Rho GDP Dissociation Inhibitor 2 Suppresses Metastasis via Unconventional Regulation of RhoGTPases

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Abstract
Rho GDP dissociation inhibitor 2 (RhoGDI2) has been identified as a metastasis suppressor in bladder cancer and possibly other cancers. This protein is a member of a family of proteins that maintain Rho GTPases in the cytoplasm and inhibit their activation and function. To understand the mechanism of metastasis suppression, we compared effects of RhoGDI1 and RhoGDI2. Despite showing much stronger inhibition of metastasis, RhoGDI2 is a weak inhibitor of Rho GTPase membrane targeting and function. However, point mutants that increase or decrease the affinity of RhoGDI2 for GTPases abolished its ability to inhibit metastasis. Surprisingly, metastasis suppression correlates with increased rather than decreased Rac1 activity. These data show that RhoGDI2 metastasis inhibition works through Rho GTPases but via a mechanism distinct from inhibition of membrane association.

Introduction
Rho GDP dissociation inhibitor 2 (RhoGDI2) was recently shown to function as a metastasis suppressor in bladder cancer and possibly other tumors (reviewed in ref. 1). Loss of RhoGDI2 expression strongly correlates with cancer stage, grade, and the development of clinical metastasis in patients. Loss of RhoGDI2 also correlates with experimental metastasis in mouse models. Reexpression of RhoGDI2 in metastatic tumor lines inhibits experimental metastasis in these models without affecting primary tumor growth or growth rate in vitro.

RhoGDI2 (or GDI2) is a member of a small family of chaperone proteins, including RhoGDI1 and RhoGDI3, which control Rho GTPases (2, 3). Whereas GDI1 is ubiquitous, GDI2 is expressed mainly in hematopoietic, endothelial, and urothelial cells (4). The Rho proteins Rho, Rac, and Cdc42 that bind GDI2 regulate many cellular functions, including cell polarity, migration, cell cycle progression, apoptosis, gene expression, vesicular trafficking, and cancer. Rho GTPases cycle between an inactive (GDP-bound) state that is mainly cytosolic and an active (GTP bound) state that is mainly membrane bound. Membrane targeting is predominantly mediated by COOH-terminal sequences that include a geranylgeranyl modification and a polybasic motif. The GDI2 bind and sequester this hydrophobic moiety and are required to maintain Rho GTPases in the cytoplasm. They also inhibit activation by GEFs and inactivation by intrinsic and GTase-activating protein–catalyzed GT hydrolysis (5, 6). Overexpression of GDI1 causes movement of Rho, Rac, and Cdc42 into the cytoplasm and inhibits their activation and function (7–11). Conversely, depletion of GDI1 increases membrane association and activation of Rho GTPases (11–13).

Here, we set out to investigate the mechanism of tumor suppression by RhoGDI2. Based on behavior of GDI1, we anticipated that tumor suppression would be linked to inhibition of Rho GTPase function. Our data unexpectedly exclude such a mechanism and instead show that GDI2 activates its main target Rac.

Materials and Methods
Cell culture and transfection. UMUC3 cells were grown in MEM supplemented with 10% fetal bovine serum, 1 mM/l sodium pyruvate, penicillin, and streptomycin (Invitrogen). T24 cells were grown in DMEM/F12 supplemented with 5% fetal bovine serum, penicillin, and streptomycin. DNA plasmids were transfected with Effectene according to the manufacturer’s instructions (Qiagen). Cells were analyzed for protein 24 h after transfection. For generation of stable green fluorescent protein (GFP)-RhoGI1–expressing UMUC3 cells, GFP-RhoGI1 constructs were transfected together with pBABE-puro (14) at a 5:1 ratio. Polyclonal populations were obtained after selection with 2 μg/mL puromycin followed by fluorescence-activated cell sorting (Flow Cytometry Core Facility, University of Virginia). For RNA interference (RNAi) experiments, T24 cells were transfected with pSuper.retro.puro-based constructs and clones were obtained following selection with puromycin (2 μg/mL).

DNA plasmids and constructs. pcDNA3.1(+)–based plasmids containing RhoGDI1 or RhoGDI2 were used as templates for PCR amplification of the coding sequences that were subsequently subcloned into pEGFP-C1 to generate the corresponding GFP fusion proteins. The N174I, I177N, and D182R mutations were introduced using the QuikChange II Site-Directed Mutagenesis kit (Stratagene). To generate FLAG-Rac, the coding sequence of human Rac was PCR amplified and subcloned into pFLAG-CMV-4 (Sigma-Aldrich). For RNAi experiments, duplicated oligos containing a sequence corresponding to nucleotides 97 to 116 in the coding region of human RhoGDI1 (5’-AAGAGCATCCAGGAGATCCA-3’) or 123 to 141 of RhoGDI2 (5’-TGATGAGAGTCTAATTAAG-3’) or control (mismatch) sequence were subcloned in pSuper.retro.puro (OligoEngine).

Immunoprecipitation and Western blotting. Stable UMUC3 cells that had been transfected with pFLAG-CMV-4-Rac were extracted in buffer containing 10 mM/l Tris-HCl (pH 7.4), 150 mM/l NaCl, 1% NP40, 8% glycerol, and protease inhibitor cocktail and immunoprecipitated with the anti-FLAG M2 antibody (Sigma-Aldrich) for 2 h at 4°C. Immunoprecipitates were washed on 100 μg/mL 3× FLAG peptide. Samples were separated by SDS-PAGE, electrophoretically transferred to nitrocellulose (Bio-Rad Laboratories), and immunoblotted with the following primary antibodies: B-2 monoclonal anti-GFP (1:1,000; Santa Cruz Biotechnology), monocular anti-RhoGDI1 (1:5,000; clone 16; BD Transduction Laboratories), polyclonal anti-D4-GDI1 (1:1,000; Spring Bioscience), AC-40 monoclonal anti-actin (1:1,000; Sigma-Aldrich), E7 monoclonal...
anti-α-tubulin (1:1,000; Developmental Studies Hybridoma Bank), 23A8 monoclonal anti-Rac1 (1:1,000; Millipore), monoclonal anti-Cdc42 (clone 44; 1:500; BD Transduction Laboratories), 26C4 monoclonal anti-RhoA (1:500; Santa Cruz Biotechnology), monoclonal anti-RhoA (1:250; Cytoskeleton, Inc.), anti-FLAG M2 monoclonal (1:5,000; Sigma-Aldrich), polyclonal anti-extracellular signal-regulated kinase 1/2 (ERK1/2; 1:1,000; Cell Signaling Technology), polyclonal anti-phospho-stress-activated protein kinase/c-Jun NH2-terminal kinase (SAPK/JNK; Thr183/Tyr185; 1:1,000; Cell Signaling Technology), polyclonal anti-SAPK/JNK (1:1,000; Cell Signaling Technology), polyclonal anti-phospho-PAK (Ser145; 1:1,000; Invitrogen), polyclonal anti-PAK (1:1,000; Santa Cruz Biotechnology), and polyclonal R18 anti-integrin β1 (gift of A.F. Horwitz, University of Virginia, Charlottesville, VA). Blots were washed and probed with secondary antibodies (horseradish peroxidase-conjugated anti-mouse or anti-rabbit immunoglobulin) followed by enhanced chemiluminescence substrate (Amersham Biosciences). Densitometric analysis was performed with Image J software.

Subcellular fractionation. Cells were washed with ice-cold PBS, scraped, and homogenized in buffer containing 10 mmol/L Tris-HCl (pH 7.5), 5 mmol/L MgCl2, 1 mmol/L DTT, 0.25 mol/L sucrose, and protease inhibitor cocktail (Sigma-Aldrich). Nuclei and unbroken cells were removed by centrifugation at 1,000 × g for 10 min at 4°C, and the postnuclear supernatant was centrifuged at 100,000 × g for 1 h at 4°C to separate the cytosolic and particulate fractions.

Pull-down assays. Cells were washed with ice-cold TBS and lysed in buffer containing 50 mmol/L Tris (pH 7.4), 500 mmol/L NaCl, 10 mmol/L MgCl2, 1% Triton X-100, 0.1% SDS, 0.5% sodium deoxycholate, and protease inhibitor cocktail (Sigma-Aldrich). Clarified lysates were then incubated with 20 µg of recombinant glutathione S-transferase (GST)-PBD or GST-RBD and Glutathione-Sepharose 4B beads (Amersham Biosciences) for 30 min at 4°C. Beads were washed with lysis buffer, eluted with sample buffer, and analyzed by immunoblotting.

In vitro growth, s.c. tumorigenesis, and experimental metastasis. Cells (10³) were seeded onto six-well plates and allowed to grow under normal growth conditions. Triplicate wells were trypsinized and counted every day using a hemacytometer (Fisher Scientific). S.c. tumor growth was assayed in 6-wk-old nude mice by injecting 10⁶ cells in 0.1 mL of serum-free medium. Tumor volume was evaluated as described (15). For experimental metastasis, mice received 2 × 10⁵ cells suspended in 0.1 mL of serum-free medium by i.v. lateral tail vein injection as described (15). At the time of euthanasia, the lungs were removed by dissection away from adjacent organs and examined grossly and microscopically. The presence, number, and size of metastatic nodules were scored. Animal experiments were carried out twice or more and results were pooled for statistical analysis.

Migration assays. Cells (5 × 10⁴) were plated onto custom-made glass-bottom 35-mm dishes coated with 2 µg/mL fibronectin. Five hours after plating, dishes were transferred to a custom-made heated stage mounted on a Nikon Diaphot-TMD inverted microscope (Nikon Corp.) and imaged every 10 min for 4 h using a CoolSnap HQ Monochrome camera (Photometrics, Roper Scientific, Inc). Temperature in the medium was maintained at 37°C and pH was controlled by addition of 25 mmol/L HEPES buffer. Medium was overlaid with mineral oil to prevent evaporation. Image acquisition was controlled by ISee software (Inovision Corp.). Tracks of individual cells were analyzed using Image J software.

Cell spreading. Cells were detached with trypsin-EDTA, pelleted, resuspended in growth medium, and replated on glass coverslips coated with 5 µg/mL fibronectin. After 4 h, cells were fixed with 3.7% formaldehyde and surface area of individual GFP-positive cells was measured using Image J software.

Results

The major function of GDI1 is thought to be inhibition of membrane targeting of Rho GTPases (11). To gain insight into the mechanism of metastasis suppression by GDI2, we performed a comparative analysis of GDI1 and GDI2 in regulating the classic Rho GTPases Rac1, Cdc42, and RhoA. We therefore established stable

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Figure 1. RhoGDI overexpression. A, lysates of UMUC3 cells stably expressing GFP, GFP-GDI1, or GFP-GDI2 were resolved by SDS-PAGE and immunoblotted for GFP and RhoGDI1. B, membrane fractions and total lysates were immunoblotted for Rac1 and integrin β1. Columns, mean of membrane/total ratio of Rac1 compared with control cells (n = 3); bars, SE. *, P < 0.01 (compared with GFP-GDI2); **, P < 0.005 (compared with GFP-GDI2). C, surface area of UMUC3 cells expressing the indicated constructs after plating on fibronectin for 4 h. Columns, mean (n = 78–102); bars, SE. *, P < 0.001 (compared with GFP-GDI2); **, P < 0.005 (compared with GFP-GDI2); ***, P < 0.001 (compared with GFP-GDI1). P values were calculated by Student’s t test.
polyclonal cell lines that overexpress GFP or GFP fusions with GD11 and GD12 (Fig. 1A). Highly metastatic UMUC3 cells that have undetectable levels of endogenous RhoGDI2 (16) were used for these studies. Immunoblotting with a RhoGDI1–specific antibody revealed that the exogenous protein was present at similar levels to endogenous RhoGDI1; thus, total levels increased ~2-fold. Western blotting for GFP showed that overexpressed GFP-GDI1 and GFP-GDI2 were present at similar levels (Fig. 1A). GD11 overexpression greatly decreased Rac targeting to the membrane fraction (80%), whereas comparable expression of GD12 had a much smaller effect (40%; Fig. 1B; Supplementary Fig. S1). This result is consistent with the weaker binding of GD12 to Rho GTPases (17).

To assess functional relevance, we compared the effect of transiently expressed GD11 and GD12 on cell spreading, which is highly dependent on Rac and Cdc42 (18). GD11 strongly inhibited cell spreading, whereas effects of GD12 were negligible (Fig. 1C).

As a complementary approach, we expressed short hairpin RNAs directed against GD11 and GD12 in nonmetastatic T24 cells that express both GD11 and GD12 (19). Two independent stable clones (clones 1 and 3) that exhibited ~50% down-regulation of GD11 were isolated, whereas GD12 levels were unaffected (Fig. 2A, top). Conversely, three independent clones (13, 15, and 17) showed significant GD12 depletion without affecting GD11 (Fig. 2A, bottom). GD12 was reduced by ~70% in clones 13 and 15 and was undetectable in clone 17. These cells were fractionated and membrane and cytosol preparations were probed for Rac1, Cdc42, and RhoA. Down-regulation of GD11 resulted in a 6- to 9-fold increase in the ratio of membrane to cytosolic Rac1, RhoA, and Cdc42 (Fig. 2B and C). By contrast, reduction of GD12 had no detectable effect. To analyze cellular functions, we assayed these clones for random migration. As expected, GD11 depletion increased migration speed 3- to 5-fold (Fig. 2D; Supplementary Fig. S2); however, down-regulation of GD12 had no effect. Thus, both overexpression and down-regulation show that inhibition of GTPase function by GD12 ranges from weak to undetectable.
As shown below, GDI2 is a stronger inhibitor of metastasis compared with GDI1 (Table 1). These results therefore raise the question whether GDI2 suppresses metastasis through Rho GTPases at all. To address this issue, we took advantage of work that identified residue I177 in GDI1, which corresponds to N174 in GDI2, as an important determinant of their differential affinity for Rho GTPases (17). We made a point mutant in GDI2 (N174I) that increases its affinity for Rho GTPases, another mutation in GDI2 (D182R) that decreases its binding (20, 21), and a mutation in GDI1 (I177N) that decreases binding to GTPases. Stable cell lines that express GFP fusions of these mutants were established and shown to express at levels similar to their wild-type (wt) counterparts (Figs. 1A and 3).

We next verified that these mutations affect binding to Rho GTPases in the predicted way. We focused on Rac1 because coimmunoprecipitation experiments showed that GDI2 binds mainly to Rac1, whereas binding to Rac2, Rac3, Cdc42, RhoA, or RhoC are very weak. First, the stable cell lines expressing GFP-GDIs were transfected with FLAG-Rac1; the cell lysates were precipitated with anti-FLAG and the amount of bound GFP-RhoGDIs was assessed. I177N GDI1 bound poorly to FLAG-Rac1 compared with its wt counterpart, N174I GDI2 showed increased binding compared with wt GDI2, and D182R GDI2 showed essentially no binding to Rac1 (Fig. 3). To examine functional correlates, we again assayed Rac membrane targeting and cell spreading. wt GDI1 was the most effective inhibitor of Rac function but this was decreased by the I177N mutation (Fig. 1B and C). N174I GDI2 inhibited Rac membrane binding and cell spreading modestly but significantly more efficiently than wt GDI2. D182R RhoGDI2 had essentially no effect on Rac function. Thus, these constructs behaved as expected.

Next, we examined their behavior in the experimental metastasis model. Cells were injected via tail veins and lung metastases were monitored (Table 1). GDI2 significantly reduced both the percentage of mice with metastatic nodules in the lungs (48% with GFP compared with 6.6% with GFP-GDI2) and the number of tumors in the tumor-bearing mice. Thus, the total tumor burden decreased by ~15-fold. GDI1 expression moderately reduced the incidence of metastasis (26.6%); however, this reduction correlates with the slower growth of these cells (Fig. 4A and B). I177N GDI1 showed both faster growth and a corresponding increase in metastases. Surprisingly, the GDI2 mutants with either higher or lower affinity for Rho GTPases lost their ability to inhibit metastases. Therefore,

### Table 1. Effect of GDIs on experimental metastasis

<table>
<thead>
<tr>
<th>Cell line</th>
<th>No. mice</th>
<th>% mice with metastases</th>
<th>Average no. metastases (in metastasis-bearing mice)*</th>
<th>Average no. metastases (in total number of mice)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFP</td>
<td>25</td>
<td>48</td>
<td>3.75 ± 0.59</td>
<td>1.8 ± 0.28</td>
</tr>
<tr>
<td>GFP-GDI1</td>
<td>15</td>
<td>26.6</td>
<td>3.75 ± 1.1</td>
<td>0.99 ± 0.29</td>
</tr>
<tr>
<td>GFP-GDI2</td>
<td>15</td>
<td>6.6</td>
<td>2</td>
<td>0.13</td>
</tr>
<tr>
<td>GFP-GDI2/N174I</td>
<td>20</td>
<td>20</td>
<td>7.25 ± 2.5</td>
<td>1.45 ± 0.5</td>
</tr>
<tr>
<td>GFP-GDI1/I177N</td>
<td>20</td>
<td>50</td>
<td>5.2 ± 2.2</td>
<td>2.6 ± 1.1</td>
</tr>
<tr>
<td>GFP-GDI2/D182R</td>
<td>20</td>
<td>55</td>
<td>9.18 ± 4.13</td>
<td>5.04 ± 2.27</td>
</tr>
</tbody>
</table>

**NOTE:** Data were pooled from two independent experiments with consistent results. Mice were sacrificed 12 wk after injection.

*Values are mean ± SE.

† P < 0.01, by χ² test (compared with GFP).

‡ P < 0.02, by Student’s t test (compared with GFP).

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Figure 3. Characterizing GDI1 and GDI2 mutants. Lysates of the indicated stable UMUC3 lines transfected with FLAG-Rac were subjected to immunoprecipitation with anti-FLAG and samples were analyzed by immunoblotting for GFP and FLAG. Anti-ERK1/2 was used as a loading control. Data are representative of three independent experiments.

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suppression of metastasis is specific to wt RhoGDI2 and cannot be attributed to general reduction of growth rates.

These results suggest that RhoGDI2 inhibits metastasis through Rho GTPases; however, this effect cannot be mediated by inhibition of GTPase function. An alternative mechanism is based on the idea that Rac, Rho, and Cdc42 each have many effectors and some effector pathways inhibit migration and invasion (22, 23). Interestingly, our previous work also implicated GDI1 in the activation mechanism for Rac (11). Thus, it seems possible that GDI2 might direct activity of a Rho GTPase toward a specific pathway that inhibits metastasis. Given that GDI2 has the highest affinity for Rac1, this GTPase is the main candidate. However, the general importance of Rac1 in metastasis precludes testing this idea using the experimental metastasis model by globally inhibiting Rac1. But as a first step, we were able to assess effects of RhoGDI constructs on Rac1 activity. Pull-down assays with the PAK effector domain were done using the cells expressing GFP, GFP-RhoGDI1, or GFP-RhoGDI2. GDI1 cells showed a decrease in Rac1 activity, as expected, whereas GDI2 overexpression consistently increased Rac1 activity compared with control GFP cells (Fig. 5A). Conversely, when knockdown lines were examined, clone 17 that had undetectable levels of GDI2 showed reduced Rac1 activity (Fig. 5B). Clones 13 and 15 did not show similar reductions, most likely because knockdown of GDI2 was less efficient. To examine this issue in more detail, effects of the point mutants on Rac1 activity were examined. Both N174I and D182R RhoGDI2 failed to affect Rac1 activation, whereas the I177N GDI1 construct lost its ability to inhibit Rac1 (Fig. 5A). Thus, metastasis suppression correlates with increased rather than decreased Rac1 activity.

To test whether elevated Rac activity is accompanied by changes in cytoskeletal architecture, filamentous actin and vinculin-containing adhesions were visualized in spreading cells. However, elevated Rac in GDI2 cells did not cause obvious increases in actin-rich protrusions or membrane ruffling (Supplementary Figs. S3 and S4). We also investigated pathways downstream of Rac that might mediate metastasis suppression. We first assayed activity of SAPK/JNK and PAK; however, no correlation was observed between activation of these pathways and metastatic potential (Supplementary Fig. S5). We also considered whether Rac1 suppresses metastasis through inhibition of RhoA. GST-Rho-kinase pull-down assays (Fig. 5C) showed no change in RhoA activity in cells expressing GDI1 or GDI2. We have not been able to conclusively measure RhoC activation, most likely due to low expression (data not shown). Thus, suppression of metastasis correlates with elevated Rac activity but not with activation of known Rac downstream pathways currently implicated in cancer.
Discussion

In this study, we set out to investigate the mechanism by which RhoGDI2 suppresses metastasis. Our results show that GDI1 and GDI2 are functionally distinct. Specifically, RhoGDI1 is a strong negative regulator of Rho GTPases, which correlates with the strength of GDI1 binding to GTPases. In contrast, GDI2 inhibits GTPase function weakly if at all, yet strongly inhibits metastasis. Surprisingly, mutations that either increase or decrease the affinity of GDI2 for GTPases abolish metastasis. These data provide strong evidence that GDI2 acts via a distinct mechanism from GDI1 and that it does not do so by inhibiting GTPase activity or function.

On the contrary, metastasis suppression correlated with increased Rac1 activity. At first glance, this result might seem to conflict with the slight increase in cytoplasmic Rac1 in the GDI2-overexpressing cells. However, GDI1 binds GTP-loaded Rac1 and can sequester V12 mutants in the cytoplasm (24). Therefore, the combination of moderate activation of Rac1 with weak inhibition of Rac1 membrane targeting is consistent with the complete absence of any detectable inhibition of Rac1 function.

The mutational studies suggest that metastasis suppression involves Rho GTPases but the blockade by both increased and decreased affinity shows that the effect involves a highly precise relationship. This situation is reminiscent of systems where mutations that either inhibit or constitutively activate GTPases or protein phosphorylation block function of the proteins (25, 26). The usual interpretation is that both types of mutations inhibit kinetic processes that involve cycling between two (or more) states. These results further support the conclusion that RhoGDI2 inhibits metastasis through a mechanism distinct from simple blockade of GTPase function.

We can at present only speculate what that mechanism might be. Available evidence suggests that GDI2 binds with highest affinity to Rac1.5 Interestingly, there is also precedent for the idea that Rac1 can act in a pathway that suppresses metastasis (22, 23). In that study, activation of Rac1 through its GEF TIAM1 specifically induced cohesion of epithelial colonies and suppressed migration and invasion. GEFs for Rho GTPases have in several cases been found to scaffold specific effectors, thereby directing GTPase activation toward specific downstream pathways (27). Although we do not see increased cell-cell adhesion in GDI2-expressing cell lines, many pathways downstream of Rac1 have been identified, one or more of which might also suppress metastatic growth. This general notion is also consistent with results that implicate GDI1 in activation of Rac1 (11). Activation of JNK or inhibition of Rho is a possible pathway for metastasis suppression (28, 29); we also examined PAK as an important Rac effector. However, our current data do not support their involvement in metastasis expression. Indeed, the failure to see elevated ruffling, JNK, or PAK activity in cells with higher Rac activity supports the idea that GDI2 specifically targets Rac toward a novel effector pathway. Taken together, these results support the idea that Rac is specifically directed toward a distinct downstream pathway.

These considerations lead us to the hypothesis that GDI2 might promote interaction of Rac1 with a specific GEF to induce activation of Rac1 through a pathway that inhibits metastasis. Mutations that either increase or decrease the affinity of GDI2 for Rac1 could inhibit this pathway because either one would decrease the rate of the reaction in which Rac1 is transferred from GDI2 to the GEF; decreased affinity would prevent the initial targeting of the GTPase, whereas increased affinity would allow targeting but prevent dissociation of GDI and thus activation of the GTPase.

In conclusion, these data show that RhoGDI2 suppresses metastasis through a mechanism that is not shared with GDI1 and that is not dependent on simple inhibition of Rho GTPases. The data can be explained if GDI2 specifically directs Rac toward an effector pathway that inhibits metastatic migration or growth. However, experimental testing must await identification of the components of this pathway and will be the focus of future work.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

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Figure 5. RhoGDI2 increases Rac activity. GST-PBD (A and B) and GST-RBD (C) pull-down assays were carried out using lysates from the indicated stably overexpressing or knockdown cell lines. Numbers represent the ratio of active/total Rac or RhoA relative to control cells (GFP in overexpressing or knockdown cell lines). Numbers represent the ratio of active/total Rac or RhoA relative to control cells (GFP in overexpressing or knockdown cell lines).
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