Cytoplasmic p21<sup>Cip1/WAF1</sup> regulates neurite remodeling by inhibiting Rho-kinase activity

Hiroyuki Tanaka,1,2,3 Toshihide Yamashita,1,3 Minoru Asada,4 Shuki Mizutani,4 Hideki Yoshikawa,2 and Masaya Tohyama1,3

1Department of Anatomy and Neuroscience and 2Department of Orthopedic Surgery, Graduate School of Medicine, Osaka University, Osaka 565-0871, Japan
3CREST, Japan Science and Technology Corporation, Kawaguchi, Saitama 332-0012, Japan
4Department of Pediatrics, Tokyo Medical and Dental University School of Medicine, Bunkyo-Ku, Tokyo 113-8519, Japan

Introduction

A key event during terminal differentiation is a permanent withdrawal from the cell cycle. Much attention has focused on regulation of components known to control progression through the cell cycle, including cyclins, cyclin-dependent kinase (Cdk)* proteins, and Cdk inhibitors. The p21<sup>Cip1/WAF1</sup> gene was identified through the interaction with Cdk2 (Harper et al., 1993), and its expression is induced by activation of wild-type p53 (el-Deiry et al., 1993), and during cellular senescence (Noda et al., 1994) and differentiation (Jiang et al., 1994). An NH<sub>2</sub>-terminal domain of p21<sup>Cip1/WAF1</sup> inhibits cyclin-Cdk kinases and a COOH-terminal domain of p21<sup>Cip1/WAF1</sup> inhibits proliferating cell nuclear antigen (Waga et al., 1994; Chen et al., 1995; Luo et al., 1995; Sherr and Roberts, 1995). These cell cycle inhibitory activities of p21<sup>Cip1/WAF1</sup> are attributable to its nuclear localization (Goubin and Ducommun, 1995; Sherr and Roberts, 1995). However, recent studies provide evidence that p21<sup>Cip1/WAF1</sup> has other biological activities in the cytoplasm. During the process of monocytic differentiation of U937 cells and HL60 cells by the treatment with vitamin D3, p21<sup>Cip1/WAF1</sup> expression was induced in the cytoplasm and this cytoplasmic p21<sup>Cip1/WAF1</sup> forms a complex with Rho-kinase and inhibits its activity in vitro and in vivo. Neurite outgrowth and branching from the hippocampal neurons are promoted if p21<sup>Cip1/WAF1</sup> is expressed abundantly in the cytoplasm. These results suggest that cytoplasmic p21<sup>Cip1/WAF1</sup> may contribute to the developmental process of the newborn neurons that extend axons and dendrites into target regions.

p21<sup>Cip1/WAF1</sup> has cell cycle inhibitory activity by binding to and inhibiting both cyclin/Cdk kinases and proliferating cell nuclear antigen. Here we show that p21<sup>Cip1/WAF1</sup> is induced in the cytoplasm during the course of differentiation of chick retinal precursor cells and N1E-115 cells. Ectopic expression of p21<sup>Cip1/WAF1</sup> lacking the nuclear localization signal in N1E-115 cells and NIH3T3 cells affects the formation of actin structures, characteristic of inactivation of Rho. p21<sup>Cip1/WAF1</sup> forms a complex with Rho-kinase and inhibits its activity in vitro and in vivo. Neurite outgrowth and branching from the hippocampal neurons are promoted if p21<sup>Cip1/WAF1</sup> is expressed abundantly in the cytoplasm. These results suggest that cytoplasmic p21<sup>Cip1/WAF1</sup> may contribute to the developmental process of the newborn neurons that extend axons and dendrites into target regions.

© The Rockefeller University Press, 0021-9525/2002/07/321/9 $5.00
The Journal of Cell Biology, Volume 158, Number 2, July 10, 2002 321–329
http://www.jcb.org/cgi/doi/10.1083/jcb.200202071
appropriate targets. For example, dorsal root ganglion neurons up to postnatal day 3 to 4 or embryonic retinal ganglion neurons can extend their neurites rapidly on myelin-associated glycoprotein, which is an effective neurite outgrowth inhibitor for adult neurons (Johnson et al., 1989; Mukhopadhyay et al., 1994; De Bellard et al., 1996; Cai et al., 2001). These findings suggest that immature neurons may have intrinsic mechanisms that confer resistance to the inhibitory molecules.

Here we show a novel function of cytoplasmic p21Cip1/WAF1. Cytoplasmic expression of p21Cip1/WAF1 was observed in newborn neurons that extensively extend neurites. As p21Cip1/WAF1 binds to Rho-kinase and inhibits its activity, changes in the cytoskeletal organization are at least partly attributable to the nonenzymatic protein inhibitor.

Results

Chick retinal neurons from E5 embryos display cytoplasmic p21Cip1/WAF1 expression

During the period of active neurogenesis, some neuroblasts enter the postmitotic state and then start migrating to their final destination. In the embryonic chick retina, ganglion cells are actively generated around embryonic day 5 (E5) (Frade et al., 1997). We examined expression of p21Cip1/WAF1 in these cells to test whether p21Cip1/WAF1 was associated with differentiation and morphogenesis of these cells. Using immunohistochemistry it was found that retinal neurons immediately after neurogenesis were migrating into deep layers (Fig. 1 A). p21Cip1/WAF1 immunoreactivity was detected in the cells at the vitreous surface of the central neural retina using a monoclonal antibody against p21Cip1/WAF1 (Fig. 1 A). These p21Cip1/WAF1-positive cells were immature retinal neurons before migration. Therefore, it is suggested that p21Cip1/WAF1 is involved in the differentiation of retinal precursor cells in vivo.

Next, we isolated neural precursor cells from E5 retinas to assess more precisely the subcellular localization of p21Cip1/WAF1. Dissociated retinal cells cultured on laminin-1 extended neurites rapidly (Frade et al., 1996b). Cells were cultured on laminin-1 in a chemically defined medium containing 1 μM insulin. Insulin used in the micromolar range is likely to be acting on insulin-like growth factor-I receptors, thus mimicking the differentiative effect of insulin-like growth factor-I on the E5 retinal cells (Frade et al., 1996a). In almost all the immature cells devoid of immunoreactivity for β-tubulin, the expression of p21Cip1/WAF1 was predominantly seen in the nucleus (Fig. 1 B). p21Cip1/WAF1 in the nucleus may contribute to a change in the cell cycle in these cells. On the other hand, in most neurons that had relatively long neurites with immunoreactivity for neuron-specific β-tubulin, p21Cip1/WAF1 was mainly localized in the cytoplasm (Fig. 1 B). These findings suggest that cytoplasmic expression of p21Cip1/WAF1 is induced in the newborn neurons.

In vitro differentiation of N1E-115 cells is associated with p21Cip1/WAF1 expression in the cytoplasm

We next used neuroblastoma N1E-115 cells to examine whether neuronal differentiation was associated with cyto-
plasmic expression of p21\textsuperscript{Cip1/WAF1} N1E-115 cells, which were induced to differentiate by DMSO, were immunostained with the anti-p21\textsuperscript{Cip1/WAF1} antibody. After 24 h of DMSO treatment, p21\textsuperscript{Cip1/WAF1} was induced in the nucleus (Fig. 2 B). However, after 4 d, a time point when the extensive neurite genesis was well evident, p21\textsuperscript{Cip1/WAF1} was mainly localized in the cytoplasm (Fig. 2 C). In this regard, the differentiation-associated cytoplasmic expression of p21\textsuperscript{Cip1/WAF1} is not restricted to chick retinal precursor cells.

**Ectopic expression of p21\textsuperscript{Cip1/WAF1} affects the morphology of N1E-115 cells**

As the cells with cytoplasmic expression of p21\textsuperscript{Cip1/WAF1} extended long neurites, and those devoid of cytoplasmic p21\textsuperscript{Cip1/WAF1} did not (Figs. 1 and 2), we hypothesized that cytoplasmic p21\textsuperscript{Cip1/WAF1} was associated with neurite elongation. Therefore, we next asked if relocalization of p21\textsuperscript{Cip1/WAF1} to the cytoplasm elicited the extension of the neurites. To address this question, the mammalian expression vector for p21\textsuperscript{Cip1/WAF1} with loss of nuclear localization signal (ΔNLS-p21; aa 1–140) as well as the full-length p21\textsuperscript{Cip1/WAF1} (full-p21; aa 1–164) was made (Asada et al., 1999). The cells transfected with ΔNLS-p21 or GFP proliferated until 48 h after transfection (Fig. 3 A), although those with full-p21 stopped proliferation. In the cells transfected with full-p21 or treated with DMSO, the protein level of cyclin D3 strongly increased (Kranenburg et al., 1995), whereas no change in the expression was found in those with ΔNLS-p21 (Fig. 3 B). Furthermore, although underphosphorylated pRb, retinoblastoma gene product, was induced and hyperphosphorylated pRb became undetectable by DMSO treatment, hyperphosphorylated pRb remained predominant in ΔNLS-p21-transfected cells during the observation period (Fig. 3 B). These data demonstrate that ΔNLS-p21 has no differentiation inducing activity in N1E-115 cells, as shown in U937 cells (Asada et al., 1999), thus enabling us to estimate the effects of p21\textsuperscript{Cip1/WAF1} without taking the differentiation effect on the cells into account. The expression level of ΔNLS-p21 in N1E-115 cells was comparable with that of endogenous p21\textsuperscript{Cip1/WAF1} in the cells with DMSO treatment for 4 d (Fig. 3 C). N1E-115 cells were transfected with these constructs and the morphological changes were assessed 48 h later. The cells with the full-length p21\textsuperscript{Cip1/WAF1} expression showed a somewhat flattened and enlarged appearance and decreased cell rounding (Fig. 3 D) compared to those with GFP expression or no transfection, whereas there was no increase in the cell population that had long neurites (Fig. 3 E). These changes may be caused by the differentiation of N1E-115 cells expressing p21\textsuperscript{Cip1/WAF1} in the nucleus (Kranenburg et al., 1995), as we observed a similar phenotype when the cells were induced to be differentiated by DMSO treatment (Kimhi et al., 1976) (unpublished data). The cells with the full-length p21\textsuperscript{Cip1/WAF1} expression extended long neurites 4 d later, a time point when the signal for p21\textsuperscript{Cip1/WAF1} was also seen in the cytoplasm (unpublished data). On the other hand, >45% of the cells transfected with ΔNLS-p21 extended long neurites (3.1-fold increase compared with the control; Fig. 3 E). This result suggests that cytoplasmic p21\textsuperscript{Cip1/WAF1} regulates neurite remodeling in N1E-115 cells.

**Effects of cytoplasmic p21\textsuperscript{Cip1/WAF1} on the cytoskeletal organization**

Overexpression of a dominant active mutant of RhoA or p160ROCK, an isofrom of Rho-kinase, induced cell rounding in N1E-115 cells (Hirose et al., 1998), but the expression of a dominant negative mutant of p160ROCK or treatment with Y-27632 (Fig. 3 E), chemical compounds with

![Figure 3](https://example.com/f3.png)
specific inhibitory activity of Rho-kinase (Uehata et al., 1997), induced significant neurite formation (Hirose et al., 1998). Our findings in N1E-115 cells, in combination with these previous reports, suggest that the neurite-promoting activity of cytoplasmic p21\(^{Cip1/WAF1}\) may be associated with Rho/Rho-kinase. Therefore, we next used NIH3T3 cells to examine whether p21\(^{Cip1/WAF1}\) would regulate actin cytoskeleton mediated by Rho. NIH3T3 cells were transfected with \(\Delta\text{NLS-p21}\), and then were serum-starved for 16 h. Incubation with serum for 10 min induced the formation of actin stress fibers, preferentially through activation of Rho (Ridley and Hall, 1992). However, NIH3T3 cells transfected with \(\Delta\text{NLS-p21}\) had little stress fiber formation after the addition of serum, whereas prominent stress fibers were found in nontransfected cells (Fig. 4, A and B). Extensive actin stress fibers were observed in the cells with the full-length p21\(^{Cip1/WAF1}\) expression (unpublished data). These results suggest that Rho-induced actin reorganization in NIH3T3 cells may be blocked by the cytoplasmic expression of p21\(^{Cip1/WAF1}\).

\[\text{p21}^{Cip1/WAF1}\text{ binds to Rho-kinase in the cytoplasm}\]

Rho-kinase was shown to work with mDia1 to elicit the Rho induced phenotype in the fibroblast (Watanabe et al., 1999). As the serum is one of the most potent activators of Rho (Ridley and Hall, 1992), loss of stress fiber formation by the expression of cytoplasmic p21\(^{Cip1/WAF1}\) in serum stimulated cells may result from the blockade of the downstream pathway of Rho. Morphological changes of N1E-115 cells by the expression of \(\Delta\text{NLS-p21}\) were comparable with those by Y-27632 (Fig. 3 E). Given that p21\(^{Cip1/WAF1}\) inhibits the activity of the apoptosis signal-regulating kinase 1 (Asada et al., 1999) as well as cyclin-Cdk kinases that are serine threonine kinases (for review see Pines, 1995), we speculated that p21\(^{Cip1/WAF1}\) might inhibit the activity of Rho-kinase, which is also a serine threonine kinase. To test the possibility that cytoplasmic p21\(^{Cip1/WAF1}\) forms a complex with Rho-kinase in the cytoplasm, coimmunoprecipitation studies were performed using the 293T cells cotransfected with GFP-\(\Delta\text{NLS-p21}\) and myc-tagged Rho-kinase. Cytoplasmic expression was well evident in the 293T cells transfected with GFP-\(\Delta\text{NLS-p21}\) (Fig. 5 A). When the lysates were immunoprecipitated with the anti-p21 \(Cip1/WAF1\) antibody, p21 \(Cip1/WAF1\) efficiently precipitated myc-tagged Rho-kinase (Fig. 5 B). In an attempt to test if the interaction of \(\Delta\text{NLS-p21}\) with Rho-kinase depends on its cellular

---

**Figure 4. Effects of cytoplasmic p21\(^{Cip1/WAF1}\) on the cytoskeletal organization.** (A) NIH3T3 cells were transfected with GFP-\(\Delta\text{NLS-p21}\). After serum starvation for 16 h, the cells were treated with 10% fetal bovine serum, fixed, and stained with rhodamine-conjugated phalloidin. (B) Quantification of the cells containing stress fibers. Data represent means ± SEM of three independent experiments. *\(, \) \(P < 0.01\) compared with GFP (Student’s \(t\) test).

**Figure 5. Cytoplasmic p21\(^{Cip1/WAF1}\), but not p21\(^{Cip1/WAF1}\) in the nucleus, precipitates Rho-kinase.** (A) Subcellular localization of ectopically expressed proteins in 293T cells. Note the difference in the localization between GFP-full-p21 and GFP-\(\Delta\text{NLS-p21}\). (B) 293T cells were cotransfected with myc-Rho-kinase in combination with GFP-full-p21 or GFP-\(\Delta\text{NLS-p21}\). The lysates were immunoprecipitated with the anti-p21\(^{Cip1/WAF1}\) antibody. Immunocomplexes were electrophoresed and blotted with anti-myc antibody. Expression of Rho-kinase and p21\(^{Cip1/WAF1}\) in the lysates was determined. (C) Interaction of p21\(^{Cip1/WAF1}\) with Rho-kinase using lysates prepared from differentiating N1E-115 cells with DMSO treatment. Immunoprecipitated p21\(^{Cip1/WAF1}\) was electrophoresed and immunoblotted with anti-Rho-kinase antibody. Anti–mouse IgG antibody was used as a negative control. (D) In vitro interaction of recombinant full-length p21\(^{Cip1/WAF1}\) and the catalytic domain of Rho-kinase (GST-CAT). S6 kinase substrate peptide (AKRRLSLLRA) and Y-27632 at the indicated concentrations were coincubated.
localization, we then tested the interaction of Rho-kinase with p21 Cip1/WAF1, which was expressed predominantly in the nucleus (Fig. 5 A). In contrast to ΔNLS-p21, only a faint signal could be detected (Fig. 5 B), despite comparable expression of the full-length and truncated forms of p21 Cip1/WAF1 in the 293T cells.

Interaction of the proteins artificially overexpressed may be difficult to detect in natural cells. Employing the anti-p21 antibody, we examined the interaction of endogenous proteins using lysates prepared from differentiating N1E-115 cells. N1E-115 cells expressed p21 Cip1/WAF1 in the cytoplasm after treatment with DMSO for 3 to 4 d (Fig. 2). In the p21 immunoprecipitates, the anti Rho-kinase antibody revealed the presence of a protein corresponding to Rho-kinase (Fig. 5 C).

The lack of an interaction of the full-length-p21 with Rho-kinase may be attributable to the difference of the localization in the cells. Therefore, we tested the in vitro interaction of the recombinant full-length p21 Cip1/WAF1 and Rho-kinase. These proteins in vitro bound to each other (Fig. 5 D). As GST fused to the fragment of Rho kinase used here corresponds to the catalytic region of Rho-kinase (GST–CAT; aa 6–553), p21 Cip1/WAF1 may directly bind to the catalytic region of Rho-kinase. This is substantiated by our finding that S6 kinase substrate peptide (AKRRLLSSLRA) as well as Y-27632 inhibited the interaction of p21 Cip1/WAF1 with Rho-kinase dose dependently (Fig. 5 D). These results suggest that p21 Cip1/WAF1 associates with Rho-kinase in the cytoplasm.

**p21 Cip1/WAF1 inhibits Rho-kinase activity**

We next investigated whether p21 Cip1/WAF1 could inhibit the activity of Rho-kinase in vitro. The kinase assay was carried out using S6 kinase substrate peptide and [γ-32P] ATP. By using a scintillation counter, the quantity of 32P-labeled substrate peptide on the phosphocellulose paper was determined. This kinetic analysis revealed that p21 Cip1/WAF1 inhibited the Rho-kinase activity toward S6 kinase substrate peptide in a dose-dependent manner (Fig. 6 A), and the IC50 value estimated was 1.43 nM.

These results prompted us to examine whether the Rho-kinase activity was inhibited by the expression of ΔNLS-p21 in vivo. 293T cells were transfected with myc-Rho-kinase and GFP. Data represent means ± SEM of three independent experiments. (B) The activity of Rho-kinase was assayed with the cells exposed to Y-27632 (10 μM) for 30 min or cotransfected with myc-Rho-kinase and p21 Cip1/WAF1 constructs.

The expression of Rho-kinase was determined by Western blot to normalize the relative activities. The relative activities were quantified compared to CPM in the control cells cotransfected with myc-Rho-kinase and GFP. Data represent means ± SEM of 3 independent experiments.

**Cytoplasmic p21 Cip1/WAF1 promotes neurite outgrowth and branching of the hippocampal neurons**

To investigate the relevance of our findings that the cytoplasmic p21 Cip1/WAF1 acts on Rho-kinase, we assessed the effects on neurons. Cultures of the hippocampal neurons from rat E18 embryos were used. We chose these neurons, as they did not express endogenous p21 Cip1/WAF1 enough to be detected by immunocytochemistry using the anti-p21 Cip1/WAF1 antibody (unpublished data). Dissociated hippocampal neurons were incubated for 48 h and transfected with ΔNLS-p21. 24 h after transfection, the cells were fixed and immunolabeled with β-tubulin III. The total neurite length per neuron, the axonal length, defined as the length of the longest neurite per neuron, the number of primary processes originating from the neuronal somata, and the number of branch points per neuron were determined (Neumann et al., 2002). The neuronal morphology of the cells expressing ΔNLS-p21 was apparently different from the control cells without transfection or expressing GFP (Fig. 7 A). The cells with the ΔNLS-p21 expression extended longer neurites and had more branch points than the control cells (GFP-expressing cells or no transfection). Ectopic expression of ΔNLS-p21 increased the total neurite length per neuron from 135.9 μm (±7.2 μm SEM) to 307.2 μm (±34.0 μm SEM), the axonal length from 66.3 μm (±3.2 μm SEM) to 162.9 μm (±18.6 μm SEM), and the number of branch points per neuron from 1.3 (±0.2 SEM) to 2.6 (±0.3 SEM). However, no change in the number of primary processes was found by overexpression of cytoplasmic p21 Cip1/WAF1 (Fig. 7 B). These results indicate that cytoplasmic p21 Cip1/WAF1 regulates neurite remodeling in the embryonic hippocampal neurons.
with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected experiments. *, P with GFP. Data represent means points per neuron were increased compared with those transfected were transfected with GFP (control) or GFP-Morphology of hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippocampal neurons transfected with GFP or GFP-Morphological analysis of primary hippoca...
mashita et al., 2002). Taking these findings into consideration, blocking the activity of Rho-kinase would be a good molecular target, as the axonal outgrowth should be promoted by blocking the downstream pathway even if Rho is activated by some cytokines or guidance molecules. In fact, Rho-kinase was shown to be a possible therapeutic target for central nervous system axon regeneration (Lehmann et al., 1999).

However, not all the neuronal cells respond to various stimuli in the same way. In PC12 cells during differentiation after nerve growth factor treatment, ectopic expression of constitutively active Rho does not cause the disappearance of neurites (Sebok et al., 1999). In dorsal root ganglion neurons up to postnatal day 3 to 4 or embryonic retinal ganglion neurons, axonal outgrowth was not significantly inhibited by myelin-associated glycoprotein, which activates Rho (Johnson et al., 1989; Mukhopadhyay et al., 1994; De Bellard et al., 1996; Cai et al., 2001; Yamashita et al., 2002). Although these reports suggest that the responses of the neurons to Rho depend on the cell context, another interpretation of the data is that immature or young neurons may have intrinsic mechanisms to overcome the inhibitory effects mediated by Rho. The molecular mechanisms that govern these phenomenon remain to be elucidated, however, our notion that cytoplasmic p21Cip1/WAF1 promotes neurite outgrowth through inactivation of Rho-kinase may be an interesting hypothesis to explain the loss of responses to Rho activation. Future studies will address these issues.

Materials and methods

Preparation of chick retina and retinal cells

Whole chick E5 embryos (White Leghorn) were fixed with 4% paraformaldehyde in PBS overnight and immersed in 30% sucrose. Cryosections (30 μm in thickness) of retinas were cut on the coronal plane, thaw mounted onto slides, and dried at room temperature. For retinal neuron culture, retinas from E5 embryos were dissected free from the pigment epithelium and dissociated as described previously (Rodriguez-Tebar et al., 1989; de la Rosa et al., 1994). Dissociated cells were plated (20,000 cells/cm²) on 4-well chamber slides (Nalge Nunc International K.K.), which were previously coated with poly-L-ornithine/laminin (Sigma-Aldrich) (Collins, 1978). Cells were cultured in DME/F12 mixture (1:1) with N2 supplement (Bottenstein and Sato, 1979), and maintained at 37°C in 5% CO2 for 12 h and fixed with 4% paraformaldehyde in PBS.

Plasmid constructs

pEGFP-full-p21 (aa 1–164) and pEGFP-ΔNLS-p21 (aa 1–140) are mammalian expression vectors for GFP fused proteins (Asada et al., 1999). Myc-Rho-kinase in pEF-BOS was provided by Dr. K. Kaibuchi (Nagoya University, Nagoya, Japan).

Cell culture and transfection

NIH3T3 cells, N1E-115 cells, and 293T cells were maintained in DME containing 10% fetal bovine serum. Lipofectamine 2000 (Invitrogen) was used for transfection. For the stress fiber formation assay, NIH3T3 cells were cultured in serum-free medium for 16 h after transfection. Stress fiber formation was evoked by incubating the cells with 10% serum for 10 min. Hippocampal neurons were prepared from E5 embryos were dissected free from the pigment epithelium and maintained at 37°C in a water-saturated atmosphere containing 5% CO2 for 12 h and fixed with 4% paraformaldehyde in PBS.

Kinase assay

The kinase reaction for Rho-kinase was carried out using a S6 Kinase Assay Kit (Upstate Biotechnology) according to the manufacturer’s instructions. Briefly, for in vitro assay, 10 μl of assay dilution buffer (ABD, 20 mM MOPS, pH 7.2, 25 mM β-glycerol phosphate, 5 mM EGTA, 1 mM sodium orthovanadate and 1 mM diethylthioctetol), 10 μl of substrate cocktail (250 μM substrate peptide [AKRRLLSLLRA] in ADB), 10 μl of the inhibitor cocktail, 10 μl of the [γ-32P] ATP mixture (magnesium/ATP cocktail including 10 μCi of the [γ-32P] ATP) and 20 μl of Rho kinase fragment (aa 1–54; Upstate Biotechnology) were mixed. After incubation with p21Cip1/WAF1 protein for 10 min at 30°C, the reaction mixtures were spotted onto the P81 phosphocellulose paper and quantified using a scintillation counter.

For the in vivo assay, 293T cells were cotransfected with myc-Rho-kinase in combination with GFP or p21Cip1/WAF1 constructs. Cells were lysed with lysis buffer (50 mM Tris-HCl, pH 7.5, 150 mM NaCl, 10% glycerol, 1% Nonidet-P40 and protease inhibitor cocktail). The cell lysates were spotted onto the P81 phosphocellulose paper and quantified using a scintillation counter.

Immunostaining

For immunohistochemistry, sections of chick retinas were permeabilized and blocked with the blocking buffer (0.1% Triton X-100, 0.1% BSA, and 5% goat serum in PBS) for 30 min at room temperature. For immunocytochemistry, cells were permeabilized and blocked with the buffer containing 0.2% Triton X-100. They were incubated overnight at 4°C with the anti-p21Cip1/WAF1 antibody (1:1000) and an anti-β-tubulin class III rabbit polyclonal antibody (TuJ1) (1:2,000; Research Diagnostic, Inc.), followed by incubation for 1 hour with Alexa 488-labeled goat anti-mouse IgG antibody (Molecular Probes) and Alexa 568-labeled goat anti-rabbit IgG antibody (Molecular Probes). Tetramethyl rhodamine isothiocyanate-labeled phalloidin (1:1,000; Sigma-Aldrich) was used to detect F-actin in NIH3T3 cells and N1E-115 cells. Hippocampal neurons were immunostained with the anti-TuJ1 antibody. When necessary, DAPI (300 nM; Wako) was used to stain the nucleus. Samples were examined under a confocal laser-scanning microscope (Carl Zeiss).
References


Neurite outgrowth by cytoplasmic p21Cip1/WAF1 | Tanaka et al. 329


