

# Merlin/*NF-2* mediates contact inhibition of growth by suppressing recruitment of Rac to the plasma membrane

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Introduction of activated p21-activated kinase (PAK) is sufficient to release primary endothelial cells from contact inhibition of growth. Confluent cells display deficient activation of PAK and translocation of Rac to the plasma membrane at matrix adhesions. Targeting Rac to the plasma membrane rescues these cells from contact inhibition. PAK's ability to release human umbilical vein endothelial cells from contact inhibition is blocked by an unphosphorylatable form of its target Merlin, suggesting that PAK promotes mitogenesis by phosphorylating, and thus inactivating, Merlin. Merlin mutants, which are pre-

sumed to exert a dominant-negative effect, enable recruitment of Rac to matrix adhesions and promote mitogenesis in confluent cells. Small interference RNA-mediated knockdown of Merlin exerts the same effects. Dominant-negative Rac blocks PAK-mediated release from contact inhibition, implying that PAK functions upstream of Rac in this signaling pathway. These results provide a framework for understanding the tumor suppressor function of Merlin and indicate that Merlin mediates contact inhibition of growth by suppressing recruitment of Rac to matrix adhesions.

## Introduction

Normal cells cease to proliferate upon establishing cell–cell adhesions (Dulbecco and Stoker, 1970). This contact-mediated inhibition of growth is critical for tissue organization and contributes to limiting the size of tissues and organs according to body plan (Gottardi and Gumbiner, 2001). Loss of contact inhibition enhances the ability of cancer cells to invade host tissues and ultimately metastasize (Hanahan and Weinberg, 2000).

It is likely that the homophilic cell adhesion proteins' cadherins initiate contact inhibition of growth, but the mechanisms are not clear. The cadherins mediate assembly of adherens junctions by associating with the actin cytoskeleton through  $\beta$ -catenin. Because  $\beta$ -catenin also transduces proliferative Wnt signaling to the nucleus, the cadherins may inhibit proliferation by reducing the levels of  $\beta$ -catenin available for Wnt signaling (for review see Gottardi and Gumbiner, 2001). Other studies suggest that cell–cell adhesion inhibits growth factor receptor signaling (Rahimi and Kazlauskas, 1999; Qian et al.,

2004) by segregating receptor tyrosine kinases (RTKs) from their cognate ligands (Vermeer et al., 2003) or by inducing dephosphorylation of their cytoplasmic tail (Lampugnani et al., 2003). In spite of these important insights, contact inhibition of growth remains a poorly understood phenomenon.

The ezrin–radixin–moesin (ERM) protein Merlin is the protein product of the *NF-2* tumor suppressor gene that is inactivated in familiar type II neurofibromatosis, as well as in sporadic Schwannomas, meningiomas, and mesotheliomas (for review see Lim et al., 2000). Mouse genetics studies indicate that Merlin may have a broader role in tumor invasion and metastasis than manifested from its specific inactivation in Schwann cells (McClatchey et al., 1998; Giovannini et al., 2000). The biochemical function of Merlin and the mechanism by which its loss contributes to tumorigenesis are not completely understood. It has been proposed that Merlin associates with the cytoplasmic tail of CD44, a hyaluronic acid receptor, to mediate contact inhibition of growth (Morrison et al., 2001). However, genetic ablation of CD44 does not result in the loss of contact inhibition, whereas knockout of Merlin induces this effect, but it does cause destabilization of cadherin-dependent adhesions (Lallemand et al., 2003). In addition, Merlin binds to paxillin and appears to modify integrin-dependent organization of the actin cytoskeleton in a density-dependent manner (Fernandez-Valle et al., 2002). Finally, there is evidence that

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Abbreviations used in this paper: ERK, extracellular signal-related protein kinase; ERM, ezrin–radixin–moesin; FN, fibronectin; HUVEC, human umbilical vein endothelial cells; PAK, p21-activated kinase; PL, poly-L-lysine; RTK, receptor tyrosine kinase; SFM, serum-free medium; siRNA, small interference RNA; VE, vascular endothelial.

The online version of this article contains supplemental material.

Merlin suppresses signaling by the small GTPase Rac (Shaw et al., 2001). This effect has been attributed to the ability of Merlin to interact with and to inhibit the Rac target effector p21-activated kinase (PAK; Kissil et al., 2003). On the other hand, PAK phosphorylates the COOH terminus of Merlin and thereby inactivates the growth-suppressive function of the protein (Kissil et al., 2002; Xiao et al., 2002). Thus, there is evidence for both inhibition of PAK by Merlin and inhibition of Merlin by PAK. It is not clear which of these two opposing functions is prevalent in the cell or, if both are relevant, how they are regulated. In addition, the mechanism by which Merlin inhibits Rac signaling and its relevance to contact inhibition are not known.

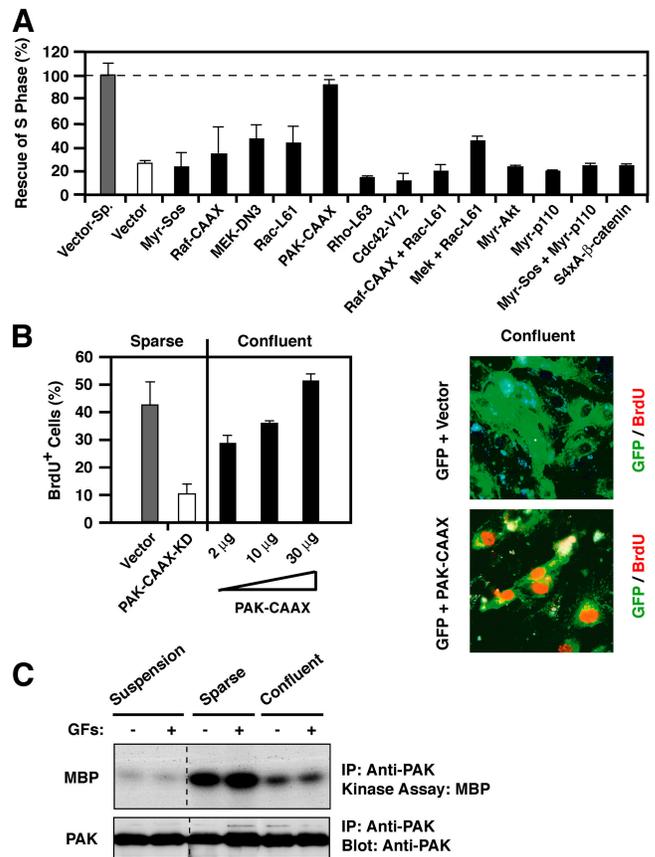
Rac is required for normal cell proliferation and migration and plays a key role in cancer progression (Sahai and Marshall, 2002). To activate its target effectors and exert its biological functions, Rac needs to translocate to the plasma membrane and dissociate from Rho-GDI (Etienne-Manneville and Hall, 2002). Prior studies have provided evidence that integrin signaling promotes recruitment of Rac to the membrane by inducing the dissociation of Rac from Rho-GDI (del Pozo et al., 2002) and/or tyrosine phosphorylation of CrkII (Abassi and Vuori, 2002). In spite of these advances, our knowledge of the signals that control recruitment of Rac and other Rho-GTPases to the plasma membrane remains fragmentary.

We provide evidence that activation of PAK is sufficient to release endothelial cells from contact inhibition. PAK exerts this effect by phosphorylating, and thus inactivating, Merlin. Biochemical and imaging studies indicate that dephosphorylated Merlin suppresses recruitment of Rac to the plasma membrane in contact-inhibited cells. These results indicate that Merlin mediates contact inhibition of growth with a signaling mechanism.

## Results

### Mitogenic activation of Ras proceeds normally, but signaling to ERK is attenuated in contact-inhibited endothelial cells

To avoid the potential effects of immortalization on growth control, we studied contact inhibition of growth in primary cultures of human umbilical vein endothelial cells (HUVEC). These cells undergo growth arrest and fail to respond to bFGF, EGF, and insulin as they become confluent and assemble vascular endothelial (VE)-cadherin-dependent junctions (Fig. S1, A–C, available at <http://www.jcb.org/cgi/content/full/jcb.200503165/DC1>). Assembly of tight junctions may prevent diffusion of peptide growth factors from the medium to the basolateral surface of polarized epithelial cells in vivo (Vermeer et al., 2003). However, experiments on cells plated on Transwell filters showed that contact inhibition of HUVEC is not caused by a segregation of RTKs from their cognate ligands (Fig. S1, A and C). In addition, GST pull-down assays with the Ras-binding domain of Raf (GST-Raf-RBD) provided evidence that cell–cell contact does not interfere with joint integrin–RTK signaling to Ras (Fig. S1 D), suggesting that the reported effect of VE-cadherin on growth factor receptor activation (Lampugnani et al., 2003) is not neces-

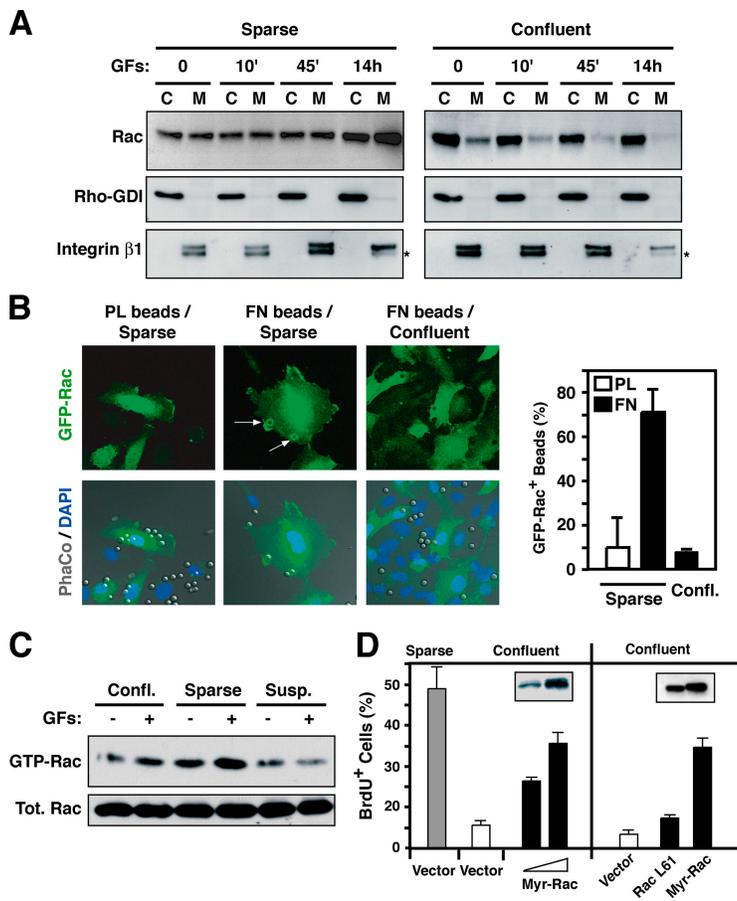


**Figure 1. Activation of PAK is sufficient for release from contact inhibition.** (A) HUVEC were transfected with GFP alone or in combination with plasmids encoding the indicated activated signaling molecules. G0-synchronized cells were plated on FN under sparse or confluent conditions. The percentage of transfected (GFP-positive) cells entering into S phase after mitogen treatment was determined by anti-BrdU staining. The percentage of sparse cells transfected with GFP alone entering in S phase ranged between 35 and 75%, depending on the experiment. This control value was normalized to 100% rescue. (B) Cells transfected with GFP in combination with the indicated doses of plasmids encoding activated PAK (PAK-CAAX) or dominant-negative PAK (PAK-CAAX-KD) were synchronized in G0 and plated on FN under either sparse or confluent conditions. The picture shows GFP-positive (green) PAK-CAAX transfectants that have incorporated BrdU (red) in spite of cell contact. (C) G0-synchronized cells were detached, kept in suspension or plated on FN under sparse or confluent conditions for 4 h, and treated with mitogens for 10 min or left untreated. Lysates were subjected to immune complex kinase assay with anti-PAK using myelin basic protein as a substrate. Error bars represent the mean  $\pm$  SD.

sary for contact inhibition. Interestingly, extracellular signal-related protein kinase (ERK) was activated in a less sustained manner in confluent cells than in sparse cells (Fig. S1 E). We note that cell–cell contact may induce attenuation of Ras to ERK signaling through inhibition of PAK (Fig. 1 C), as PAK functions downstream of Ras to promote activation of ERK (King et al., 1998). These observations indicate that cell contact does not inhibit signaling to Ras but attenuates activation of ERK in HUVEC.

### PAK activation is sufficient to release endothelial cells from contact inhibition

To identify the mechanism by which cell–cell contact inhibits cell proliferation, we used a functional complementation



**Figure 2. Contact inhibition proceeds through suppression of the recruitment of Rac to the plasma membrane.** (A) G0-synchronized HUVEC were detached and plated on FN under either sparse or confluent conditions. 4 h later, they were stimulated with mitogens for the indicated times and subjected to subcellular fractionation. The cytosolic (C) and crude membrane (M) fractions were isolated as described in Materials and Methods. 2  $\mu$ g of proteins from each fraction were analyzed by immunoblotting with the indicated antibodies. Asterisks point to the integrin pre- $\beta$ 1 subunit. (B) Cells transfected with GFP-Rac were synchronized in G0 and plated on FN under either sparse or confluent conditions. 4 h later they were treated with FN-coated beads for 25 min, fixed, and stained with DAPI (blue). Arrows point to FN-coated beads that had induced recruitment of GFP-Rac. The graph shows the percentage of cell-bound FN or PL beads that had caused recruitment of Rac under the indicated conditions. (C) G0-synchronized cells were plated on FN under sparse or confluent conditions or kept in suspension and treated with mitogens for 10 min or left untreated. GTP-Rac was measured by pull-down with GST-PAK-PBD. (D) Cells were cotransfected with GFP and empty vector or two different doses of HA-tagged myristoylated Rac (Myr-Rac) or with HA-Rac-L61. G0-synchronized cells were plated on FN under sparse or confluent conditions and incubated with mitogens and BrdU for 20 h. The percentage of transfected cells entering S phase was determined as described in Fig. 1 A. Expression levels were determined by immunoblotting with anti-HA (insets). Error bars represent the mean  $\pm$  SD.

approach. HUVEC were transiently transfected with plasmids encoding GFP in combination with the activated versions of various signaling proteins. BrdU incorporation was used to evaluate the ability of each activated signaling protein, and certain combinations thereof, to promote proliferation of confluent HUVEC. Notably, activated PAK (PAK-CAAX) effectively rescued progression through G1 and entry into S phase in confluent HUVEC (Fig. 1 A), and it did so in a dose-dependent manner (Fig. 1 B). None of the other activated signaling proteins tested were able to exert this effect as efficiently as activated PAK (Fig. 1 A). In particular, membrane-targeted p110 (myr-p110) and Akt (myr-Akt), as well as unphosphorylatable, stabilized  $\beta$ -catenin (S35/37/41/45A- $\beta$ -catenin-S4xA- $\beta$ -catenin), did not promote entry into S phase in contact-inhibited HUVEC, suggesting that inhibition of phosphatidylinositol-3 kinase or  $\beta$ -catenin does not play a significant role in contact inhibition of growth. Activated  $\beta$ -catenin's lack of effect is consistent with the observation that genetic ablation of  $\beta$ -catenin does not induce growth arrest but, instead, releases HUVEC from contact inhibition (Lampugnani et al., 2003). Similarly negative results were obtained with activated versions of Cdc42 (Cdc42-V12) and Rho A (Rho-L63; Fig. 1 A). By contrast, activated Rac (Rac-L61), Raf (Raf-CAAX), and MEK (MEK- $\Delta$ N3) exerted a partial effect (Fig. 1 A), suggesting that inhibition of Rac and ERK may contribute to contact inhibition of growth. Control experiments indicated that none of the constructs tested in-

duced significant apoptosis (>5%) in confluent HUVEC. We note that VE-cadherin-mediated adhesion protects HUVEC from apoptosis (Carmeliet et al., 1999). These results indicate that activation of PAK is sufficient to release HUVEC from contact inhibition.

To examine the effect of cell-cell contact on PAK activation, HUVEC were plated on fibronectin (FN) under either sparse or confluent conditions in the presence or absence of growth factors and subjected to PAK assay. In agreement with prior results (del Pozo et al., 2000), adhesion to FN induced strong activation of PAK in sparse cells, whereas growth factor stimulation did not exert this effect in suspended cells (Fig. 1 C), suggesting that integrin engagement is necessary and sufficient for activation of PAK. Notably, PAK was not activated in cells plated on FN under confluent conditions, whether they were treated with growth factors or not (Fig. 1 C), indicating that cell contact suppresses activation of PAK.

To examine whether PAK activation is necessary for normal cell proliferation, we used a dominant-negative approach. As shown in Fig. 1 B, expression of a kinase-dead version of PAK (PAK-CAAX-KD) prevented the entry into S phase of HUVEC plated on FN under sparse conditions. These results suggest that integrin-mediated activation of PAK is necessary for cell cycle progression and imply that cell-cell adhesion inhibits cell proliferation by preventing the activation of PAK.

### Contact inhibition proceeds through suppression of recruitment of Rac to the membrane

PAK is a well established target effector of Rac (Etienne-Manneville and Hall, 2002). However, constitutively active Rac-L61 did not fully rescue cell cycle progression in confluent HUVEC, whereas activated PAK did (Fig. 1 A). We considered the possibility that Rac-L61 did not exert a proproliferative effect in confluent cells because of incorrect targeting. To examine whether cell–cell contact interferes with the recruitment of Rac to the plasma membrane, we used biochemical fractionation and optical imaging methods. HUVEC were plated on FN under either sparse or confluent conditions for 4 h and treated with growth factors. At various times after mitogenic stimulation the cells were subjected to biochemical fractionation and immunoblotting. As shown in Fig. 2 A, the crude membrane fraction of cells plated on FN under sparse conditions contained a significant amount of Rac (~25% of the total). Mitogenic stimulation did not modify the proportion of Rac in the crude membrane fraction of these cells. These observations are in agreement with the model that RTKs induce GTP-loading on Rac, whereas integrins mediate its recruitment to the membrane and coupling to target effectors (del Pozo et al., 2000, 2002). Parenthetically, prolonged mitogenic stimulation led to increased levels of Rac in both the cytosolic and the crude membrane fraction of sparse cells, suggesting that Rac levels increase in mid-to-late G1 in HUVEC. Interestingly, most of the total Rac (>95%) remained in the cytosolic fraction in confluent cells, indicating that the translocation of Rac to the membrane fraction is impaired in confluent cells (Fig. 2 A). This result indicates that cell contact suppresses recruitment of Rac to the plasma membrane.

To confirm and extend this result, we used optical imaging. HUVEC were transiently transfected with GFP fused to wild-type Rac under conditions inducing low levels of expression (~10-fold lower than endogenous Rac by immunoblotting), plated on FN under sparse or confluent conditions, and imaged by confocal microscopy. As expected, GFP-Rac localized to lamellipodia and membrane ruffles in sparse cells. Analysis of Z-sections indicated that most of the protein associated with the ventral membrane in these cells. By contrast, GFP-Rac appeared predominantly distributed throughout the cytoplasm in confluent cells (unpublished data). To obtain more quantitative data and to determine if, and to what extent, cell contact specifically suppresses the recruitment of Rac to matrix adhesions, we applied FN- or control poly-L-lysine (PL)-coated beads to sparse or confluent HUVEC. As shown in Fig. 2 B, the FN-coated beads caused efficient recruitment of GFP-Rac in sparse cells, but they did not exert this effect in confluent cells. The PL beads promoted negligible recruitment of Rac in sparse cells, as anticipated. These results indicate that cell–cell contact suppresses integrin-dependent recruitment of Rac to the plasma membrane.

To examine the effect of cell contact on activation of Rac, we conducted pull-down experiments with GST-PAK. We observed that cell contact inhibits growth factor-induced activation of Rac only partially, whereas loss of matrix adhesion

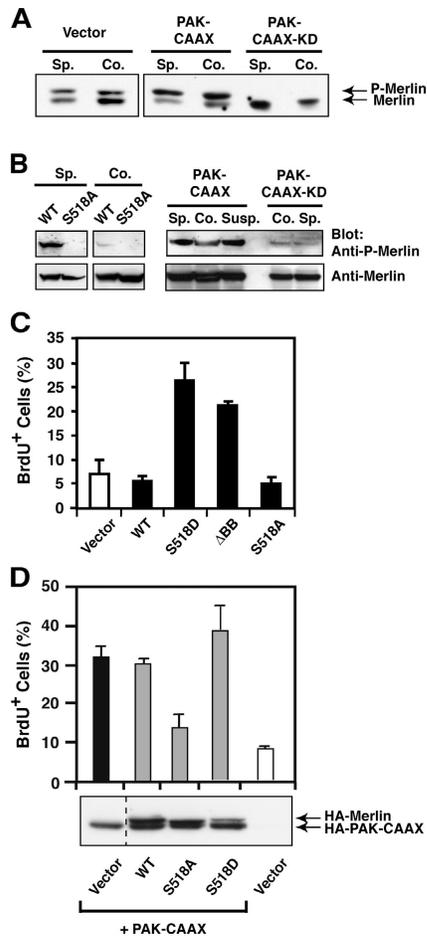
suppresses this event to a significant extent (Fig. 2 C). Although we cannot exclude other mechanisms, we posit that the partial decrease of GTP loading on Rac observed in confluent cells is a consequence of reduced recruitment to the plasma membrane, and hence activation, of Rac by RTKs. Prior studies have shown that a fraction of Rac is activated transiently during the formation of cell–cell junctions (Ehrlich et al., 2002). We believe it is unlikely that this local and transient activation of Rac influenced the outcome of our experiment because the cells were plated under confluent conditions for 4 h before growth factor treatment and GST pull-down assay, and control experiments had indicated that this time is sufficient for assembly of cell–cell junctions. These results are consistent with the hypothesis that cell contact inhibits Rac signaling predominantly by inhibiting localization of Rac to the membrane.

Rac signaling promotes progression through G1 in HUVEC (Mettouchi et al., 2001) and several other cell types (Etienne-Manneville and Hall, 2002). If Rac needs to associate with the plasma membrane to be properly coupled to its target effectors, inhibition of this process may underlie contact inhibition. To examine this hypothesis, we tested whether targeting wild-type Rac to the membrane was sufficient to release HUVEC from contact inhibition. Cells were transfected with Myr-Rac, which carries a Src myristoylation site at its NH<sub>2</sub> terminus, but no additional mutations. BrdU incorporation indicated that this membrane-targeted form of Rac rescues a large fraction of HUVEC from contact inhibition whereas Rac-L61 was much less effective (Fig. 2 D). Because Myr-Rac does not carry mutations reducing its GTPase activity, its ability to promote proliferation of confluent HUVEC indicates that targeting Rac to the plasma membrane is sufficient to release cells from contact inhibition of growth. Together, these observations imply that contact inhibition of growth involves the inhibition of membrane recruitment of Rac.

### Activated PAK releases HUVEC from contact inhibition through the phosphorylation of Merlin

The aforementioned results suggest that contact inhibition proceeds through the suppression of membrane recruitment of Rac and the inactivation of PAK, but they do not explain why inhibition of PAK causes growth arrest. To address this question, we sought to identify the target effector through which PAK releases HUVEC from contact inhibition. We focused on the PAK substrate Merlin because it is a tumor suppressor protein and its growth-suppressing activity is regulated by phosphorylation (Bretscher et al., 2002). In contrast, the other known target effectors of PAK (with the exception of Raf; see poor rescue by activated Raf in Fig. 1 A) regulate the actin cytoskeleton (Bokoch, 2003).

PAK phosphorylates Merlin at Serine 518, disrupting the interaction between the NH<sub>2</sub>-terminal protein 4.1 ERM domain and the COOH-terminal tail of the protein (Shaw et al., 2001; Kissil et al., 2002; Xiao et al., 2002). To examine the potential role of PAK's phosphorylation of Merlin in release from contact inhibition, HUVEC were transfected with HA-tagged Merlin in combination with empty vector, activated PAK (PAK-CAAX), or dominant-negative PAK (PAK-CAAX-KD) and were plated



**Figure 3. PAK releases cells from contact inhibition by phosphorylating Merlin.** (A) HUVEC were transfected with HA-tagged Merlin in combination with empty vector or plasmids encoding PAK-CAAX or PAK-CAAX-KD. G0-synchronized cells were plated on FN under sparse (Sp.) or confluent (Co.) conditions. After incubation with growth factors for 20 h, the cells were lysed and subjected to high resolution SDS-PAGE followed by immunoblotting with anti-Merlin. The top band corresponds to the phosphorylated form of Merlin and the bottom band to the unphosphorylated form. (B) Total lysates prepared as in A were subjected to standard SDS-PAGE and immunoblotting with anti-phospho-Merlin (Ser518) or anti-Merlin. (C) Cells were cotransfected with GFP and empty vector or vectors encoding the indicated forms of Merlin. G0-synchronized cells were plated on FN under confluent conditions and incubated with mitogens and BrdU for 20 h. The percentage of transfected cells entering S phase was determined as described in Fig. 1. (D) Cells were cotransfected with GFP and empty vector or vectors encoding activated PAK (PAK-CAAX) in combination with the indicated forms of Merlin. The percentage of transfected cells entering S phase was determined as in Fig. 1. PAK-CAAX and various forms of Merlin were tagged with HA and detected by immunoblotting with anti-HA antibody. Error bar represents the mean  $\pm$  SD.

under either sparse or confluent conditions in the presence of growth factors. High resolution SDS-PAGE followed by immunoblotting with anti-HA was used to monitor the mobility shift caused by the phosphorylation of Merlin (Shaw et al., 2001). Control transfectants plated under confluent conditions contained more dephosphorylated Merlin as compared with those plated under sparse conditions (Fig. 3 A). In addition, activated PAK induced significant phosphorylation of Merlin in confluent cells, whereas dominant-negative PAK caused an almost complete dephosphorylation of the protein in sparse cells

(Fig. 3 A). Immunoblotting with an antibody that specifically recognizes Merlin phosphorylated at Serine 518 showed that Merlin is significantly phosphorylated at this site in cells plated under sparse conditions, but not in those plated under confluent conditions (Fig. 3 B). In addition, activated PAK caused significant phosphorylation of Merlin at Serine 518 in confluent and in suspended cells, whereas kinase-dead PAK did not exert this effect (Fig. 3 B). These results identify a potential role for Merlin phosphorylation at Serine 518 in exit from contact inhibition.

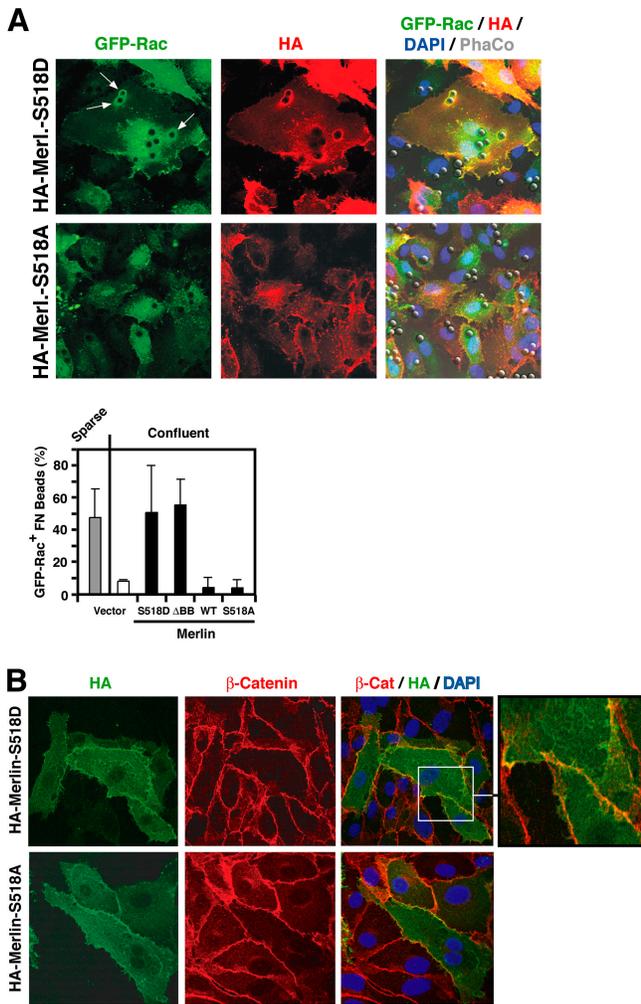
Overexpression of mutant forms of Merlin that are presumed to disrupt head-to-tail association of the protein causes hyperproliferation in the fly wing (LaJeunesse et al., 1998) and transforms rodent fibroblasts (Johnson et al., 2002). It has been argued that these mutants exert a dominant-negative effect on the growth-suppressive function of endogenous wild-type protein (Bretscher et al., 2002). To examine if PAK controls membrane recruitment of Rac through Merlin, we used two such mutants: Merlin- $\Delta$ BB, which carries a deletion of the Blue Box, which is a short amino acid segment in the protein 4.1 ERM domain thought to be involved in head-to-tail association (LaJeunesse et al., 1998); and Merlin-S518D, which carries a serine to aspartic acid permutation at the PAK phosphorylation site and thus mimics the phosphorylated form of Merlin (Johnson et al., 2002).

HUVEC were transfected with vector alone or HA-tagged forms of wild-type Merlin, Merlin- $\Delta$ BB, Merlin-S518D, and Merlin-S518A (which cannot be phosphorylated by PAK) and plated under confluent conditions in the presence of growth factors. BrdU incorporation experiments indicated that Merlin- $\Delta$ BB and Merlin-S518D induce a significant fraction of confluent HUVEC to progress through G1 and enter into S phase (Fig. 3 C). By contrast, wild-type Merlin and Merlin-S518A did not exert this effect. It is likely that Merlin- $\Delta$ BB and Merlin-S518D rescue HUVEC from contact inhibition by exerting a dominant-negative effect on the growth-suppressive function of endogenous wild-type protein. In addition, or instead, these mutants may directly stimulate cell proliferation. These findings are consistent with the hypothesis that phosphorylation of Merlin mediates exit from contact inhibition.

We next used BrdU incorporation to examine the ability of Merlin-S518A to interfere with PAK's ability to rescue HUVEC from contact inhibition. HUVEC were transfected with activated PAK in combination with HA-tagged Merlin-S518A or, as controls, HA-tagged Merlin-WT, HA-tagged Merlin-S518D, or vector alone. As shown in Fig. 3 D, Merlin-S518A inhibited PAK's ability to rescue cell proliferation in confluent HUVEC, whereas wild-type Merlin did not exert this effect, and Merlin-S518D enhanced the proliferative effect of activated PAK. These findings imply that PAK releases HUVEC from contact inhibition of growth through phosphorylation of Merlin.

### Merlin mediates contact inhibition by suppressing membrane recruitment of Rac

Previous studies have suggested that the "closed," dephosphorylated form of Merlin suppresses Rac signaling (Shaw et al., 2001; Kissil et al., 2002), raising the possibility that PAK func-



**Figure 4. Open forms of Merlin promote recruitment of Rac to matrix adhesions.** (A) HUVEC were transfected with GFP-Rac in combination with empty vector or vectors encoding HA-tagged Merlin-S518D, Merlin-ΔBB (BB), Merlin-WT, and Merlin-S518A. FN-coated beads were applied for 25 min to G0-synchronized cells plated on FN under confluent conditions. The cells were then fixed and stained with anti-HA to detect HA-Merlin (red) and DAPI (blue). The graph shows the percentage of GFP-Rac-positive beads under the indicated conditions. Arrows point to FN-coated beads that had induced recruitment of GFP-Rac. (B) Cells were transfected with vectors encoding HA-tagged Merlin-S518D or Merlin-S518A. G0-synchronized cells were plated on FN under confluent conditions and subjected to double staining with antibodies to β-catenin (red) and HA (green). The inset shows that Merlin-S518D localizes in part to adherens junctions, but does not disrupt them. Error bar represents the mean ± SD.

tions upstream of Rac during release from contact inhibition. We thus examined if Merlin suppresses recruitment of Rac to matrix adhesions in confluent cells. HUVEC were transfected with GFP-Rac, alone or in combination with HA-tagged Merlin-S518D, Merlin-ΔBB, Merlin-WT, Merlin-S518A, or empty vector. The cells were plated under confluent conditions and incubated with FN-coated beads. Confocal microscopy indicated that expression of Merlin-ΔBB or Merlin-S518D restores recruitment of GFP-Rac to FN-coated beads in confluent HUVEC (Fig. 4 A). Notably, anti-HA staining indicated that both mutant forms of Merlin localize underneath FN-coated beads (Fig. 4 A and not depicted), in agreement with the hy-

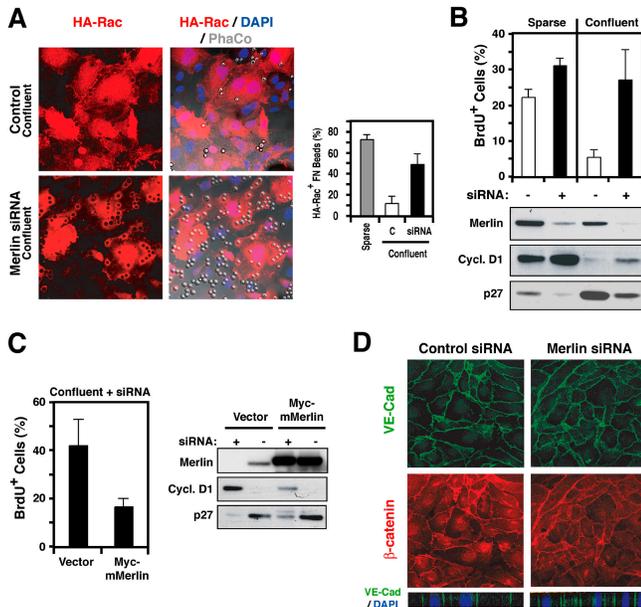
pothesis that they interfere with the ability of endogenous Merlin to suppress integrin-mediated recruitment of Rac. These observations are consistent with the hypothesis that Merlin suppresses recruitment of Rac to matrix adhesions in contact-inhibited cells.

Cre-mediated deletion of Merlin causes a disruption of cell-cell junctions in mouse embryonic fibroblasts and keratinocytes, suggesting the possibility that Merlin mediates its growth-suppressive function by stabilizing cadherin-dependent adhesion and, thereby, inducing inhibitory cadherin signaling (Lallemand et al., 2003). However, immunofluorescent staining with anti-β-catenin provided evidence that Merlin-S518D does not cause a significant disruption of adherens junctions under our experimental conditions (Fig. 4 B), suggesting that Merlin uses a direct signaling mechanism to mediate contact inhibition in HUVEC. Both Merlin-S518 and Merlin-S518A localized in part to the inner aspect of the plasma membrane and in part to the cytoplasm in these experiments (Fig. 4 B). Together, the results of these experiments suggest that Merlin mediates contact inhibition of growth by suppressing recruitment of Rac to matrix adhesions.

#### siRNA-mediated knockdown of Merlin promotes recruitment of Rac to matrix adhesions and releases cells from contact inhibition

The aforementioned experiments are consistent with the model that the dephosphorylated, closed form of Merlin suppresses recruitment of Rac to the membrane, but they do not exclude the possibility that the phosphorylated, “open” form of Merlin exerts an independent and positive effect on cell proliferation. To directly test if Merlin mediates contact inhibition of growth by suppressing recruitment of Rac to matrix adhesions, we used RNA interference. Transfection of a small interference RNA (siRNA) targeting human Merlin was sufficient to rescue integrin-dependent recruitment of GFP-Rac to the plasma membrane in confluent HUVEC (Fig. 5 A). Notably, knockdown of Merlin induced a large fraction of confluent HUVEC to progress through G1 and enter into S phase after mitogenic stimulation (Fig. 5 B). Immunoblotting revealed that the siRNA inhibited Merlin expression by >80%. As expected, the Merlin knockdown cells escaping contact inhibition had elevated levels of cyclin D1 and decreased levels of p27 (Fig. 5 B). However, cyclin D1 was not up-regulated and p27 was not down-regulated as effectively as they normally are in sparse cells. We attribute this partial result to the incomplete suppression of Merlin expression after siRNA transfection.

To control for potential off-target effects of the siRNA or activation of the interferon response, we used a rescue approach. The HUVEC were transfected with a cDNA encoding mouse Merlin that is insensitive to the siRNA we used to inhibit human Merlin and were subjected to RNA interference. As shown in Fig. 5 C, BrdU incorporation and immunoblotting with anti-cyclin D1 and anti-p27 indicated that reexpression of Merlin restores contact inhibition of growth in Merlin knockdown HUVEC. These results provide evidence that Merlin is necessary and sufficient to block membrane recruitment of Rac

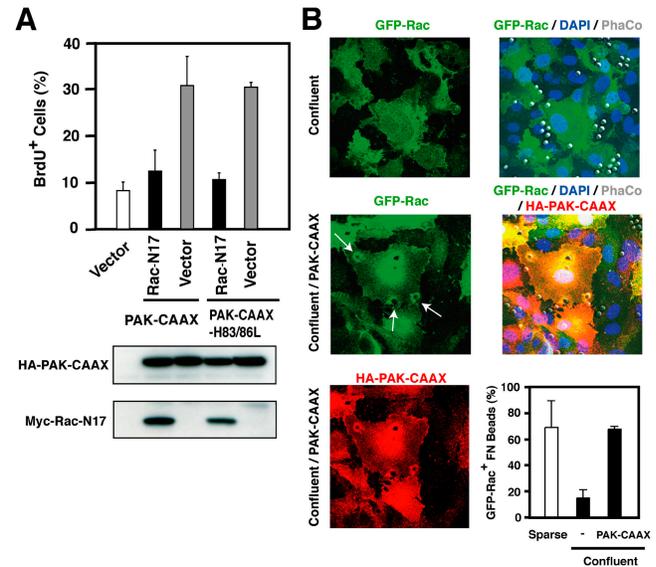


**Figure 5. Merlin mediates contact inhibition of growth by suppressing membrane recruitment of Rac.** (A) HUVEC were electroporated with GFP-Rac and then either transfected with a siRNA oligonucleotide targeting human Merlin or mock-transfected as a control. 36 h later, cells were synchronized in G<sub>0</sub>, detached, and plated on FN under either sparse or confluent conditions, as indicated, and treated with FN beads. The graph shows the percentage of GFP-Rac-positive beads under the indicated conditions. (B) Cells were transfected with a siRNA oligonucleotide targeting human Merlin (+). G<sub>0</sub>-synchronized cells were detached, plated on FN under sparse or confluent conditions, and incubated with mitogens and BrdU for 20 h. The graph shows the percentage of cells entering S phase under the indicated conditions. Total lysates were subjected to immunoblotting with the indicated antibodies. (C) Cells were electroporated with a vector encoding Myc-tagged mouse Merlin (mMerlin) or empty vector and transfected with the anti-human siRNA oligonucleotide. After 36 h, cells were synchronized in G<sub>0</sub>, detached, and plated on FN under confluent conditions for 4 h. The cells were either incubated with mitogens and BrdU for 20 h to measure entry into S phase or treated with mitogens for 12 h and subjected to immunoblotting with the indicated antibodies. (D) siRNA-transfected cells were detached and plated on FN-coated coverslips under confluent conditions in the presence of growth factors. After 20 h, they were subjected to double immunofluorescent staining with anti-VE-cadherin (green) and anti- $\beta$ -catenin (red). The bottom panels are XZ section views of VE-cadherin and DAPI staining. Error bars represent the mean  $\pm$  SD.

and to mediate contact inhibition of growth, in agreement with the hypothesis that the dephosphorylated closed form of Merlin suppresses cell proliferation, whereas the phosphorylated open form does not exert this effect.

To examine if suppression of Merlin causes disruption of cell-cell adhesion in HUVEC, cells treated with Merlin or control siRNA were plated under confluent conditions and subjected to double immunofluorescent staining with anti-VE-cadherin and anti- $\beta$ -catenin antibodies. As shown in Fig. 5 D, transient inhibition of Merlin expression did not have an obvious deleterious effect on cell-cell junctions. These observations support the hypothesis that Merlin controls cell proliferation by a direct signaling mechanism.

Finally, we wanted to obtain additional evidence that suppression of Merlin enhances Rac signaling in HUVEC. After transfection of Merlin or control siRNA, HUVEC were plated



**Figure 6. PAK promotes recruitment of Rac to matrix adhesions.** (A) Cells were cotransfected with GFP and empty vector, or vector encoding activated PAK (PAK-CAAX) or Pak-CAAX-H83/86L, in combination or not with dominant-negative Rac (Rac-N17). G<sub>0</sub>-synchronized cells were plated on FN under confluent conditions and incubated with mitogens and BrdU for 20 h. The percentage of transfected cells entering S phase was determined as described in Fig. 2. PAK-CAAX was tagged with HA and hence detected by immunoblotting with anti-HA, whereas Rac-N17 was tagged with Myc and thus detected with anti-Myc. (B) HUVEC were transfected with GFP-Rac in combination with empty vector or vector encoding activated PAK (PAK-CAAX). They were then synchronized in G<sub>0</sub> and plated on FN under sparse or confluent conditions. FN-coated beads were applied for 25 min. The cells were fixed and stained with anti-HA to detect PAK-CAAX (red) and DAPI to stain nuclei (blue). Arrows point to FN-coated beads that induced recruitment of GFP-Rac. The graph shows the percentage of GFP-Rac-positive beads under the indicated conditions. Error bars represent the mean  $\pm$  SD.

under sparse conditions to facilitate detection of Rac-dependent structures, such as lamellipodia and ruffles, and subjected to double immunofluorescent staining with anti-paxillin antibodies and phalloidin. As shown in Fig. S2 (available at <http://www.jcb.org/cgi/content/full/jcb.200503165/DC1>), suppression of Merlin expression caused a significant loss of focal adhesions and stress fibers in HUVEC. Concomitantly, the cells formed extensive lamellipodia and ruffles. These observations suggest that loss of Merlin enhances Rac signaling in HUVEC.

### PAK controls recruitment of Rac to matrix adhesions

PAK is a key target effector of Rac, but it can also function upstream of Rac (Bokoch, 2003), raising the possibility that PAK functions in proliferative signaling through Rac-mediated activation of target effectors other than PAK. This data supports the hypothesis that PAK regulates Rac translocation to the membrane through phosphorylation and inactivation of Merlin. To confirm that PAK functions upstream of Rac during release from contact inhibition, we first tested if PAK rescues cells from contact inhibition through Rac. HUVEC were transfected with activated PAK, alone or in combination with dominant-negative Rac. As shown in Fig. 6 A, dominant-negative Rac

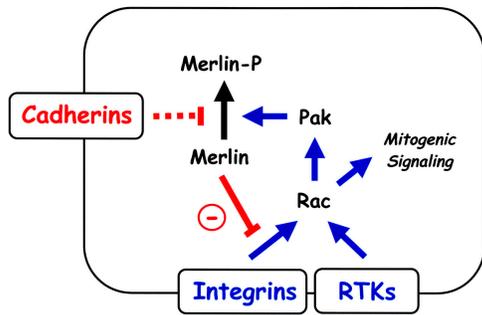


Figure 7. **Hypothetical model of Merlin's function.** Cadherin-initiated adhesion prevents activation of Pak in contact-inhibited cells and thereby causes accumulation of dephosphorylated Merlin. This closed form of Merlin suppresses integrin-mediated recruitment of Rac, and hence mitogenic signaling. Upon release from contact inhibition, Pak phosphorylates and inactivates Merlin, allowing recruitment of Rac to the membrane and mitogenic signaling.

(Rac-N17) suppressed PAK's ability to release confluent HUVEC from contact inhibition, suggesting that PAK functions upstream of Rac in this process. A mutation crippling the CRIB domain (H83/86L) did not impair the ability of activated PAK to rescue HUVEC from contact inhibition, indicating that this effect does not require Rac binding to PAK. As expected, dominant-negative Rac also interfered with the ability of the CRIB domain mutant form of activated PAK to release cells from contact inhibition (Fig. 6 A). These findings indicate that PAK functions upstream of Rac in release from contact inhibition.

We examined if activated PAK rescues recruitment of Rac to integrin-dependent adhesions in confluent cells. HUVEC were transfected with GFP-Rac, alone or in combination with activated PAK, plated under confluent conditions, and treated with FN-coated beads. Fig. 6 B shows that activated PAK promotes recruitment of Rac to FN-coated beads in confluent cells. Interestingly, activated PAK accumulated underneath FN-coated beads in "rescued" cells, which is in agreement with the hypothesis that it promotes cell proliferation by inducing recruitment of Rac to matrix adhesions (Fig. 7 B). These observations indicate that PAK controls recruitment of Rac to matrix adhesions by a signaling mechanism and imply that intercellular contact interferes with this process.

## Discussion

Rac promotes normal cell proliferation and cancer invasion (Sahai and Marshall, 2002). To exert its functions, Rac needs to dissociate from Rho-GDI and attach to the inner aspect of the plasma membrane. Our study provides evidence that the tumor suppressor Merlin mediates contact inhibition of growth by blocking recruitment of Rac to matrix adhesions. Upon activation, PAK reverses this inhibition by phosphorylating, and thus inactivating, Merlin. These results place Merlin at the center of a novel tumor suppressor–oncogene circuit and provide a framework to interpret its function in tumorigenesis.

We have observed that PAK signaling is sufficient to release endothelial cells from contact inhibition. By contrast, activation of other mitogenic signaling pathways, including those

involving  $\beta$ -catenin, phosphatidylinositol-3 kinase, and ERK, does not exert this effect. Upon introduction in sparse cells, dominant-negative PAK promotes growth arrest, suggesting that PAK kinase activity is required for normal cell cycle progression. Activated PAK promotes recruitment of Rac to matrix adhesions in confluent cells, whereas dominant-negative Rac blocks PAK's ability to release cells from contact inhibition, indicating that PAK promotes mitogenesis by inducing recruitment of Rac to matrix adhesions. Two distinct mutant forms of Merlin, Merlin- $\Delta$ BB and Merlin-S518D, which are presumed to exert a dominant-negative effect, promote recruitment of Rac to matrix adhesions and release cells from contact inhibition. By contrast, an unphosphorylatable form of Merlin, Merlin-S518A, suppresses PAK's ability to release HUVEC from contact inhibition. These observations indicate that PAK promotes recruitment of Rac to matrix adhesions and mitogenesis by phosphorylating and thereby inactivating Merlin.

Several lines of evidence indicate that Merlin's ability to suppress Rac function is necessary and sufficient for contact inhibition of primary endothelial cells. Constitutively active PAK, dominant-negative Merlin, and membrane-targeted Rac are each sufficient to release HUVEC from contact inhibition. Conversely, dominant-negative PAK promotes growth arrest when introduced in cells that are not contact inhibited. In addition, siRNA-mediated knockdown of Merlin is sufficient to promote recruitment of Rac to matrix adhesions and mitogenesis of confluent HUVEC, excluding the possibility that the open form of Merlin directly promotes recruitment of Rac to the membrane and mitogenesis. Thus, our results support the hypothesis that the closed, dephosphorylated form of Merlin inhibits proliferation and mediates contact inhibition by suppressing activation of Rac, whereas the open, phosphorylated form does not exert this effect. In addition, our results suggest that the open, phosphorylated form may inhibit the growth-suppressive function of the closed, dephosphorylated form. Future studies will be required to elucidate the molecular basis of this effect. Finally, we cannot exclude the possibility that the open form of Merlin has additional functions, as it has been reported that Merlin-S518D enhances filopodia formation in rat Schwannoma cells (Surace et al., 2004).

Under growth-permissive conditions, joint integrin-RTK signaling causes recruitment and activation of Rac and, thus, of PAK. We propose that, upon phosphorylation by PAK, Merlin loses its ability to inhibit recruitment of Rac to the membrane, thus facilitating Rac-PAK signaling. This positive feed-forward mechanism of signal amplification would cause robust activation of Rac. Finally, activated Rac would promote cell proliferation through target effectors that were distinct from PAK. We speculate that, upon cell–cell contact cadherin signaling suppresses activation of PAK, leading to the accumulation of unphosphorylated Merlin. This form of Merlin would finally block proliferation by suppressing recruitment of Rac to the membrane (Fig. 7). Several aspects of this model require further experimental examination. Specifically, it will be important to address the mechanism by which cadherin-dependent adhesion suppresses PAK and the mechanism by which Merlin inhibits recruitment of Rac to the membrane. In

addition, future studies will have to examine whether the growth-suppressive pathway identified here also operates in other normal cell types.

Merlin's function as a tumor suppressor has been investigated intensively. Merlin<sup>-/-</sup> fibroblasts and keratinocytes display defective cadherin-dependent junctions and do not undergo growth arrest upon becoming confluent (Lallemand et al., 2003), suggesting that Merlin exerts its tumor suppressor function by stabilizing cell–cell junctions. In this model, Merlin functions upstream of cadherins, either by facilitating their assembly or by preventing their disassembly, and it thus inhibits proliferative signaling indirectly. In contrast, we have observed that dominant-negative or siRNA-mediated inhibition of Merlin rescues HUVEC from contact inhibition of growth without disrupting cell–cell junctions. We attribute this apparent discrepancy to the use of different methods of inhibiting Merlin function and/or different cell types. The effect of genetic ablation is permanent and complete, whereas the effect of dominant-negative inhibition or siRNA-mediated knockdown is transient and often incomplete. In addition, it is known that Rac signaling participates in both the assembly and the disassembly of cell–cell junctions, and the extent to which it promotes these contrasting functions may vary with cell type (Braga, 2002). It is thus possible, and indeed likely, that genetic ablation of Merlin causes a more robust up-regulation of Rac signaling than dominant-negative or siRNA-mediated inhibition. In addition, fibroblasts and keratinocytes may be more sensitive to the effect of loss of Merlin function on cell–cell junctions than endothelial cells. Regardless of what specific mechanism explains this apparent discrepancy, our results indicate that inhibition of Merlin can rescue cells from contact inhibition without disrupting their junctions, supporting the hypothesis that Merlin regulates proliferation by a direct signaling mechanism. Similarly, studies in *Drosophila Melanogaster* support the notion that the ERM protein Moesin promotes epithelial organization by inhibiting Rho signaling rather than by functioning as a cytoskeletal linker (Speck et al., 2003).

The biochemical function of Merlin is poorly understood. Merlin interacts with the integrin signaling component paxillin (Fernandez-Valle et al., 2002) that functions, together with PKL, as a scaffold to recruit PAK and PIX, a GEF for Rac, to focal complexes (Turner, 2000). Hence, Merlin may inhibit recruitment of Rac by the paxillin–PKL–PIX complex until it becomes phosphorylated and thus inactivated by PAK. In addition, PAK phosphorylates Rho-GDI at Ser 101/174, promoting its dissociation from Rac (DerMardirossian et al., 2004). Although this mechanism can contribute to the recruitment of Rac to matrix adhesions, our results clearly show that PAK functions in this process also by phosphorylating Merlin. Merlin has been shown to bind to Rho-GDI in vitro (Maeda et al., 1999), raising the possibility that Merlin stabilizes the association of Rac with Rho-GDI. However, we have failed to detect association of endogenous Merlin and Rho-GDI in endothelial cells by coimmunoprecipitation (unpublished data). Finally, recent studies suggest that integrins control recruitment of Rac to the membrane by organizing cholesterol-rich membrane micro-

domains (del Pozo et al., 2004), and dephosphorylated Merlin tends to accumulate in these microdomains (Stickney et al., 2004), suggesting the possibility that Merlin inhibits recruitment of Rac to these membrane domains.

Rho family GTPases promote cell proliferation and migration, and they mediate Ras transformation in vitro. However, unlike Ras proteins Rho GTPases do not acquire mutations that impair their GTPase activity and cause constitutive activation in human cancer (Sahai and Marshall, 2002). It is possible that these mutations are not sufficient to cause transformation because they do not overcome the barrier imposed by cytoplasmic segregation. PAK1 is amplified in some ovarian and breast cancers (Bekri et al., 1997; Schram et al., 2003). In addition, elevated levels of PAK1 have been detected in breast and colorectal cancer (Balasenthil et al., 2004; Carter et al., 2004). Finally, PAK4 is overexpressed in various carcinoma lines (Callow et al., 2002). Based on our results, we speculate that PAK may promote tumorigenesis by functionally inactivating Merlin and elevating Rac signaling.

## Materials and methods

### Cell culture and materials

HUVEC were obtained from Clonetics. Cells were synchronized in G0 by growth factor deprivation, detached, and replated on dishes or coverslips coated with 15 µg/ml of human plasma FN (BD Biosciences) at  $2.5 \times 10^4$  per cm<sup>2</sup> (sparse) or  $1.5 \times 10^5$  per cm<sup>2</sup> (confluent). After incubation in serum-free medium (SFM; GIBCO BRL) for 4 h, the cells were stimulated with growth factors (20 ng/ml bFGF, 1 µg/ml heparin, 10 ng/ml EGF, 10 µg/ml insulin, 10 µg/ml transferrin, and 1 µg/ml selenous acid) for the times indicated in the figure legends. For some experiments, the cells were cultured on FN-coated polycarbonate filters (0.4-µm pore size; Transwell Costar). The following antibodies were purchased: anti-Rac1 (Upstate Biotechnology); anti-RhoGDI, anti-cyclin D1 (A-12), anti-p27 (C-19), anti-Erk2 (C-14), anti-PAK (N-20), and anti-Merlin (A-19, C-18; Santa Cruz Biotechnology, Inc.); anti-β-actin (Sigma-Aldrich); anti-phospho-ERK (Cell Signaling); anti-Ras and anti-VE-cadherin (BD Biosciences); and anti-HA (Babco). Rabbit antibodies to β-catenin and to phosphorylated Ser518 in Merlin were described previously (McCrea et al., 1993; Kissil et al., 2002).

### Expression vectors

We used expression vectors encoding wild-type and mutant forms of Rac1 (pcDNA3 Rac-L61, Rac-N17, Myr-Rac [a gift from M. del Pozo, Centro Nacional Investigaciones Cardiovasculares, Madrid, Spain], pEGFP-Rac [Rac1 was subcloned into pEGFP vector (CLONTECH Laboratories, Inc.)], and pXJ40-HA-Rac), Cdc42 (pZip Cdc42-V12), RhoA (pcDNA3 RhoA-L63), p110-PI3K (pCG-myr-p110), MEK1 (pMCL-MEK1-ΔN3, S222D), Raf (pZip-RafCAAX), Sos (pcDNA3 Myr-Sos1), PAK (pXJ40-PakCAAX), Akt (pCMV-Myr-Akt), β-catenin (a gift from C. Gortardi, Northwestern University, Chicago, IL; pCS1-HA-S35/37/41/45A-β-catenin or HA-S4xA-β-catenin), and Merlin (pXJ40-HA-Merlin; full-length Merlin was subcloned from pBluescript II-Merlin [obtained from S. Tsukita, Kyoto University, Kyoto, Japan]). The rest of the constructs were previously described (Mettouchi et al., 2001). The Merlin I mutants S518D, S518A, and ΔBB (deletion of amino acid residues 177–183) and PAK mutants PAK-CAAX-K298R and PAK-CAAX-H83/86L were generated by site-directed mutagenesis using the Quickchange kit (Stratagene) according to the manufacturer's instructions.

### Cell proliferation

For transfection,  $5 \times 10^6$  cells were resuspended in 300 µl SFM with the indicated amounts of expression vectors in combination with pEGFP-F (encoding farnesylated EGFP) and electroporated at 300 V and 450 µF. Cells were allowed to recover in complete medium for 12 h. They were then synchronized in G0, detached, and replated on FN-coated coverslips under confluent conditions. After 4 h in SFM, cells were incubated with growth factors and 10 µM BrdU (Boehringer) for 20 h. After fixation, they

were stained with anti-BrdU mAb (Boehringer) and TRITC-conjugated anti-mouse IgGs (The Jackson Laboratory) to measure the percentage of GFP-positive cells that had incorporated BrdU.

### Biochemistry

PAK was immunoprecipitated from cell lysates with anti-Pak1 antibodies (N-20; Santa Cruz Biotechnology, Inc.) and subjected to kinase assay with myelin basic protein as a substrate, as previously described (Yablonski et al., 1998). The samples were also probed by immunoblotting with the same antibody. GTP-Ras and GTP-Rac were pulled down from 800  $\mu$ g of total proteins using GST-Raf-RBD or GST-Pak67-150, respectively, before immunoblotting with specific antibodies. For subcellular fractionation, cells were homogenized with a Dounce homogenizer in cold hypotonic buffer (10 mM Tris, pH 7.4, 1.5 mM MgCl<sub>2</sub>, 5 mM KCl, 1 mM EDTA, and protease inhibitors). After pelleting nuclei and intact cells by centrifugation at 750 g for 10 min, the supernatants were spun at 10<sup>5</sup> g for 1 h. The resulting supernatants containing the cytosolic fraction were kept aside, whereas the pellets were extracted with radioimmunoprecipitation buffer and briefly clarified at 10<sup>5</sup> g for 5 min to recover the crude membrane fraction. An equal amount of proteins from the cytosolic or membrane fractions were analyzed by immunoblotting.

### Optical imaging

Cells were transfected with a vector encoding GFP-Rac (pEGFP-Rac1) in combination with constructs encoding various forms of PAK or Merlin. 12 h after transfection, cells were starved for 24 h, detached, and replated on FN-coated coverslips in SFM without growth factors. After an additional 4 h, 6.5- $\mu$ m polystyrene latex beads (Interfacial Dynamics Corp.) were applied to the cells for 25 min at a beads to cell ratio of 40:1 (del Pozo et al., 2002). Beads were washed with bicarbonate buffer, incubated with 50  $\mu$ g/ml FN or 100  $\mu$ g/ml PL at RT for 1 h, and washed with PBS. Cells were fixed in 4% PFA, permeabilized in 0.2% Triton X-100/PBS, blocked in 2.5% BSA/goat serum, and incubated with primary antibodies or rhodamine-conjugated phalloidin (0.1  $\mu$ g/ml, Sigma-Aldrich). Samples were examined on an inverted microscope using 40 and 63 $\times$  1.5 oil immersion lenses (Axiovert 200M; Carl Zeiss Microimaging, Inc.). Confocal analysis was performed with an LSM510 instrument (Carl Zeiss Microimaging, Inc.).

### RNA interference

The siRNA oligonucleotide TGGCCACGAAGCACTGAT was designed to target human but not mouse Merlin and was synthesized by the RNA interference Facility of the Memorial Sloan-Kettering Cancer Center. Cells were cultured in 6-well plates (Transwell Costar) until 40% confluent and transfected with 1 ml of Opti-MEM (GIBCO BRL) containing 4  $\mu$ l of Oligofectamine (Invitrogen) and 5  $\mu$ l of 20  $\mu$ M siRNA for 4 h. Cells were then returned to complete SFM containing 20% FBS and growth factors for 24 h and then deprived of growth factors for 24 h before the assays. For optical imaging, cells were first electroporated with HA-Rac (pXJ40-HA-Rac1) and 3 h later detached and replated for transfection of siRNA. Cotransfection of fluorescent-labeled RNA oligo revealed that the efficiency of siRNA transfection was >90%.

### Online supplemental material

Fig. S1 shows that a large fraction of sparse HUVEC progress through G1 and enter S phase after growth factor stimulation, whereas only a minor fraction of confluent cells progress through the cell cycle under otherwise identical conditions. Confluent HUVEC undergo growth arrest as they establish VE-cadherin-dependent junctions. Contact inhibition in these cells is not due to segregation of RTKs from their cognate ligands or inhibition of signaling to Ras and ERK. Fig. S2 shows that knockdown of Merlin promotes formation of lamellipodia in sparse HUVEC. Online supplemental material is available at <http://www.jcb.org/cgi/content/full/jcb.200503165/DC1>.

We thank M. Arpin, M. del Pozo, C. Gottardi, J. Kissil (The Wistar Institute, Philadelphia, PA), and S. Tsukita for reagents. We are grateful to members of our laboratory and to C. Gottardi and B. Gumbiner (University of Virginia, Charlottesville, VA) for discussions, to A. Mino for pEGF-Rac1, to E. Choi for help with the siRNA experiments, and to the Molecular Cytology Facility of the Memorial Sloan-Kettering Cancer Center (MSKCC) for help.

This study was supported by National Institutes of Health grants to F.G. Giancotti (R01 CA78901) and MSKCC (P30 CA08748) and a postdoctoral fellowship from the Uehara Memorial Foundation to T. Okada.

Submitted: 30 March 2005

Accepted: 19 September 2005

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