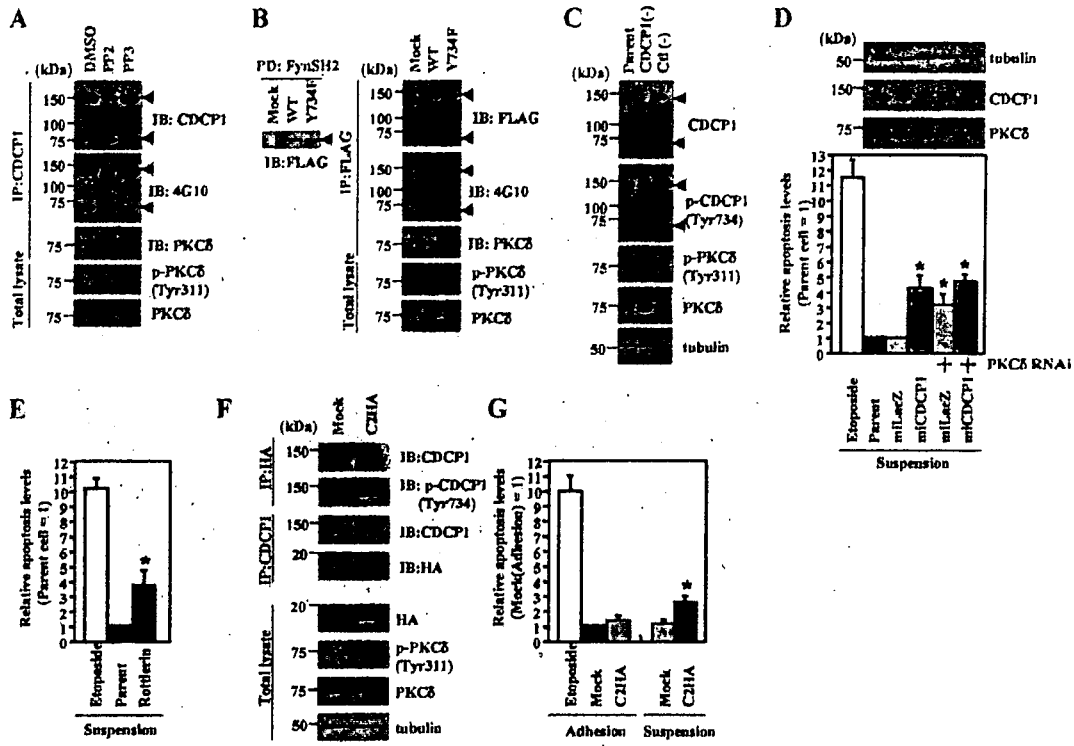

FIG. 6. PKCδ is a signaling molecule downstream of CDCP1 during anoikis resistance. (A) Treatment with the SFK inhibitor PP2 blocked the physical association between PKCδ and CDCP1 and at the same time suppressed phosphorylation of PKCδ at Tyr311. A549 cells treated with 10 μM of PP2 and 10 μM of PP3 in suspension culture were collected and subjected to immunoprecipitation with anti-CDCP1 antibody (ab1377) and immunoblotting (IB) with the indicated antibodies. The phospho-specific antibody against PKCδ (p-PKCδ [Tyr311]) total cell lysate was used to detect the phosphorylation of PKCδ, and the expression of PKCδ was also confirmed. (B) CDCP1 mutants were expressed in COS7 cells and pulled down (PD) with GST-FynSH2 protein. The samples pulled down were immunoblotted with FLAGM2 antibody (left). CDCP1 mutants were transiently transfected in A549 cells. After 24 h, cells were collected and subjected to immunoprecipitation (IP) with anti-FLAGM2 antibody. The immunoprecipitates were subjected to immunoblotting with the indicated antibodies. Each total cell lysate was used to detect the phosphorylation and the expression of PKCδ. (C) A549 cells treated with CDCP1 stealth siRNA and control siRNA were collected and subjected to immunoblotting with the indicated antibodies. (D) The effect of PKCδ on apoptosis was determined by apoptosis assay. PKCδ stealth siRNA was transiently transfected into CDCP1-defective A549 cell clones and control miLacZ clones. After 48 h, each cell clone (1.0×10^4 cells) was reseeded onto MPC-coated 96-well plates and cultured for 24 h. The cells were lysed and examined for apoptosis using a cell death ELISA kit (Roche). The total apoptotic level of A549 cells was examined by treatment with etoposide (25 μM). The relative apoptosis levels are shown as the level of apoptosis compared with the parent cells. The error bars represent standard deviations, and the asterisks indicate statistically significant differences ($P < 0.01$) between the parent and each of the other cells. Expression of CDCP1 and PKCδ was determined by Western blotting with the indicated antibodies (top). (E) The effect of PKCδ activation on apoptosis was determined by apoptosis assay. A549 cells (1.0×10^4 cells) were seeded onto MPC-coated 96-well plates and treated or not with Rottlerin (5 μM). The relative apoptosis levels after culture for 24 h are shown as the level of apoptosis compared with parent cells. The error bars represent standard deviations, and the asterisk indicates a statistically significant difference ($P < 0.01$) between the parent and Rottlerin-treated cells. (F) The C2 domain of PKCδ with the HA tag (C2HA) was expressed in A549 cells. After 24 h, cells were collected and subjected to immunoprecipitation with anti-CDCP1 (ab1377) or anti-HA antibody. Immunoprecipitates were subjected to immunoblotting with the indicated antibodies. Total cell lysate was used to detect the expression of C2HA and the phosphorylation level of endogenous PKCδ in A549 cells. (G) The cells transiently transfected with C2HA or mock vector, as indicated (1.0×10^4 cells), were cultured in normal and MPC-coated 96-well plates. After 24 h, the cells were lysed and apoptosis was examined using a cell death ELISA kit (Roche). The relative apoptosis levels are shown as the level of apoptosis in each of the cells compared with the control mock cells in adhesion culture. The error bars represent standard deviations, and the asterisk indicates a statistically significant difference ($P < 0.05$) between the mock cells and each of the other cells in suspension culture.

adenocarcinoma cells in a suspended condition but not in an adherent condition (Fig. 4C). This phenomenon strongly suggests that CDCP1 is involved in the suppression of anoikis, a form of apoptosis triggered by disruption of cell-matrix interactions.

The molecules and signaling pathways in the anoikis resistance of human cancer cells are not sufficiently understood. Previous reports have shown that oncogenes encoding, e.g., Ras, Src, and their downstream signaling molecules, such as PI 3-kinase/Akt and MAPK, are critical players in compensating for the cell survival signals derived from matrix attachment via integrins (9, 16). Inhibition of PI 3-kinase/Akt and Erk1/2 does not induce apoptosis in lung cancer cells, while SFK inhibitor causes apoptosis in these cells (32, 33). This study has revealed that the inhibition of SFKs blocked anchorage independence in lung cancer cells without affecting the phosphorylation state of PI 3-kinase/Akt, Erk1/2, or p38MAPK (Fig. 1D). These results suggest that SFKs are critical regulators of anoikis in cancer cells. On the other hand, the inhibition of SFKs was effected independently of the PI 3-kinase/Akt pathway.

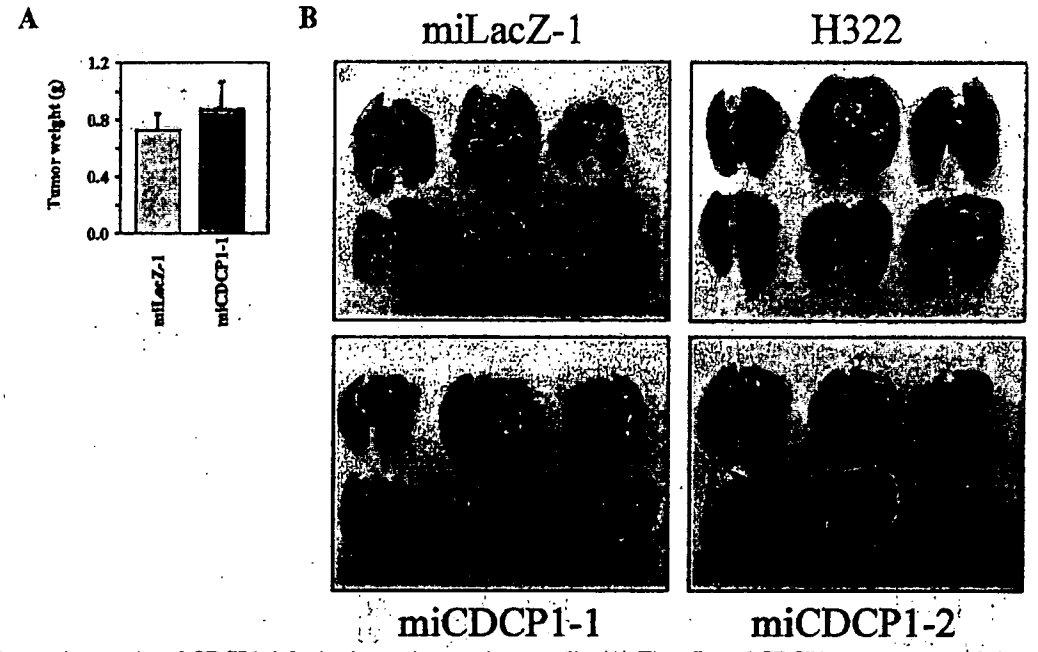

FIG. 7. Metastatic capacity of CDCP1-defective lung adenocarcinoma cells. (A) The effect of CDCP1 on tumor growth in nude mice was determined as described in Materials and Methods. The data represent the weights of tumors from the miCDCP1-1 clone or the miLacZ-1 clone (n = 3). The error bars indicate standard deviations. (B) The metastatic potential was evaluated from the number of metastatic cell nodules in mouse lungs after injection of tumor cells from the tail vein (n = 6). Lung tissues were fixed with 10% formaldehyde solution. Many metastatic nodules were observed in the control A549 miLacZ-1 clone, while fewer nodules were observed in the miCDCP1-1 and miCDCP1-2 clones and H322 cells. The number of mice with obvious lung metastasis and the average number of metastatic nodules per mouse for each cell clone are shown in Table 1.

CDCP1 is a potent substrate of SFKs within cells, and its function is likely modulated by phosphorylation of the tyrosine residues in the cytoplasmic domain (2, 3, 5). In our study, the SFK inhibitor PP2 inhibited phosphorylation of CDCP1, and at the same time, soft-agar colony formation of A549 cells was also inhibited (Fig. 1A, PP2). In fact, the level of tyrosine phosphorylation of CDCP1 is associated with the capacity for anchorage independence in lung cancer cells (Fig. 3C). Together with the observation that apoptosis of H322 cells in suspension culture was inhibited by overexpression of CDCP1 and Fyn kinase together but not CDCP1 or Fyn kinase alone, or by the Y734F mutant of CDCP1, this suggested that active SFKs confer anoikis resistance through tyrosine phosphorylation of CDCP1.

Among the SFKs, the expression of c-Src, Fyn, and c-Yes is commonly observed in human solid tumors (31). In this study, we detected the expression of c-Src, Fyn, and c-Yes in the suspension culture of A549 cells (Fig. 1B, Parent). Among these kinases, Fyn and c-Yes may regulate CDCP1-mediated cell survival in A549 cells, since these kinases are associated with CDCP1 (Fig. 3A and B), and downregulation of Fyn or c-Yes inhibits soft-agar colony formation in A549 cells (Fig. 1A). On the other hand, the amount of phosphorylated CDCP1 was either partially or remarkably reduced by Fyn or c-Yes dicer siRNA, respectively (data not shown), supporting the claim that these two members of the SFKs have a considerable effect on the phosphorylation of CDCP1. A dynamic balance of active SFK and protein tyrosine phosphatase activities regulates the phosphorylation of CDCP1 during cell attachment (5). This balance may shift when integrin signaling is shut off by cell detachment. As shown in Fig. 3D, dynamic changes in the amount of tyrosine-phosphorylated CDCP1 were also caused by changes in the expression level of CDCP1, although it is not yet clearly understood how the expression of CDCP1 is regulated by the cell detachment/attachment signal.

Benes et al. (2) recently reported that the C2 domain of PKCδ associates with phosphorylated CDCP1. Several studies have also reported on the phosphorylation of PKCδ by SFKs (19, 30), but the regulatory mechanism of PKCδ phosphorylation remains unclear. Our study found that PKCδ was remarkably phosphorylated in suspended A549 cells and also confirmed a physical association through the regulation of the phosphorylation state of CDCP1 in A549 lung adenocarcinoma cells (Fig. 6A, B, and C). Both the expression of CDCP1

TABLE 1. Effects of CDCP1 downregulation on lung cancer metastasis in vivo[a]

Cells	Metastasis[b]	No. of nodules in lung[c]
A549 miLacZ	6/6	12.8
H322	1/6	1.3
A549 miCDCP1-1	1/6	0.2
A549 miCDCP1-2	1/6	0.5

[a] Mice were sacrificed 100 days after inoculation.
[b] Data are shown as the number of mice bearing tumors in the lung/total number of mice.
[c] Average number of metastatic tumor nodules larger than 2 mm in the lung per mouse.

and the association of CDCP1 with SFKs are required for the phosphorylation of PKCδ, which suggests that CDCP1 mediates the phosphorylation of PKCδ by SFKs. We found that an increased level of apoptosis was observed with the treatment of siRNA for PKCδ or with the PKC inhibitor Rottlerin in A549 cells in a suspension condition (Fig. 6D and E). Moreover, inhibition of the association between CDCP1 and PKCδ, by expressing the C2 domain of PKCδ, suppressed the tyrosine phosphorylation of PKCδ and increased the level of apoptosis in A549 cells in a suspension condition at the same time (Fig. 6F and G). It is speculated that CDCP1-mediated tyrosine phosphorylation and the activation of PKCδ lead to the suppression of apoptosis in A549 cells.

Tyrosine phosphorylation of PKCδ is a critical regulatory factor for PKCδ activity and results in the elevation of both tyrosine phosphorylation and the activity of PKCδ in various cells stimulated with substances such as phorbol esters, growth factors, and hormones (21, 22, 23, 27, 29). It was also reported that tyrosine phosphorylation of PKCδ by Src actually increased PKCδ activity (1, 11). On the other hand, several reports have shown that active PKCδ possesses an antiapoptotic function. For example, the activation of PKCδ by fibroblast growth factor has an antiapoptotic effect in PC12 cells (34) and a reduction of PKCδ activity by using a kinase-dead mutant of PKCδ induced apoptosis in lung cancer cells (7). Further evidence that supports PKCδ as a suppressor of apoptosis includes the requirement for active PKCδ during cell transformation mediated by insulin-like growth factor I receptor (23) and the induction of anchorage-independent growth and increased metastatic potential of breast cancer cells overexpressing PKCδ (17, 18). Our observation that tyrosine-phosphorylated PKCδ serves an antiapoptotic function in lung cancer cells supports these reports, although it appears that PKCδ has both proapoptotic and antiapoptotic functions, which are dependent on the specific circumstances and modes of action (4).

Taken together, it is strongly suggested that CDCP1 is a docking protein between SFKs and PKCδ and that CDCP1-SFK complex-dependent PKCδ phosphorylation plays a significant role in the control of anoikis resistance in lung adenocarcinoma cells. Further study is required to identify the signal downstream of tyrosine-phosphorylated PKCδ.

Finally, this study suggests that CDCP1 is a novel regulator of anoikis resistance under the control of SFKs in lung adenocarcinoma cells and that PKCδ, which is associated with and conditionally phosphorylated by the CDCP1-SFK complex, is a good candidate as a signal mediator of anoikis resistance. It was found that CDCP1 is essential in vivo for lung cancer metastasis in the mouse model (Fig. 7), indicating that CDCP1 is actually a modulator of the later processes of cancer metastasis through the regulation of anoikis. Further investigation of the specific functions of CDCP1 in normal cells and its disorders in cancer may yield important information that will help determine a clinical target for lung cancer metastasis.

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Functional analysis of Src homology 3-encoding exon (exon 2) of p130Cas in primary fibroblasts derived from exon 2-specific knockout mice

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p130Cas (Cas, Crk-associated substrate) is an adaptor molecule composed of a Src homology 3 (SH3) domain, a substrate domain (SD) and a Src binding domain (SBD). The SH3 domain of Cas associates with focal adhesion kinase (FAK), but its role in cellular function has not fully been understood. To address this issue, we established and analyzed primary fibroblasts derived from mice expressing a truncated Cas lacking exon 2, which encodes the SH3 domain (Cas Δexon 2). In comparison to wild-type cells, Cas exon $2^{\Delta/\Delta}$ cells showed reduced motility, which could be due to impaired tyrosine-phosphorylation of FAK and Cas, reduced FAK/Cas/Src/CrkII binding, and also impaired localization of Cas Δexon 2 to focal adhesions on fibronectin. In addition, to analyze downstream signaling pathways regulated by Cas exon 2, we performed microarray analyses. Interestingly, we found that a deficiency of Cas exon 2 up-regulated expression of CXC Chemokine Receptor-4 and CC Chemokine Receptor-5, which may be regulated by IκBα phosphorylation. These results indicate that the SH3-encoding exon of Cas participates in cell motility, tyrosine-phosphorylation of FAK and Cas, FAK/Cas/Src/CrkII complex formation, recruitment of Cas to focal adhesions and regulation of cell motility-associated gene expression in primary fibroblasts.

Introduction

Cas is composed of an N-terminal Src homology 3 (SH3) domain, a substrate domain (SD) that consists of a cluster of Tyr-Xaa-Xaa-Pro (YXXP) motifs (one YLVP, four YQXPs, nine YDXPs and one YAVP), a C-terminal Src binding domain (SBD) and other regions (Sakai *et al.* 1994). The SH3 domain binds to the proline-rich region of various signaling molecules, such as focal adhesion kinase (FAK) (Polte & Hanks 1995), PTP-1B (Liu *et al.* 1996), PTP-PEST (Garton *et al.* 1997), C3G (Kirsch *et al.* 1998) and CIZ (Nakamoto *et al.* 2000). The SD offers docking sites for the SH2 domain of several molecules including CrkII, Nck and an inositol 5′-phophatase, SHIP2 (SH2-containing inositol 5-phosphatase) in a tyrosine-phosphorylation-dependent manner (Mayer *et al.* 1995; Schlaepfer *et al.* 1997; Prasad *et al.* 2001). The SBD is rich in proline and serves as a binding site for the SH2 and SH3 domains of Src kinase (Nakamoto *et al.* 1996).

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Physiologically, Cas becomes tyrosine phosphorylated in response to various extracellular stimuli, such as integrin engagement (Nojima *et al.* 1995; Vuori & Ruoslahti 1995), which recruits Cas from cytoplasm to focal adhesions (Nakamoto *et al.* 1997). Tyrosine-phosphorylated Cas binds to CrkII, forming a Cas/CrkII complex (Vuori *et al.* 1996), which subsequently leads to the activation of the Rac–JNK pathway (Dolfi *et al.* 1998; Kiyokawa *et al.* 1998a). In addition, over-expression of Cas promotes cell motility, depending on its association with FAK and CrkII (Cary *et al.* 1998; Klemke *et al.* 1998).

To clarify biological roles of Cas, we generated Cas-deficient mice (Honda *et al.* 1998). Cas-deficient embryos died *in utero* at 12.5 dpc showing marked systemic congestion and growth retardation (Honda *et al.* 1998). Histologically, the heart was poorly developed and blood vessels were prominently dilated. Electron microscope analysis of the heart revealed disorganization of myofibrils and disruption of Z-disks (Honda *et al.* 1998). Cas-deficient fibroblasts showed impaired actin stress fiber formation, defects in cell migration, delayed cell spreading and resistance to Src-induced transformation (Honda *et al.* 1998, 1999). These results demonstrated that Cas is an actin-assembly molecule, which plays an essential role in embryonic development, cytoskeletal organization and Src-induced cellular transformation. Subsequently, to examine the role of each domain of Cas in these processes, we performed a compensation assay by expressing a series of Cas mutants in Cas-deficient fibroblasts (Huang *et al.* 2002). The results showed that motifs containing YDXP were indispensable for actin cytoskeleton organization and cell migration, suggesting that CrkII-mediated signaling regulates these biological processes (Huang *et al.* 2002). In contrast, C-terminal SBD was essential for cell migration, Src-induced transformation and membrane localization of Cas, but was dispensable for the organization of actin stress fibers (Huang *et al.* 2002). Although the above results provided insights in the roles of SD and SBD, the role of the SH3 domain of Cas, which has been shown to associate with various signaling molecules, remains unclear.

To address this issue, we generated mice deficient in Cas exon 2, which produce a truncated Cas protein lacking the SH3 domain. Heterozygous (Cas exon $2^{+/\Delta}$) mice, which were apparently normal, were intercrossed to produce homozygous (Cas exon $2^{\Delta/\Delta}$) mutants. Cas exon $2^{\Delta/\Delta}$ mice died *in utero* at 12.5–13.5 dpc and the detailed analysis of the embryonic lethality of the Cas exon $2^{\Delta/\Delta}$ mice is underway and will be published elsewhere. In this report, we established primary fibroblasts from Cas exon 2-deficient embryos and investigated the roles of Cas exon 2 in cellular functions.

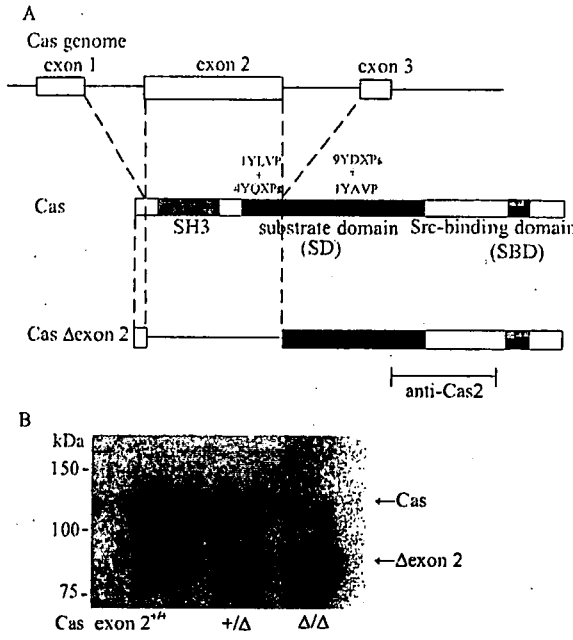

Figure 1 (A) Schematic illustration of Cas genome, Cas full-length product (Cas) and a truncated Cas protein lacking the exon 2-derived region (Cas Δexon 2). As compared to Cas, Cas Δexon 2 is deficient in the whole SH3 domain and one YLVP and four YQXP motifs. The position of the peptides for generating anti-Cas2 is also shown. (B) Western blot to detect Cas Δexon 2 protein. Thirty micrograms of cell lysates extracted from the wild-type (Cas exon $2^{+/+}$), heterozygous (Cas exon $2^{+/\Delta}$) and homozygous (Cas exon $2^{\Delta/\Delta}$) fibroblasts were separated by 7.5% SDS-PAGE, blotted to a nitrocellulose membrane and probed with 1:2000 diluted an anti-Cas antibody. Molecular weight markers are shown on the left.

Results

Cas exon $2^{\Delta/\Delta}$ cells are slower to initiate migration in the wound healing assay

To investigate functional defects caused by Cas exon 2-deficiency, we established primary fibroblasts from Cas exon 2-deficient (Cas exon $2^{\Delta/\Delta}$) embryos. Figure 1A shows the schematic diagram representing Cas Δexon 2. Cas exon 2 contains the entire SH3 domain and a part of the SD domain containing one YLVP and four YQXP motifs. It encodes 211 amino acids and the predicted molecular weight of Cas exon 2 is about 23 kDa. The expression of Cas Δexon 2 protein in Cas exon $2^{\Delta/\Delta}$ fibroblasts was detected almost as the expected size by Western blotting using an antibody against Cas, anti-Cas2 (Sakai *et al.* 1994) (Fig. 1B). Using the fibroblasts,

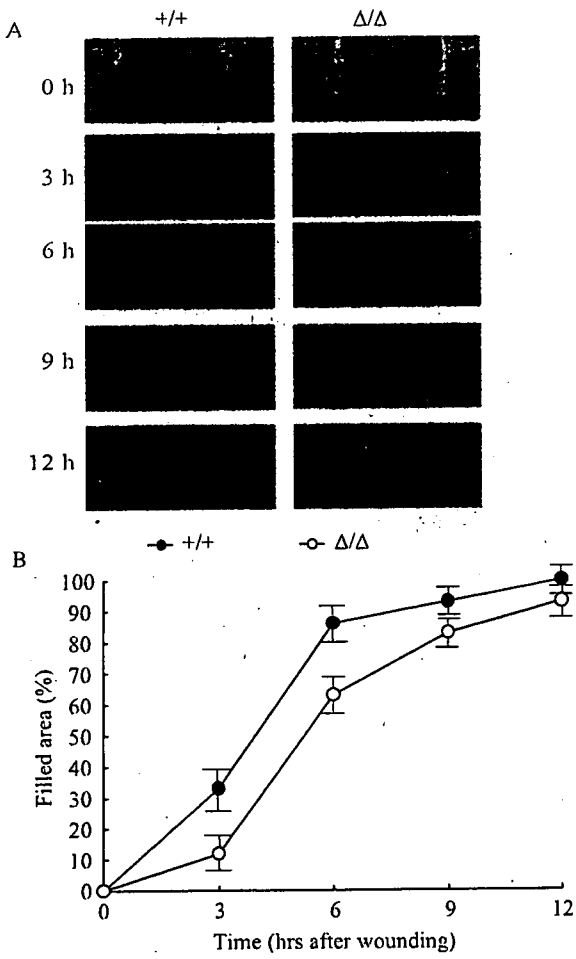

Figure 2 Delayed migration of Cas exon $2^{\Delta/\Delta}$ cells in the initial phase in the wound healing assay. (A) Photographs of Cas exon $2^{+/+}$ cells and Cas exon $2^{\Delta/\Delta}$ cells at 0, 3, 6, 9 and 12 h after wounding. Cells were first grown to confluence in plastic culture dishes, and a wound was made in the cell monolayer using a sterile micropipette tip. Cell movement was assessed 0, 3, 6, 9 and 12 h after wounding. Photographs were taken under a microscope with an objective of 100×. (B) The percentage of reduced distance between the nuclei of cells at each time period relative to the distance between two rims in the cleared field at the beginning was taken as the index (*error bars* show the standard deviation). Results presented here are representative mean values of three independent experiments.

we first performed wound healing cell migration assays. Migratory processes were assessed at 0, 3, 6, 9 and 12 h after wounding (Fig. 2A). Mean percentages of the filled area at each time points are shown in Fig. 2B. Three hours after wounding, Cas exon $2^{+/+}$ cells had filled over 30% of the gap and the cells migrating from both ends of the wound had achieved cell–cell contact. In contrast, only 10% of the area was filled by Cas exon $2^{\Delta/\Delta}$ cells. After 6 and 9 h, the migration deficit in Cas exon $2^{\Delta/\Delta}$ cells was less apparent but still present, and at 12 h the gap was almost filled in both types of the cells. This result demonstrated that Cas exon $2^{\Delta/\Delta}$ cells were deficient in ability to migrate, especially in the early phase of the response.

Cas exon $2^{\Delta/\Delta}$ cells show reduced spreading activity on fibronectin (FN)

We next examined the roles of Cas exon 2 in cell attachment, cell adhesion and cell spreading on FN. The morphological changes in Cas exon $2^{+/+}$ and Cas exon $2^{\Delta/\Delta}$ cells were observed at 30, 60 and 120 min after plating on FN-coated dishes (Fig. 3A). The mean percentages of flattened cells at each time point are shown in Fig. 3B. The disparity in cell spreading was most apparent 30 min after plating, when more than 70% of the Cas exon $2^{+/+}$ cells had already flattened, while only 37% of Cas exon $2^{\Delta/\Delta}$ cells showed a flattened phenotype. The spreading delay in Cas exon $2^{\Delta/\Delta}$ cells continued and was still observed at 120 min. These results demonstrated that Cas exon $2^{\Delta/\Delta}$ cells had a reduced ability to spread on FN.

The deficiency of Cas exon 2 impaired formation of the FAK/Cas/CrkII complex, tyrosine-phosphorylation of FAK and Cas, and FAK/Src binding on FN

Upon FN stimulation, integrin clustering promotes FAK autophosphorylation at Tyr397, which creates a binding site for the SH2 domain of Src (Mitra *et al.* 2005). FAK/Src binding leads to the conformational activation of Src and results in an activated FAK/Src signaling complex (Schlaepfer *et al.* 2004), which enhances tyrosine-phosphorylation of Cas (Sakai *et al.* 1994; Mitra *et al.* 2005) Tyrosine-phosphorylated Cas binds to CrkII through the SD domain with preference for YDXP motifs (Songyang *et al.* 1993), which subsequently leads to activate downstream small GTP-binding proteins through C3G (Kiyokawa *et al.* 1998a,b; Klemke *et al.* 1998) and plays a key role in cell migration (Fig. 8A).

We then investigated whether the deficiency of Cas exon 2 might affect Cas' association with its major signaling molecules, FAK (Polte & Hanks 1995), Src (Nakamoto *et al.* 1996) and CrkII (Mayer *et al.* 1995) to which Cas binds through its SH3, SBD and SD, respectively. Protein aliquots extracted from Cas exon $2^{+/+}$ and

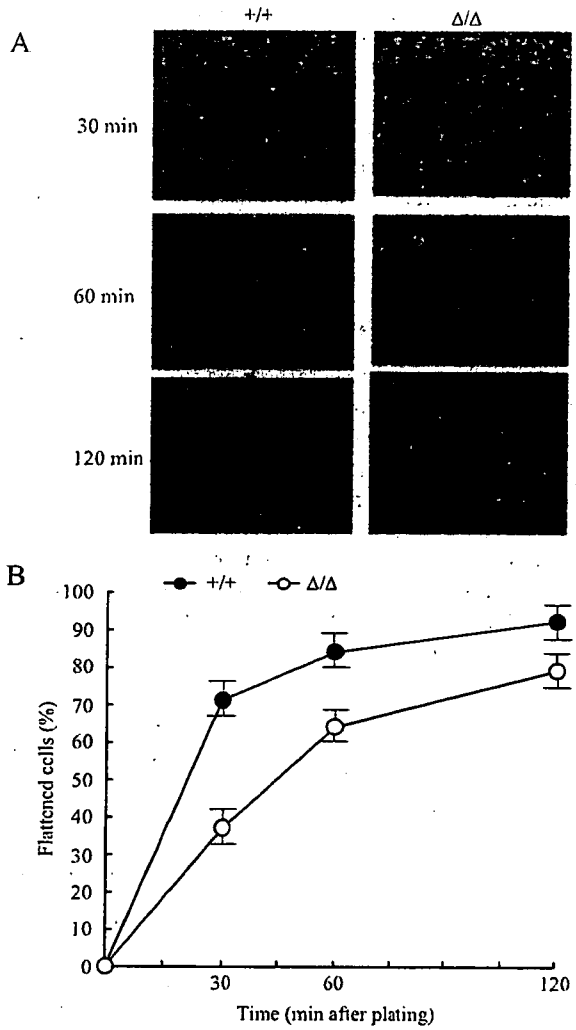

Figure 3 Reduced spreading ability of Cas exon $2^{\Delta/\Delta}$ cells on FN. (A) Photographs of Cas exon $2^{+/+}$ cells and Cas exon $2^{\Delta/\Delta}$ cells at 30, 60 and 120 min after plating on FN-coated dishes. Cells were added to FN-coated dishes and incubated at 37 °C for indicated times. Photographs were taken under a microscope with an objective of 100×. (B) Cell spreading was quantitated by calculating the percentages of spread cells (*error bars* show the standard deviation). Single cells that were phase-bright with rounded morphology were scored non-spread, whereas those that possessed a flattened shape and looked phase-dark were scored as spread. Results presented here are representative mean values of eight independent fields of three experiments.

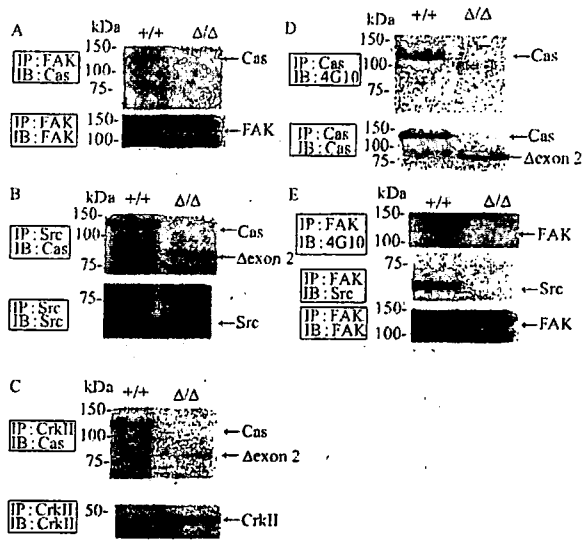

Figure 4 Impaired FAK/Cas/CrkII complex formation, tyrosine-phosphorylation of FAK and Cas, and FAK/Src binding upon FN stimulation in Cas exon $2^{\Delta/\Delta}$ cells. Serum-starved Cas exon $2^{+/+}$ cells and Cas exon $2^{\Delta/\Delta}$ cells were cultured on FN-coated dishes for 1 h, harvested and lysed with 1% Triton lysis buffer. (A) FAK immunoprecipitates (IP : FAK) were probed with anti-Cas (IB : Cas) or anti-FAK (IB : FAK). (B) Src immunoprecipitates (IP : Src) were probed with anti-Cas (IB : Cas) or anti-Src (IB : Src). (C) CrkII immunoprecipitates (IP : CrkII) were probed with anti-Cas (IB : Cas) or anti-CrkII (IB : CrkII). (D) Cas immunoprecipitates (IP : Cas) were probed with 4G10 (IB : 4G10) or anti-Cas (IB : Cas). (E) FAK immunoprecipitates (IP : FAK) were probed with 4G10 (IB : 4G10), anti-Src (IB : Src) or anti-FAK (IB : FAK).

Cas exon $2^{\Delta/\Delta}$ cells plated on FN were immunoprecipitated with antibodies against either FAK, Src or CrkII and immunoprecipitated proteins were blotted with anti-Cas2. As shown in Fig. 4A, wild-type Cas was associated with FAK, whereas Cas Δexon 2 could not bind to FAK. By contrast, Fig. 4B shows that Src bound to both Cas and Cas Δexon 2 at similar levels. We then analyzed possible alteration in CrkII binding to Cas in Cas exon $2^{\Delta/\Delta}$ cells. As shown in Fig. 4C, in Cas exon $2^{+/+}$ cells, stable complex formation of Cas and CrkII was detected, whereas in Cas exon $2^{\Delta/\Delta}$ cells, the binding activity of CrkII to Cas Δexon 2 was significantly reduced. We then analyzed whether the deficiency of Cas exon 2 might affect tyrosine-phosphorylation of Cas. As shown in Fig. 4D, Cas Δexon 2 was not tyrosine-phosphorylated upon FN stimulation. In addition, we could not detect FAK tyrosine-phosphorylation and FAK/Src binding (Fig. 4E). These results indicated that Cas exon 2-deficiency impaired formation of the FAK/Cas/CrkII complex, tyrosine-phosphorylation of FAK and Cas, and FAK/Src binding upon FN stimulation.

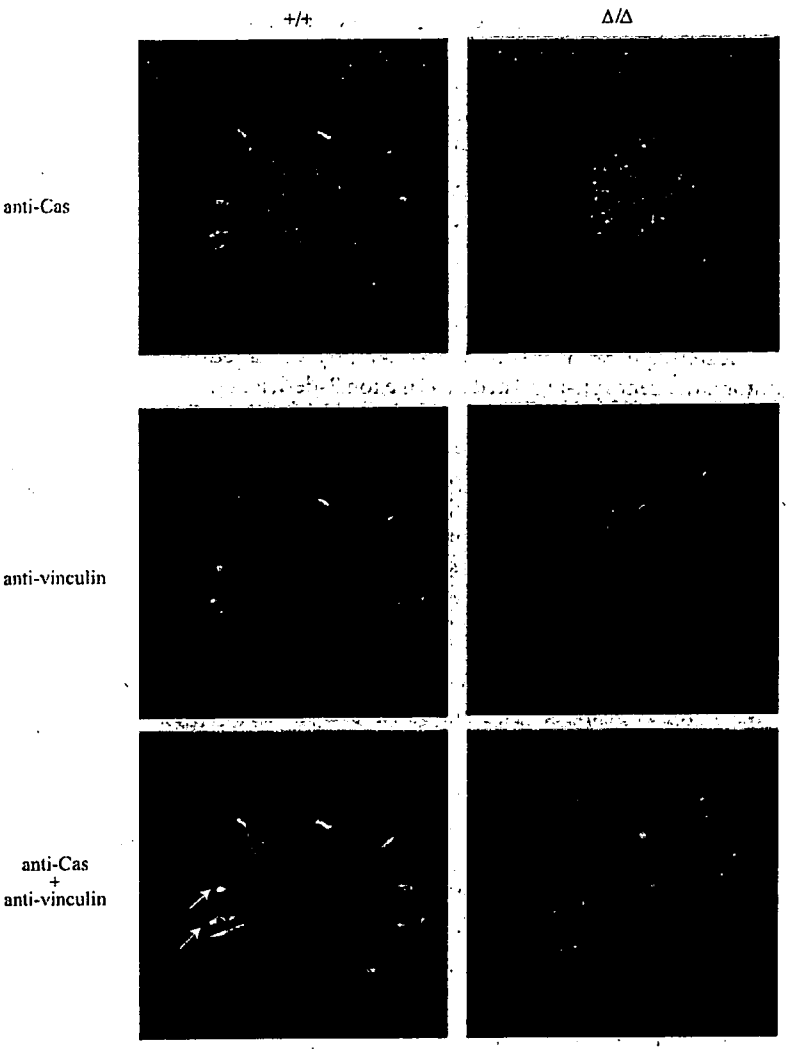

Figure 5 Cas exon 2 is required for the localization of Cas to focal adhesions upon FN stimulation. Cas exon $2^{+/+}$ and Cas exon $2^{\Delta/\Delta}$ cells grown on FN-coated coverslips were stained with anti-Cas and anti-vinculin (hVIN-1) antibodies. Texas red-labeled secondary antibody targeted the anti-Cas antibody and Fluorescein-labeled secondary antibody labeled the anti-vinculin antibody. Following FN stimulation, wild-type Cas was recruited to focal adhesions, as demonstrated by the yellow double staining pattern (left lower panel, indicated by *arrows*), whereas Cas Δexon 2 remained in the cytoplasm and did not concentrate at focal adhesions (right lower panel).

Cas exon 2 is required for the localization of Cas to focal adhesions upon FN stimulation

We compared the subcellular localization of wild-type Cas and Cas Δexon 2 in primary fibroblasts stimulated by FN. Cas exon $2^{+/+}$ and Cas exon $2^{\Delta/\Delta}$ cells grown on FN-coated coverslips were stained with an anti-Cas2. Anti-vinculin (hVIN-1) staining was also performed to identify focal adhesions. As shown in Fig. 5, following FN stimulation, wild-type Cas was recruited to focal adhesions as previously reported (Nakamoto *et al.* 1997), as demonstrated by the yellow double staining pattern (Fig. 5, left lower panel, indicated by *arrows*), whereas Cas Δexon 2 was retained mainly in the cytoplasm and was not concentrated at focal adhesions (Fig. 5, right lower panel). The results indicated that Cas exon 2 is required for the localization of Cas to focal adhesions upon FN stimulation.

The deficiency of Cas exon 2 up-regulated cell adhesion-associated genes including CXC Chemokine Receptor-4 (CXCR4), CC Chemokine Receptor-5 (CCR5) and thrombospondin 4 in primary fibroblasts

To further characterize the role of Cas exon 2 in intracellular signaling, we performed microarray analyses to investigate alterations in gene expression caused by Cas exon 2-deficiency. RNA samples extracted from Cas exon $2^{+/+}$, Cas exon $2^{+/\Delta}$ and Cas exon $2^{\Delta/\Delta}$ fibroblasts

(12.5 dpc, two embryos for each genotype) were subjected to microarray analysis as described in Experimental procedures. Gene expression patterns of Cas exon $2^{\Delta/\Delta}$ fibroblasts were compared with those of Cas exon $2^{+/+}$ and Cas exon $2^{+/\Delta}$ cells. The complete microarray data set is available from the gene expression omnibus (GEO) database (accession no. GSE8357). Expressed sequence tags were excluded and genes that showed more than a 3.0-fold change in expression are presented in Table 1. One interesting aspect of the result is that cell migration- and cell adhesion-associated genes, such as chemokine ligands/receptors and thrombospondin, were listed among the genes up-regulated by Cas exon 2-deficiency. We thus confirmed the up-regulation of these genes in Cas exon $2^{\Delta/\Delta}$ fibroblasts by quantitative real-time RT-PCR analysis. The results showed that the expression levels of three genes, CXCR4, CCR5 and thrombospondin 4, were significantly enhanced by Cas exon 2-deficiency. The changes in expression measured by microarray analysis correlated well with data from quantitative real-time RT-PCR analyses (Fig. 6). These results demonstrated that the loss of Cas exon 2 induced expression of CXCR4, CCR5 and thrombospondin 4, genes involved in cell motility in primary fibroblasts.

Phospho-IκBα level was augmented in Cas exon $2^{\Delta/\Delta}$ fibroblasts

We then examined the underlying molecular mechanism for the up-regulated expression of CXCR4 and CCR5 in Cas exon $2^{\Delta/\Delta}$ fibroblasts. It is already demonstrated that the extracellular signal-activated transcription factor nuclear factor-κB (NF-κB) regulates the expression of some chemokine ligands/receptors, including CXCR4 (Helbig *et al.* 2003; Kukreja *et al.* 2005) and CCR5 (Kim *et al.* 2006). Activation of NF-κB requires phosphorylation of IκBα. Thus, we compared phospho-IκBα levels between Cas exon $2^{+/+}$ and Cas exon $2^{\Delta/\Delta}$ fibroblasts. As shown in Fig. 7, the phosphorylation level of IκBα was significantly augmented in Cas exon $2^{\Delta/\Delta}$ cells as compared to Cas exon $2^{+/+}$ cells. These results indicated that that the NF-κB signaling pathway was activated by Cas exon 2 deficiency, which would play a role in up-regulated expression of CXCR4 and CCR5 in Cas exon $2^{\Delta/\Delta}$ fibroblasts.

Discussion

Cas is an adaptor molecule implicated in various biological processes, such as cell adhesion, cell migration, cell apoptosis, cell transformation and bacterial infection (Defilippi *et al.* 2006). Structurally, Cas is an adaptor

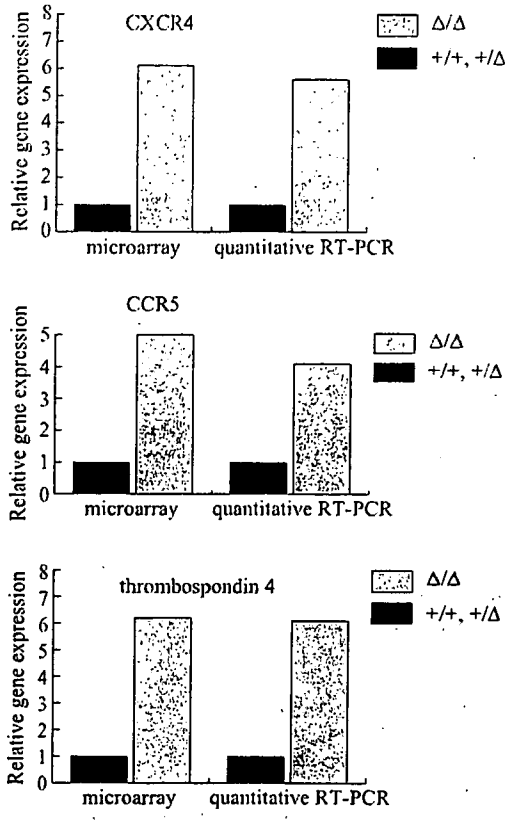

Figure 6 Up-regulated expression of CXCR4, CCR5 and thrombospondin 4 in Cas exon $2^{\Delta/\Delta}$ fibroblasts. RNA samples extracted from Cas exon $2^{+/+}$, Cas exon $2^{+/\Delta}$ and Cas exon $2^{\Delta/\Delta}$ fibroblasts (12.5 dpc, three embryos for each genotype) were used. The changes in expression levels determined by microarray (left) or quantitative real-time RT-PCR (right) are shown.

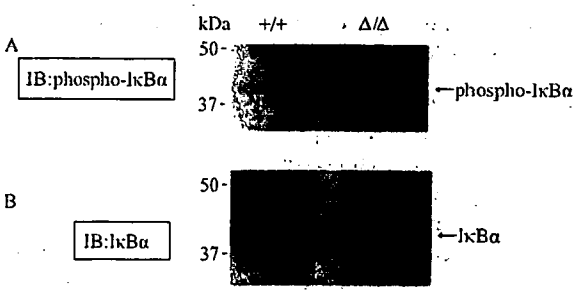

Figure 7 Increased phosphorylation of IκBα in Cas exon $2^{\Delta/\Delta}$ fibroblasts. Cas exon $2^{+/+}$ cells and Cas exon $2^{\Delta/\Delta}$ cells were harvested and lysed with 1% Triton lysis buffer. Equal amounts of total cell lysates were blotted with anti-phospho-IκBα (A) or an anti-IκBα (B).

Table 1 (A) Genes up-regulated in Cas exon $2^{\Delta/\Delta}$ fibroblasts

Fold change	Description	UniGene
46.72	Jumonji, AT rich interactive domain 1D (Rbp2 like)	Mm.262676
12.8	Chemokine (C–C motif) ligand 12	Mm.867
11.2	Killer cell lectin-like receptor, subfamily A, member 2	Mm.4783
7.812	SPARC-like 1 (mast9, hevin)	Mm.29027
6.172	Thrombospondin 4	Mm.20865
6.06	Chemokine (C–C motif) receptor 5	Mm.14302
5.988	Astrotactin 1	Mm.329586
5.714	EGF-like-domain, multiple 6	Mm.37707
5.263	Chemokine (C–C motif) ligand 3	Mm.1282
5.102	Chemokine (C–C motif) ligand 9	Mm.2271
5.025	Chemokine (C–X–C motif) receptor 4	Mm.1401
4.484	Lipoprotein lipase	Mm.1514
4.444	Carbonic anhydrase 2	Mm.1186
4.405	SLAM family member 7	Mm.164642
4.405	RAS-like, estrogen-regulated, growth-inhibitor	Mm.46233
4.149	Macrophage scavenger receptor 1	Mm.239291
4	Odd-skipped related 2 (*Drosophila*)	Mm.46336
3.984	X-linked lymphocyte-regulated 3a	Mm.195091
3.921	C-type lectin domain family 14, member a	Mm.280563
3.831	Schlafen 8	Mm.347694
3.802	Interferon activated gene 203	Mm.261270
3.623	G-protein coupled receptor 65	Mm.378924
3.584	Hepatitis A virus cellular receptor 2	Mm.72168
3.571	Sciellin	Mm.244003
3.333	Adrenomedullin receptor	Mm.2857
3.257	Matrix metalloproteinase 12	Mm.2055
3.236	Cytochrome b-245, β polypeptide	Mm.200362
3.205	Interferon, α-inducible protein 27	Mm.271275
3.195	Prostaglandin E receptor 2 (subtype EP2)	Mm.4630
3.185	Mannose receptor, C type 1	Mm.2019
3.175	Complement component 2 (within H-2S)	Mm.283217
3.155	C-type lectin domain family 4, member d	Mm.299633
3.115	Disabled homolog 2 (*Drosophila*)	Mm.240830

(B) Genes down-regulated in Cas exon $2^{\Delta/\Delta}$ fibroblasts

Fold change	Description	UniGene
−14.19	Xlr-related, meiosis regulated	Mm.14300
−14.17	Kallikrein 24	Mm.378954
−8.397	RIKEN cDNA E130012A19 gene	Mm.24506
−7.892	Vomeronasal 1 receptor, D7	Mm.160377
−7.051	RIKEN cDNA 4933413N12 gene	Mm.158581
−6.949	Probasin	Mm.8034
−6.489	Fibroblast growth factor 16	Mm.154768
−6.432	Phosphatidylinositol glycan, class H	Mm.281044
−5.785	Interleukin-1 receptor-associated kinase 4	Mm.279655
−5.717	RIKEN cDNA 4921517J23 gene	Mm.291129
−5.645	Forkhead box A1	Mm.4578
−5.54	RIKEN cDNA 4931406I20 gene	Mm.318331
−5.344	Phosphatase, orphan 1	Mm.133075
−5.058	RIKEN cDNA 1700020N01 gene	Mm.54306
−5.029	myosin, heavy polypeptide 1, skeletal muscle	Mm.340118

Continued overleaf

Table 1 *Continued*

Fold change	Description	UniGene
−4.676	Thyrotropin releasing hormone receptor	Mm.309350
−4.635	Elongation protein 4 homolog (*S. cerevisiae*)	Mm.33870
−4.213	Leukotriene A4 hydrolase	Mm.271071
−4.191	Serine dehydratase-like	Mm.5162
−4.171	Actin related protein M2	Mm.30958
−4.135	Component of Sp100-rs	Mm.362648
−4.058	RIKEN cDNA C230093N12 gene	Mm.4065
−3.843	Procollagen, type II, α1	Mm.2423
−3.734	Calcitonin receptor-like	Mm.75467
−3.528	SRY-box containing gene 10	Mm.276739
−3.46	Profilin 3	Mm.348015
−3.436	Defensin β7	Mm.207067
−3.329	Titin-cap	Mm.10762
−3.329	Melanocortin 3 receptor	Mm.57183
−3.311	Flavin containing monooxygenase 1	Mm.976
−3.271	RIKEN cDNA 2410017P07 gene	Mm.338605
−3.231	Transketolase-like 1	Mm.25057
−3.216	Expressed sequence AU041707	Mm.200898
−3.211	Chromobox homolog 1 (*Drosophila* HP1 β)	Mm.29055
−3.104	Deleted in azoospermia-like	Mm.280641
−3.045	Forkhead box G1	Mm.4704

molecule composed of SH3, SD and SBD (Fig. 1A), and exerts its biological function by interacting various intracellular molecules, such as FAK, CrkII and Src, through its different functional domains. In this paper, to primarily focus on the role of Cas SH3 in cellular function, we established and analyzed primary fibroblasts from mice that were engineered to produce truncated Cas lacking the exon 2-derived region containing the whole SH3 domain (Cas Δexon 2).

As expected from a previous study (Polte & Hanks 1995), we demonstrated that Cas Δexon 2 lost its ability to bind to FAK but retained the ability to bind to Src, irrespective of FN stimulation (Fig. 4A and B and data not shown). In addition, we found that upon FN stimulation, the binding activity of Cas Δexon 2 to CrkII was significantly reduced (Fig. 4C). This result seems curious since the YDXP motifs in the SD, that are the preferred binding site to the CrkII SH2 domain when phosphorylated (Songyang *et al.* 1993), are all conserved in Cas Δexon 2. To investigate the underlying mechanism, we analyzed tyrosine-phosphorylation of Cas between two types of cells. Upon FN stimulation, Cas was apparently tyrosine-phosphorylated in Cas exon $2^{+/+}$ cells as previously reported (Nojima *et al.* 1995), whereas we could not detect tyrosine-phosphorylation of Cas Δexon 2 in Cas exon $2^{\Delta/\Delta}$ cells (Fig. 4D). In addition, we examined tyrosine-phosphorylation of FAK, which is the primary event following integrin stimulation. Surprisingly, FAK was not tyrosine-phosphorylated in Cas exon $2^{\Delta/\Delta}$ cells (Fig. 4E). Furthermore, FAK/Src binding was not detected in Cas exon $2^{\Delta/\Delta}$ cells (Fig. 4E), probably owing to impaired tyrosine-phosphorylation of FAK. These results indicate that Cas exon 2 is essential for FAK auto-phosphorylation upon FN. This idea is in line with a previous study, in which Cas lacking SH3 failed to bind to CrkII, which subsequently abolished FAK/Cas/CrkII complex formation as well as FAK auto-phosphorylation by FN (Iwahara *et al.* 2004). The underlying mechanism for impaired tyrosine-phosphorylation of FAK in Cas exon $2^{\Delta/\Delta}$ cells remains unclear. One possibility is that the constitutive FAK/Cas binding might be essential for conformational change of FAK tyrosine-phosphorylation. Alternatively, the FAK/Cas complex formation might be required for FAK to keep the tyrosine-phosphorylated state. A previous study showed that CrkII knockdown reduces integrin-stimulated FAK Tyr397 autophosphorylation (Iwahara *et al.* 2004). Therefore, the Cas/CrkII complex may also affect tyrosine-phosphorylation of FAK as an upstream regulator in reverse (Iwahara *et al.* 2004).

We also compared the intracellular localization of Cas and Cas Δexon 2 upon FN stimulation. In contrast to Cas to be localized to focal adhesions as previously reported (Nakamoto *et al.* 1997), no clear localization of

Cas Δexon 2 at focal adhesions was found (Fig. 5). Impaired recruitment of Cas to focal adhesions following FN stimulation was reported in Src-deficient cells (Nakamoto *et al.* 1997), and Src can be regarded as a recruiting molecule of Cas to focal adhesions (Kaplan *et al.* 1995; Honda *et al.* 1999). Although Cas Δexon 2 and wild-type Cas have comparable binding abilities to bind Src (Fig. 4B), Cas Δexon 2 was not found in focal adhesions (Fig. 5), indicating that Cas exon 2 plays an essential role in the localization of Cas to focal adhesions upon FN stimulation. This idea is supported by our previous finding that Cas lacking SH3 failed to localize at focal adhesions on FN stimulation when expressed in COS-7 cells (Nakamoto *et al.* 1997). While the mechanism is not clear, one possibility is that when Cas Δexon 2 is recruited to focal adhesions by Src, FAK is not tyrosine-phosphorylated and cannot bind to Cas Δexon 2 and Src, which in turn would allow release of Cas Δexon 2 from focal adhesions. Another possibility is that the impaired FAK/Src complex leads to reduced activation of Src, which could not recruit Cas Δexon 2 to focal adhesions. It is possible that impaired tyrosine-phosphorylation of FAK and Cas leads to incomplete formation of FAK/Cas/Src/CrkII complex and impaired localization of Cas to focal adhesions, which resulted in delayed cell migration (Fig. 2) and spreading on FN (Fig. 3). A previous study using the Cas SD mutants and examining their ability to heal the wound revealed that the effective wound healing was achieved by Cas variants containing at least four of the YDXP/YAVP motifs, the major phosphorylation sites of Cas SD (Shin *et al.* 2004). Since YDXP/YAVP motifs, which serve main binding sites to CrkII, are all conserved in Cas exon $2^{\Delta/\Delta}$ cells (see Fig. 1A), it would be unlikely that the reduced motility is due to the lack of YLVP/YQXP motifs existing in exon 2. In addition, we found that the defects observed in Cas exon $2^{\Delta/\Delta}$ cells were less apparent than those in $Cas^{-/-}$ cells (Honda *et al.* 1999). The reason might be that since Cas exon $2^{\Delta/\Delta}$ cells retain the YDXP/YAVP motifs and the SBD as compared to $Cas^{-/-}$ cells, these domains would partly participate in downstream signaling. In fact, a slight amount of CrkII could bind to Cas upon FN stimulation (Fig. 4C).

To identify downstream molecules regulated by Cas exon 2, we investigated the expression profile of Cas exon $2^{\Delta/\Delta}$ fibroblasts using microarray methods (Table 1). Interestingly, we found that cell migration- and cell adhesion-associated genes, such as chemokine ligands/receptors and thrombospondin, were up-regulated by Cas exon 2 deficiency. We previously compared the expression profile of $Cas^{-/-}$ fibroblasts with that in Cas-re-expressing fibroblasts using the same methods (Nakamoto *et al.* 2002), but could not detect changes in expression of chemokine ligands/receptors and thrombospondins. Thus, the expression changes in these genes (chemokine ligands/receptors and thrombospondins) may be specifically regulated by Cas exon 2-mediated signals.

We also demonstrated that the phospho-IκBα level was augmented in Cas exon $2^{\Delta/\Delta}$ cells, indicating that the NF-κB signaling pathway was activated by Cas exon 2 deficiency (Fig. 7). Based on this result, it is conceivable that up-regulated expression of CXCR4 and CCR5 in Cas exon $2^{\Delta/\Delta}$ fibroblasts is, at least in part, dependent on IκBα phosphorylation. The mechanism underlying the activation of NF-κB signaling and up-regulated expression of CXCR4 and CCR5 is not clear. One possibility is that since the 5′-promoter region of FAK contains NF-κB binding sites, the NF-κB transcription factor might play a role in regulating FAK transcription (Golubovskaya *et al.* 2004). It would also be possible that NF-κB is activated to compensate for the impaired tyrosine-phosphorylation of FAK and FAK/Cas binding in Cas exon $2^{\Delta/\Delta}$ cells.

In summary, we demonstrated that Cas exon 2 plays an essential role in cell migration, cell spreading on FN, tyrosine-phosphorylation of FAK and Cas, FAK/Cas/Src/CrkII complex formation and recruitment of Cas to focal adhesions in primary fibroblasts. In addition, we showed that Cas exon 2-deficiency significantly up-regulated expression of CXCR4 and CCR5, molecules implicated in cell motility (Fig. 8). Our findings define the biological roles of Cas exon 2 and provide novel insights into Cas SH3 function in intracellular signaling.

Experimental procedures

Antibodies

A polyclonal antibody against Cas, anti-Cas2, was generated as previously described (Sakai *et al.* 1994). Antibodies against FAK, Src and CrkII were from Santa Cruz Biotechnology, Santa Cruz, CA, anti-phosphotyrosine antibody 4G10 was from Upstate Biotechnology, Lake Placid, NY and hVIN-1 was from Sigma, St. Louis, MO. Anti-IκBα and anti-phospho-IκBα were from Cell Signaling Technology, Danvers, MA. Anti-Fluorescein-labeled and Texas red-labeled secondary antibodies were from Invitrogen, Carlsbad, CA.

Cultivation of primary fibroblasts

Cas exon $2^{+/\Delta}$ mice were intercrossed and embryos at 12.5 dpc were collected. Heads and internal organs were used for genotyping and primary embryonic fibroblasts were isolated from the remaining of embryos and cultured in Dulbecco's modified Eagle's

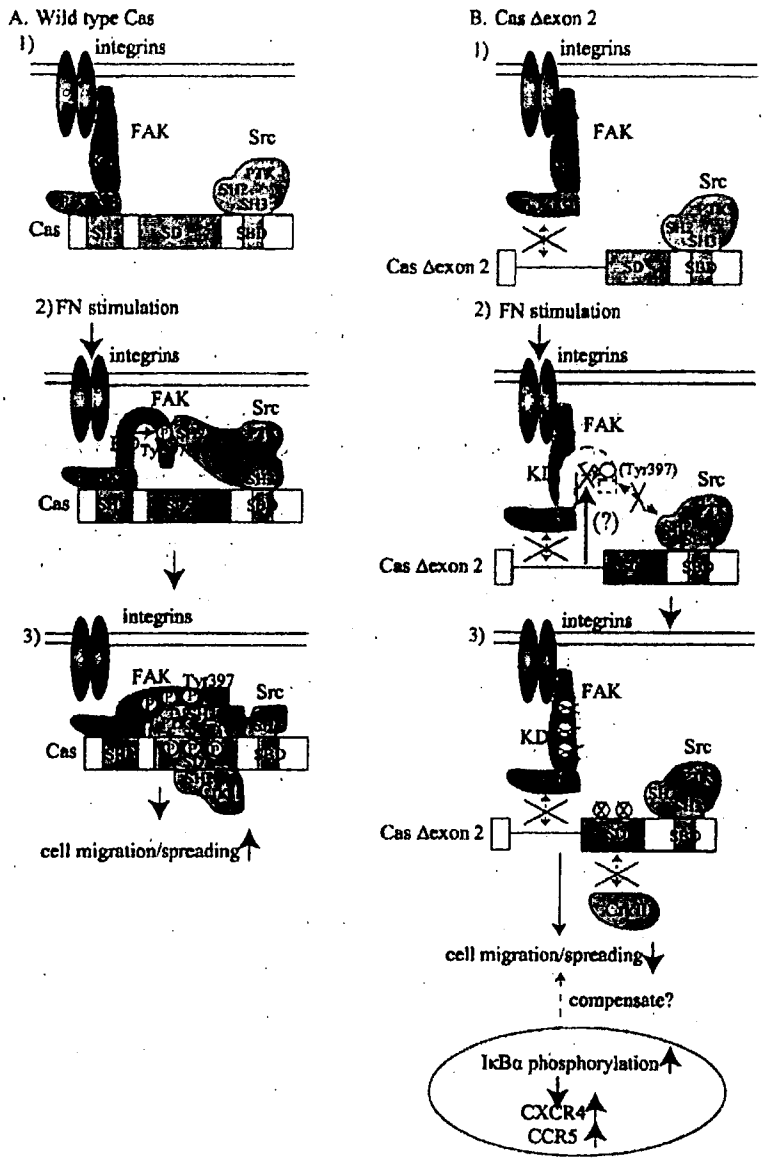

Figure 8 (A) Models for a signaling network involving wild-type Cas. (1) Cas binds to the proline-rich region of FAK through its SH3 domain and binds to the SH3 domain of Src through its Src binding domain (SBD) in unstimulated cells. (2) Upon FN stimulation, integrin clustering promotes FAK autophosphorylation at Tyr397, which creates a binding site for the SH2 domain of Src. (3) FAK/Src binding leads to the conformational activation of Src and results in an activated FAK/Src signaling complex. FAK/Cas binding and activated Src are linked to enhanced tyrosine-phosphorylation of Cas. Tyrosine-phosphorylated Cas binds to CrkII SH2 domain through the SD domain with preference for YDXP motifs and the Cas/CrkII complex plays a key role in cell migration/spreading. (B) Models for a signaling network involving Cas Δexon 2. (1) Cas Δexon 2 binds to Src but cannot bind to FAK in unstimulated cells because Cas binds to proline-rich region of FAK through its SH3 domain, which is missing from Cas Δexon 2. (2) Upon FN stimulation, FAK cannot be auto-phosphorylated by an unknown mechanism (possibly involving Cas SH3) and fails to bind to the SH2 domain of Src. Impaired FAK/Src complex leads to reduced activation of the FAK/Src signaling complex. (3) Because FAK is not tyrosine-phosphorylated and Src is not activated, Cas Δexon 2 cannot be tyrosine-phosphorylated and binding of CrkII to Cas Δexon 2 is impaired. Owing to impaired FAK/Cas/Src/CrkII complex, Cas exon 2-deficiency results in delay in cell migration/spreading. Cas exon 2-deficiency also enhances the expression of CXCR4 and CCR5, which may be dependent on IκBα phosphorylation. These factors may be up-regulated to compensate for the cellular functions affected by Cas exon 2-deficiency.

medium (DMEM) with 10% fetal bovine serum (FBS), penicillin (100 U/mL) and streptomycin (100 μg/mL) at 37 °C with 5% CO_2. Experiments were performed between three and five passages.

Immunoblotting and immunoprecipitation

Immunoblotting and immunoprecipitation were performed essentially as previously described (Huang *et al.* 2002). Proteins were extracted by lysing cells in ice-cold 1% Triton lysis buffer [50 mM Tris–HCl PH 8.0, 150 mM NaCl, 1% Triton X-100, 100 mM NaF, 1 mM Na_3VO_4]. For Western blotting, samples were separated by SDS-PAGE and probed with indicated antibodies. Positive signals were visualized with an enhanced chemiluminescence system (Amersham, Uppsala, Sweden). For immunoprecipitation, 500 μg protein aliquots were incubated with the indicated antibodies for 2 h at 4 °C and subsequently with Protein A-Sepharose (Invitrogen) for 1 h at 4 °C. Beads were washed 4 times with 1% Triton lysis buffer and boiled in sample buffer prior to SDS-PAGE analysis.

Cell stimulation with FN

Serum-starved cells were removed from the culture dishes by 0.05% trypsin treatment and were resuspended in DMEM. Culture dishes were coated overnight with 10 μg/mL FN (Chemicon, Temecula, CA) at 4 °C. The suspended cells were then plated on FN-coated dishes and incubated at 37 °C for various periods of time as described previously (Iwahara *et al.* 2004).

Wound healing cell migration assay

The wound healing cell migration assay was performed according to a method used previously (Honda *et al.* 1999). In brief, cells were first grown to confluence in plastic culture dishes, and a wound was made in the cell monolayer using a sterile micropipette tip. Then cells were washed 3 times with PBS and cultured at 37 °C in DMEM containing 10% FBS. Cell movement was assessed 3, 6, 9 and 12 h after wounding. The percentage of reduced distance between the nuclei of cells at each time period relative to the distance between two rims in the cleared field at the beginning was taken as the index.

Cell spreading assay

The cell spreading assay was performed as previously described (Honda *et al.* 1999). In brief, serum-starved cells were removed from the culture dishes by exposure to 0.05% trypsin–EDTA, and 2×10^5 cells in a volume of 1 mL DMEM were added to 35 mm tissue culture dishes coated with 10 μg/mL FN. The dishes were incubated at 37 °C for the indicated periods of time. Single cells that were phase-bright with rounded morphology were scored as non-spread, whereas those that possessed a flattened shape and looked phase-dark were scored as spread. The number of spread cells was calculated as percentage of the total cells in eight independent fields.

Immunofluorescence

Immunofluorescence was performed as previously described (Nakamoto *et al.* 1997). Cells were grown on FN-coated coverslips (Matsunami, Osaka, Japan) for 90 min. They were washed 3 times with phosphate-buffered saline (PBS) and fixed with 3.7% formaldehyde in PBS. The fixed cells were washed twice with PBS and permealized with 0.2% Triton-X in PBS. The cells were rinsed and then blocked in PBS plus 3% bovine serum albumin (Sigma). Primary antibodies were used at the following dilutions for 3 h at room temperature in a humidified chamber: 1 : 200 for anti-Cas2, and 1 : 200 for hVIN-1. The coverslips were washed 3 times with PBS and treated with secondary antibodies at the recommended dilutions. After three washes with PBS, the coverslips were mounted in a 1 : 2 mixture of glycerol and PBS. The cells were examined with a LSM5 PASCAL confocal microscopic system (Carl Zeiss, Germany).

Microarray analysis

Total RNA was extracted from primary fibroblasts using TRIzol Reagent (Invitrogen) according to the manufacturer's protocol. Two micrograms of total RNA from each sample were labeled using One-cycle Target Labeling and Control Reagents (Affymetrix, Santa Clara, CA) and hybridized with a GeneChip slide (Mouse Genome 430 2.0 Array, Affymetrix). Hybridization was performed at 45 °C for 16 h. After hybridization, slides were washed, dried and scanned using the GeneChip Scanner 3000 (Affymetrix). The array results were analyzed using GeneSpring (Agilent Technologies, Santa Clara, CA).

Quantitative real-time RT-PCR analysis

To confirm the differences in expression levels of the genes identified, we used fluorescent-based quantitative real-time RT-PCR with a TaqMan probe. RT-PCR was performed in 20 μL reaction mixtures containing 4 μL of 5 × LightCycler Taqman Master (Roche), 200 nM each primer and 100 nM Universal Probe-Library probe (Roche, Basel, Switzerland). Amplification reaction was carried out in a 384-well reaction plate in a spectrofluorimetric thermal cycler (ABI PRISM 7900 Sequence Detector, Applied Biosystems, Foster City, CA). A threshold cycle (Ct) for each sample was calculated by the point in which the fluorescence exceeded the threshold limit. To normalize the samples for loading total RNA equivalent, the second real-time PCR assay was performed targeting the 18S ribosomal RNA gene.

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Hyperphosphorylated Cortactin in Cancer Cell Plays an Inhibitory Role in Cell Motility

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Abstract

Cortactin is frequently overexpressed in cancer cells, and changes of the levels of its tyrosine phosphorylation have been observed in several cancer cells. However, how the expression level and phosphorylation state of cortactin would influence the ultimate cellular function of cancer cells is unknown. In this study, we analyzed the role of cortactin in gastric and breast cancer cell lines using RNA interference technique and found that knockdown of cortactin inhibited cell migration in a subset of gastric cancer cells with a lower level of its tyrosine phosphorylation, whereas it greatly enhanced cell migration and increased tyrosine phosphorylation of p130Cas in other subsets of cells with hyperphosphorylated cortactin. Consistent results were obtained when hyperphosphorylation of cortactin was induced in MCF7 breast cancer cells by expressing Fyn tyrosine kinase. Additionally, immunostaining analysis showed that knockdown of hyperphosphorylated cortactin resulted in the recruitment of p130Cas to focal adhesions. These results suggest that cortactin hyperphosphorylation suppresses cell migration possibly through the inhibition of membrane localization and tyrosine phosphorylation of p130Cas.

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Introduction

Protein phosphorylation by tyrosine kinases functions as a major switch in cellular biological signaling events through modulating protein-protein interaction and protein conformation. Substrates of Src family kinases (SFK) play essential roles in various cellular events by mediating tyrosine phosphorylation–dependent signals. Because cortactin was originally identified as a v-Src substrate, it has been shown to play a critical role in the organization of the cytoskeleton (1). The cortactin gene *EMS1* is located on chromosome 11q13, a region amplified in several cancers such as head and neck squamous carcinoma and breast cancer (2-6). Cortactin is a modular protein that contains several motifs and domains involved in protein-protein interactions. An NH_2-terminal acidic domain mediates its binding to Arp2/3, which regulates actin assembly, followed by an adjacency of six-and-a-half tandem repeats of 37 amino acids called cortactin repeats domain. There is a proline-rich domain immediately upstream of the SH3 domain, which also contains tyrosine residues phosphorylated by Src family kinases (7, 8). At the carboxyl terminus, there is a Src homology 3 (SH3) domain binding to several proteins, including cortactin binding protein1 (CortBP1/Shank2; ref. 9) and N-WASP (10). Cortactin is a substrate of tyrosine kinases, including SFKs, Fer, and Syk (11-13), and of serine/threonine kinases, including Erk and PAK (14, 15). Among the Src family, Fyn kinase seems to play a specific role in the cortactin function in some tumors because highly phosphorylated cortactin was shown to associate with Fyn kinase in metastatic murine melanoma in our previous study (16). However, how cortactin phosphorylation affects intercellular signaling pathways for cell dynamics control and other functions is not understood.

It has been shown that cell motility involves coordination of multiple signaling pathways regulating cell-substrate adhesion or actin polymerization (17, 18). A docking protein, p130Cas (Crk-associated substrate), is one of the key components of integrin-mediated signaling pathways, which conducts cell migration and actin filament reorganization in a tyrosine phosphorylation–dependent manner (19, 20). The COOH-terminal domain of p130Cas has both consensus SH3 and SH2 domains, binding sites for SFKs, which are mainly responsible for the phosphorylation of p130Cas (21).

In this study, we investigated the role of cortactin in human gastric cancer cell lines using RNA interference technique and discovered that knockdown of cortactin led to suppression of cell migration of the cells in which phosphorylation of cortactin is at basal level, whereas it increased cell migration of the cells in which cortactin is highly phosphorylated. It was also observed that knockdown of cortactin resulted in enhancement of cell motility of breast cancer cell line MCF7 in which phosphorylation level of cortactin was elevated by exogenously introduced Fyn kinase. In both cases, marked elevation in tyrosine phosphorylation of p130Cas was specifically and consistently observed by knockdown of hyperphosphorylated cortactin. We propose that tyrosine phosphorylation of cortactin may function as a molecular switch buffering the change in cell motility.

Results

Effect on Cortactin Knockdown on Cell Migration of Gastric Cancer Cells

Levels of tyrosine phosphorylation of cortactin were examined in human gastric cancer cell lines HSC57,

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HSC44As3, HSC44PE, and HSC58As9 established in National Cancer Center Research Institute, Japan (22), along with a breast carcinoma cell line MCF7 that possesses amplification of cortactin gene, *EMS1* (2). Expression of total cortactin was at similar levels (Fig. 1A, *bottom*), whereas there was a significant difference in tyrosine phosphorylation among these cell lines (Fig. 1A, *top*). HSC57, HSC44As3, and MCF7 cells exhibited a low level of tyrosine phosphorylation of cortactin, whereas HSC44PE and HSC58As9 showed hyperphosphorylation of cortactin as also indicated by the ratio of tyrosine-phosphorylated cortactin to total cortactin (Fig. 1A).

We knocked down cortactin expression by small interfering RNA (siRNA) to investigate the function of cortactin in the regulation of cell motility in various cancer cells using the Transwell assay. It was confirmed by immunoblotting that >80% of cortactin expression was down-regulated at 72 hours after initiation of siRNA treatment (Fig. 1B). Interestingly, knockdown of cortactin increased cell migration in HSC44PE and HSC58As9 cells with hyperphosphorylated cortactin, whereas it impaired cell motility in HSC57, Hsc44As3, and MCF7 cells with a low level of phosphorylated cortactin (Fig. 1C). Essentially similar effect on cell migration was seen by another siRNA, cort-siRNA2 (data not shown). To further confirm the migration-promoting effect of cortactin siRNA in HSC44PE cells, we expressed mouse cortactin (mcort-WT), which is well conserved to human cortactin by the retrovirus vector (4), along with the mutant mouse cortactin (mcort-Mut), which lacks all three putative tyrosine phosphorylation sites by exchanging tyrosine residues 421, 466, and 482 to phenylalanine (F421F466F482). Wild-type cortactin but not the mutant

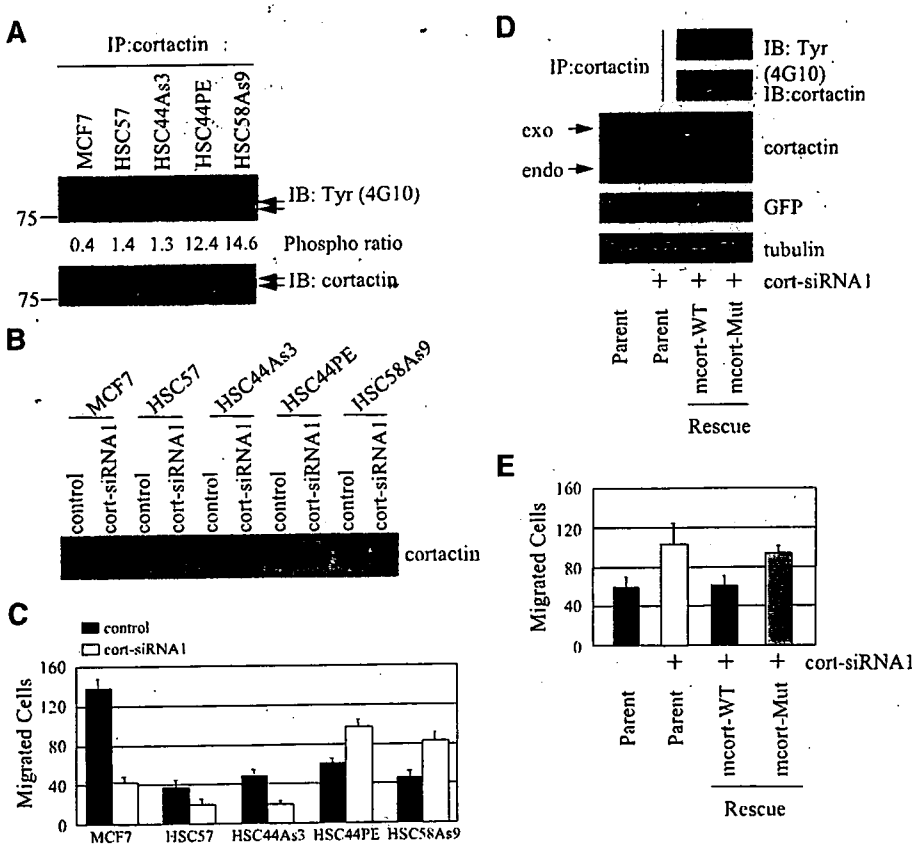

FIGURE 1. Changes in cell motility by knockdown of cortactin in gastric and breast cancer cells. **A.** To evaluate expression and tyrosine phosphorylation of cortactin, cell lysates of gastric and breast cancer cell lines were immunoprecipitated (*IP*) with anti-cortactin antibody (2 μg/mL), and immunoblotted by anti-phosphotyrosine antibody (4G10) and anti-cortactin antibody. Arrows, positions of cortactin isoforms (p85/80). MCF7, HSC57, and HSC44As3 cells exhibited a low level of tyrosine phosphorylation of cortactin, whereas HSC44PE and HSC58As9 showed hyperphosphorylation of cortactin. Quantification of tyrosine-phosphorylated cortactin is noted under the panel. Bottom, the expression of total cortactin. **B.** Amounts of cortactin in these cell lines at 72 h after siRNA treatment. **C.** Cell motility in various cancer cell lines was evaluated by numbers of migrated cells on the membrane. Knockdown of cortactin by siRNA led to inhibition of cell migration in HSC57, HSC44As3, and MCF7 cells with hypophosphorylated cortactin, whereas it resulted in increase of cell migration in HSC44PE and HSC58As9 cells with hyperphosphorylated cortactin. **D.** HSC44PE cells (*Parent*) and HSC44PE cells stably expressed mouse cortactin (*mcort-WT*) or F421F466F482 triple mutant of mouse cortactin (*mcort-Mut*) fused with GFP were treated with or without cortactin siRNA. Cells were lysed 72 h after treatment and immunoblotted for cortactin and GFP. The concentration of total proteins was confirmed by the same membrane rehybridized with anti–α-tubulin antibody. Cortactin siRNA down-regulates endogenous human cortactin (*endo*) but not exogenous mouse cortactins (*exo*). Tyrosine phosphorylation of mouse cortactins was analyzed by immunoprecipitation of total cortactin and immunoblotting with anti-phosphotyrosine antibody (4G10). The quantification of immunoprecipitated cortactin is shown in the bottom (*IB: cortactin*). **E.** Effect of the rescue of mouse cortactin expression on cell migration in cortactin knockdown HSC44PE cells were analyzed as described. Rescue of tyrosine-phosphorylated cortactin (*mcort-WT*) affected the inhibition of cell migration but nontyrosine-phosphorylated cortactin (*mcort-Mut*) did not.

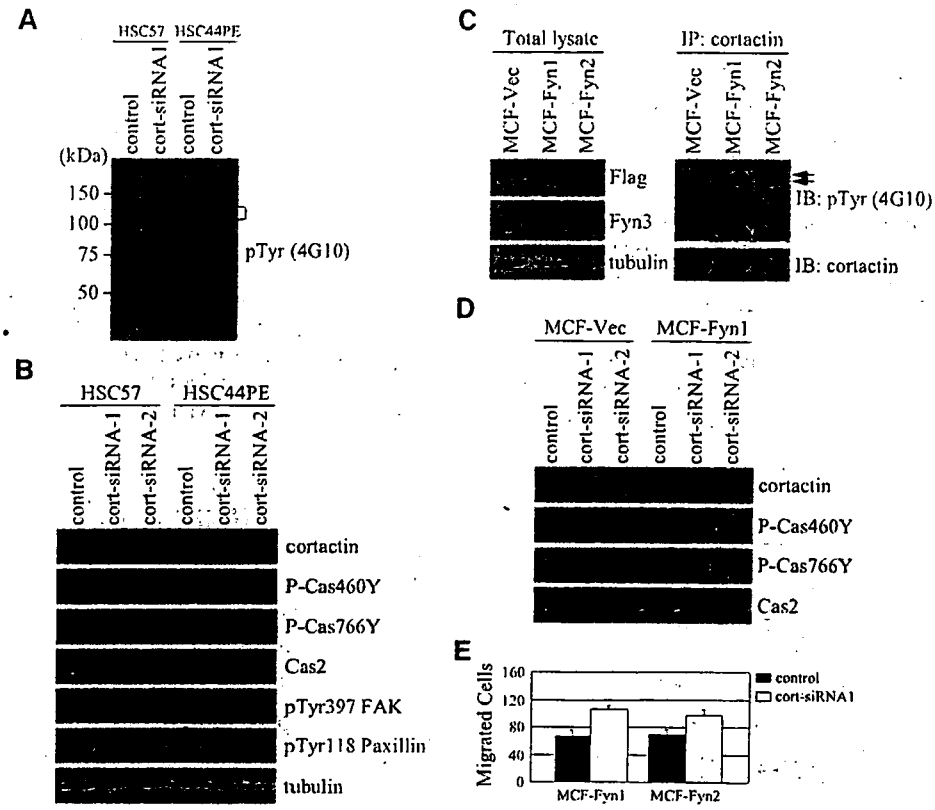

FIGURE 2. Analysis of cell motility in MCF clones with hyperphosphorylated cortactin. **A.** HSC57 and HSC44PE cells were treated with cortactin siRNA for 72 h; the whole-cell lysates were subjected to immunoblotting assay by antibody 4G10 to see phosphotyrosine-containing proteins. The phosphotyrosine-containing protein around 120 to 130 kDa was significantly enhanced (*square bracket*). **B.** Marked elevation of phosphorylation of p130Cas at tyrosine 460 and tyrosine 766 in HSC44PE cells was confirmed by specific anti-phospho-Cas antibodies (P-Cas460Y and P-Cas766Y) using two independent cortactin siRNAs. Immunoblotting by anticortactin, anti-Cas2, anti-phospho-FAK (Tyr^{397}), anti-phospho-paxillin (Tyr^{118}), and anti-tubulin antibodies are also shown. **C.** Stable clones of MCF7 cells expressing Flag-tagged Fyn kinase (MCF-Fyn1 and MCF-Fyn2) or vector alone (MCF-Vec) were established (see Materials and Methods). Left, immunoblotting by anti-Flag, anti-Fyn3, and anti-tubulin antibodies to show high expression of Flag-Fyn in these clones. Right, the tyrosine phosphorylation of cortactin was markedly induced in MCF-Fyn1 and MCF-Fyn2 clones with no significant change in total cortactin expression. **D.** The enhancement of phosphorylation of p130Cas at tyrosine 460 and tyrosine 766 in MCF-Fyn1 cells treated with two independent cortactin siRNAs was confirmed by specific anti-phospho-Cas antibodies (P-Cas460Y and P-Cas766Y). **E.** The effect of cortactin siRNA on cell migration of MCF7-Fyn clones was analyzed as described.

cortactin could block the elevation of cell migration induced by siRNA of cortactin in HSC44PE cells, suggesting that cortactin is actually suppressing migration of HSC44PE cells in a tyrosine phosphorylation–dependent manner. These results indicate that cortactin might differentially exert negatively and positively regulating functions in cell migration depending on its tyrosine phosphorylation.

Cortactin was originally identified as a substrate of SFKs. Among SFKs expressing in solid tumor cells, Fyn kinase was shown to play central roles in the tyrosine phosphorylation of cortactin in murine melanoma cells in our previous study (16). Treatment by a Src family specific inhibitor PP2 significantly reduced tyrosine phosphorylation of cortactin in HSC44PE cells (Supplementary Fig. S1A), suggesting that Src family kinases are actually responsible for tyrosine phosphorylation of cortactin in HSC44PE cells. Relatively high expression of Fyn kinase along with stable association between Fyn and cortactin was observed in HSC44PE cells (Supplementary Fig. S1B and S1C), suggesting the possibility that Fyn kinase is involved in hyperphosphorylation of cortactin in HSC44PE cells.

Knockdown of Cortactin Enhanced Tyrosine Phosphorylation of p130Cas in the Cells with Hyperphosphorylation of Cortactin

By knockdown of cortactin, tyrosine phosphorylation of a 125 to 130 kDa protein was remarkably enhanced in HSC44PE cells but not in HSC57 cells (Fig. 2A). In HSC44PE cells treated with cortactin siRNA, dramatically increased tyrosine phosphorylation of p130Cas was observed using phosphospecific antibody of p130Cas (P-Cas460Y) at the exactly same position where the 125 to 130 kDa protein was detected by 4G10 (Fig. 2B), whereas anti-phospho-FAK (Tyr^{397}) and phospho-paxillin (Tyr^{118}) antibodies failed to detect a significant change of phosphorylation state (Fig. 2B). We also generated another phosphospecific antibody against p130Cas (P-Cas766Y; see Materials and Methods), and found consistent elevation in tyrosine phosphorylation of p130Cas by P-Cas766Y antibody in HSC44PE cells treated with two independent siRNAs for cortactin (Fig. 2B). On the other hand, the level of phosphorylation of p130Cas was not significantly elevated in HSC57 cells (Fig. 2B). There were no clear changes