mutants were transiently co-transfected into nonadherent MEF expressing HA-tagged versions of p38 or JNK. Rac1 (Q61L/F37A) activated both JNK and p38 kinases, while Rac1 (Q61L/Y40C) had no effect on JNK, and a reduced effect on p38 (Fig. 8, A and B). We next expressed these mutants with the cyclin A-luciferase reporter in nonadherent MEF. As previously observed for Rac1 (Leu-61), neither Rac1 (Q61L/F37A) nor Rac1 (Q61L/Y40C) were able to activate cyclin A promoter activity (Figs. 1A and 8C). However, addition of SB203580, a specific inhibitor of the p38 pathway (31, 32), resulted in strong cyclin A promoter activity in nonadherent Rac1 (Leu-61)-ex-
pressing cells (Fig. 8C). Indeed, cyclin A expression was as high as that observed in the presence of Cdc42Hs (Leu-61). Similarly, the Rac1 double mutant (Rac1 (Q61L/F37A)) impaired in inducing actin polymerization and focal complex formation (30), activated cyclin A transcription upon inhibition of the p38 pathway (Fig. 8C). In contrast, the Rac1 (Q61L/Y40C) mutant did not activate cyclin A transcription under these conditions (Fig. 8C). This strongly suggests that inactivation of p38 kinase activity is required for the suppression of the block to proliferation as measured by activation of cyclin A transcription. This hypothesis is supported by experiments with a dominant negative form of p38 (YFp38), which led to an activation of cyclin A promoter activity when expressed in conjunction with Rac1 (Leu-61) (Fig. 8C).

In conclusion, inactivation of p38 pathway is required, but not sufficient, for the proliferation of nonadherent MEF. Therefore, anchorage-independent MEF proliferation might result from a dynamic balance involving inactivation of p38 kinase activity and activation of an effector distinct from JNK which interacts with Cdc42Hs.

### DISCUSSION

Fibroblasts require both mitogens and integrin-mediated attachment for growth (26, 33, 34). When deprived of anchorage, many adherent cell lines fail to undergo several G1-specific cell cycle-related transitions, even in the presence of growth factors (1, 35–39). However, no such studies have been carried out in primary cells. Stable expression of activated Ras or Cdc42Hs in rodent cell lines has been shown to overcome anchorage-dependent requirements to various extents. However, expression of a mutated Ras is known to induce a wide variety of responses including both gene expression and alterations in cellular morphology. Moreover, it has become clear that the great biological diversity observed within existing cell lines can at least in part be accounted for by the large array of integrin combinations which are expressed at the cell surface. As a result, many cell type-specific differences exist between normal and transformed cells, as well as between cell lines whose proliferation is strictly anchorage-dependent. The differences observed in established cell lines are probably the result of adaptive events that have occurred during cell culture. Thus, the use of primary cells as opposed to immortalized cell lines is particularly important for the investigation of pathways controlling anchorage-independent cell proliferation. Moreover, the use of different experimental conditions to study the links between anchorage and proliferation has also led to many apparent discrepancies. Specifically, growth on soft agar is different from growth in liquid suspension. Some mutants, selected for their ability to form colonies in soft agar are unable to proliferate in liquid suspension (24). In order to overcome these difficulties, we studied the requirements for anchorage-independent proliferation of pri-
in a fully anchorage-independent context. A strong synergy was
believed to be the role of Cdc42 in transformation appears to be largely independent of Rac (18, 20). Furthermore, Rac and Cdc42Hs have been shown to delineate distinct pathways that cooperate to transform NIH 3T3 cells (2). Consistent with this, the Cdc42Hs double mutant Cdc42Hs (Q61L/F37A), which is unable to activate Rac (30), was still able to induce cyclin A transcription and cooperate with Ras. These observations suggest that the hierarchy established between Ras, Cdc42, and Rac in the control of cell morphology (40, 41) is not necessarily valid for other processes. Altogether, we show that pathways downstream of Rac1 are required for full Ras signaling, but are not required for Cdc42Hs signaling, in controlling cell cycle progression of MEF cultured under anchorage-free conditions.

Both Cdc42Hs and Rac (but not Rho) can activate the JNK/SAPK and the p38/HOG MAP kinases cascades in adherent cells (12, 13), thereby affecting gene transcription. JNK phosphorylates c-Jun at serines 63 and 73, and this transcription factor is implicated in G1 progression by inducing cyclin D1 expression (42). Nevertheless, a recent study showed that phosphorylation of serines 63 and 73 of c-Jun was required for protection against UV-induced apoptosis but not for cell proliferation (42). Accordingly, JNK activity is not detected in cells growing on a solid support, and in our work cyclin D1 is normally induced and present in nonadherent MEF. Consistent with this, we show here that a dominant negative form of JNK was unable to inhibit Cdc42Hs-induced cyclin A transcription in MEF cultured under anchorage free conditions. In contrast, p38 MAPK activity has been proposed to participate in the control of the G1/S transition of some cells (22, 43). Whereas it has been previously shown that Cdc42Hs inhibits proliferation of adherent NIH3T3 cells (22), we show here that it leads to the opposite effect in nonadherent MEFs. Interestingly, however, modulation of p38 kinase activity seems to be instrumental in both situations. In adherent NIH 3T3 cells, inhibition of proliferation is associated with an activation of p38 activity. In contrast, under anchorage-free conditions, we found that Cdc42Hs-mediated cyclin A induction and progression of MEF through G1/S was associated with impaired p38 activity. Moreover, inhibition of p38 activity allowed Rac1-induced cyclin A transcription. These results indicate that Rac1 and Cdc42Hs use distinct pathways to activate p38 kinase. It is clear that inhibition of p38 kinase activity is not sufficient to trigger proliferation, and additional signals modulated by Cdc42Hs or Rac1 are necessary. It has been postulated that these events require actin polymerization and focal complex formation. However, in our study a Rac1 double mutant (Rac1 (Q61L/F37A)), unable to induce either membrane ruffling or the formation of focal complexes (30), was nevertheless able to induce...
G₁ progression when p38 kinase activity was inhibited. In summary, this study indicates a novel role for Cdc42 in the control of anchorage-independent cell cycle progression. Under these conditions, Cdc42 activity results in a down-regulation of p38 MAPK activity and the Cdc42 effector domain is redirected from JNK to another downstream effector. These findings suggest that unravelling the Cdc42Hs signaling cascade will shed some light on the mechanisms by which a cell integrates peripheral cues into a coordinated proliferation program.

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