Leukemogenic kinase FIP1L1-PDGFRA and a small ubiquitin-like modifier E3 ligase, PIAS1, form a positive cross-talk through their enzymatic activities

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Key words
FIP1L1-PDGFRA, leukemogenesis, phosphorylation, PIAS1, sumoylation

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Funding Information
Japan Society for the Promotion of Science (Kakenhi grant nos. 25461404 [to T.K.] and 26890001 [to M.O.]) and by a research fund from the North Japan Hematology Study Group.

Received August 31, 2016; Revised November 21, 2016; Accepted November 30, 2016

Cancer Sci | 2017 | vol. 108 | no. 2 | 200–207
doi: 10.1111/cas.13129

Post-translational modifications are intrinsic for numerous cellular processes. One such post-translational modification is sumoylation, through which the small ubiquitin-like modifier (SUMO) protein is covalently attached to lysine residues in target proteins. Sumoylation regulates the functional roles of target proteins, such as subcellular localization, protein stability, protein–protein interactions, and activities of transcriptional factors. Similar to the ubiquitin system, SUMO attachment to a substrate passes through three enzymatic steps: catalysis by a SUMO E1-activating enzyme, a SUMO E2-conjugating enzyme, and a SUMO E3 ligase. A SUMO E3 ligase mediates an E2 enzyme and specific substrates, and it facilitates SUMO transfer.1,2 One of the representative E3 enzymes is protein inhibitor of activated signal transducer and activator of transcription (STAT)1 (PIAS1), which was initially isolated as a molecule that interacts with activated STAT1 and inhibits STAT1-mediated gene activation.3 Although PIAS1 regulates many transcriptional factors associated with cytokine signaling, PIAS1 also controls molecules that play crucial roles in cell proliferation and oncogenesis.4

Fusion tyrosine kinases play a crucial role in the development of hematological malignancies. FIP1L1-PDGFRA is a leukemogenic fusion kinase that causes chronic eosinophilic leukemia. As a constitutively active kinase, FIP1L1-PDGFRA stimulates downstream signaling molecules, leading to cellular proliferation and the generation of an anti-apoptotic state. Contribution of the N-terminal FIP11 portion is necessary for FIP11-PDGFRA to exert its full transforming activity, but the underlying mechanisms have not been fully characterized. We identified PIAS1 as a FIP11-PDGFRA association molecule by yeast two-hybrid screening. Our analyses indicate that the FIP11 portion of FIP11-PDGFRA is required for efficient association with PIAS1. As a consequence of the association, FIP11-PDGFRA phosphorylates PIAS1. Moreover, the kinase activity of FIP11-PDGFRA stabilizes PIAS1. Therefore, PIAS1 is one of the downstream targets of FIP11-PDGFRA. Moreover, we found that PIAS1, as a SUMO E3 ligase, sumoylates and stabilizes FIP11-PDGFRA. In addition, suppression of PIAS1 activity by a knockdown experiment resulted in destabilization of FIP11-PDGFRA. Therefore, FIP11-PDGFRA and PIAS1 form a positive cross-talk through their enzymatic activities. Suppression of sumoylation by ginkgolic acid, a small molecule compound inhibiting a SUMO E1-activating enzyme, also destabilizes FIP11-PDGFRA, and while the tyrosine kinase inhibitor imatinib suppresses FIP11-PDGFRA-dependent cell growth, ginkgolic acid or siRNA of PIAS1 has a synergistic effect with imatinib. In conclusion, our results suggest that sumoylation by PIAS1 is a potential target in the treatment of FIP11-PDGFRA-positive chronic eosinophilic leukemia.

Another post-translational modification is phosphorylation. Many tyrosine kinases are stimulated by growth factors, and the activation of tyrosine kinases leads to cell proliferation. In addition, these kinases are closely associated with cancer development.5 The fusion tyrosine kinase FIP11-PDGFRA was identified from patients with idiopathic hypereosinophilic syndrome.6,7 This fusion gene has been observed in 10–20% of patients with eosinophilia and, therefore, eosinophilia with FIP11-PDGFRA is now diagnosed as chronic eosinophilic leukemia (CEL) according to the WHO disease classification.8–13 This fusion kinase is constitutively active and its kinase activity is essential for cellular transformation.6,7,14–16 As proliferation of CEL cells is dependent on the kinase activity of FIP11-PDGFRA, imatinib, which was originally developed for treatment of CML but also inhibits the kinase activity of PDGFRA, is also effective for patients with CEL.6,8,9,11,12 As a leukemogenic fusion kinase, FIP11-PDGFRA stimulates downstream effectors. Some effector molecules, including phosphatidylinositol 3-kinase, ERK1/2, JNK, p38 MAPK, JAK2, STAT5, protein kinase B (PKB/c-akt), and...
Src-homology 2 domain-containing phosphatase 2, have been identified in the context of leukemic transformation.\(^{(15,17–20)}\) Although the C-terminal kinase portion of FIP1L1-PDGFRα is essential for activation of downstream substrates, the N-terminal FIP1L1 portion also plays a crucial role in cellular transformation. The FIP1L1 portion is necessary for the transforming activity of human primary hematopoietic progenitor cells in which the FIP1L1 portion is indispensable for activation of STAT5 and PKB/c-akt.\(^{(15)}\) In addition, full-length FIP1L1-PDGFRα accumulates in the nucleus and has a higher proliferating activity than that of the C-terminal PDGFRα portion of FIP1L1-PDGFRα.\(^{(16)}\) Based on these reports, it is thought that the FIP1L1 portion directs FIP1L1-PDGFRα into the nucleus and plays a crucial role in the development of CEL. However, little is known about the transforming pathway mediated by the FIP1L1 portion.

We have therefore tried to characterize a molecule interacting with FIP1L1-PDGFRα to elucidate the leukemogenic role of the FIP1L1 portion, and we isolated PIAS1 as a FIP1L1-PDGFRα association molecule. Our data show that there is a positive cross-talk between FIP1L1-PDGFRα and PIAS1. FIP1L1-PDGFRα phosphorylates and stabilizes PIAS1. PIAS1 sumoylates and stabilizes FIP1L1-PDGFRα. The reciprocally positive interaction between FIP1L1-PDGFRα and PIAS1 through different activities could be crucial for the transforming activity of FIP1L1-PDGFRα. Moreover, the sumoylation system by PIAS1 could be a potential target in the treatment of FIP1L1-PDGFRα-positive CEL.

**Materials and Methods**

**Plasmid construction.** Flag-tagged or T7-tagged expression vectors of full-length FIP1L1-PDGFRα (FIP1L1-PDGFRα-FL), a kinase-dead mutant of FIP1L1-PDGFRα (FIP1L1-PDGFRα-KD), and a deletion mutant with only the C-terminal portion of PDGFRα (PDGFRα-C) have been described previously. These vectors are named pFLAG-FIP1L1-PDGFRα, pFLAG-FIP1L1-PDGFRα-KD, pCGT-FIP1L1-PDGFRα-FL, pCGT-FIP1L1-PDGFRα-KD, and pCGT-PDGFRα-C, respectively. For yeast two-hybrid screening, full-length FIP1L1-PDGFRα cDNA was cloned into pBTM116 (Clontech, Mountain View, CA, USA) and named pBTM116-FIP1L1-PDGFRα. Full-length human PIAS1 cDNA was amplified by PCR and cloned into a pCI-neo-6×Myc expression vector that had been generated by inserting human PIAS1 cDNA into a pCI-neo-6×Myc vector that had been generated by inserting a fragment containing six copies of the Myc epitope into pCI-neo (Promega, Madison, WI, USA). The vector was named pCI-6×Myc-PIAS1. A 6×Myc-tagged expression vector of PIAS1 mutant lacking SUMO-E3 ligase activity was generated by introducing a cysteine-to-serine mutation at amino acid position 351 of PIAS1, by means of site-directed mutagenesis. The 6×Myc-tagged PIAS1 was amplified by PCR and cloned into the pTRE3G-ZsGreen1 (Clontech) vector for a tetracycline-inducible system (Clontech, Mountain View, CA, USA) and then cultured for 36–48 h and subsequently subjected to analysis. The amount of the transfected vector was determined by adjusting the expression level of the product. A tetracycline-inducible vector [Clontech] was used to analyze the stability of PIAS1. pTRE3G-Myc-PIAS1 and pCMV-Tet3G were cotransfected into HEK293 cells with either pFLAG-FIP1L1-PDGFRα-FL or pFLAG-FIP1L1-PDGFRα-KD. After 4 h, the cells were divided into four culture dishes and cultured with fresh media. Cells in one dish were cultured without doxycycline, and cells in the other three dishes were cultured with 1 μg/mL doxycycline. After 24 h of incubation, the culture media were replaced with fresh media without doxycycline, and this point was set as the starting time. The cells were then harvested after 24 h and the cell lysates were subjected to immunoblotting. To establish an HEK293-derived stable cell line expressing FIP1L1-PDGFRα, HEK293 cells were transfected with pFLAG-FIP1L1-PDGFRα-FL. After 2 days of transfection, the cells were selected with 500 μg/mL G418 (Sigma, St. Louis, MO, USA). The established cell line, HEK293-FIP1L1-PDGFRα-FL, was used for a knockdown experiment. For RNA interference, siRNAs for human PIAS1 (Stealth RNAi VHS41400 and VHS41401) and for murine PIAS1 (Stealth RNAi MSS242277 and MSS285778) and a negative control (#12935-200) were purchased from Invitrogen. To establish BAF-B03-derived stable cell lines expressing FIP1L1-PDGFRα and its mutants, we used the retrovirus packaging kit Eco (TaKaRa). BAF-B03 cells were infected with pDON-FLAG-FIP1L1-PDGFRα-FL or each mutant of FIP1L1-PDGFRα, and the cells were selected with 500 μg/mL G418. Ginkgoic acid was purchased from Calbiochem (San Diego, CA, USA) and used for an experiment to inhibit sumoylation. Imatinib was a kind gift from Novartis and was used to inhibit the kinase activity of FIP1L1-PDGFRα.

**Immunoprecipitation, immunoblotting, and immunostaining.** Anti-FLAG M2 antibody and anti-β-actin antibody (AC-15) were purchased from Sigma, anti-T7 tag antibody (PM022) and anti-Myc antibody (PL14) were from Medical and Biological Laboratories, anti-T7 tag antibody was from Novartis (Basel, Switzerland), anti-phosphotyrosine antibody (PY-20) was from Beckman Coulter (Fullerton, CA, USA), anti-PDGFRα antibody (#3164) was from Cell Signaling (Danvers, MA, USA), and anti-PIAS1 antibodies (ab32219 and ab77231) were from Abcam (Cambridge, UK). For immunoblotting, the cells were lysed in RIPA buffer (50 mM
Tris–HCl (pH 8.0), 150 mM NaCl, 1% NP-40, 0.1% SDS, and 0.5% sodium deoxycholate) supplemented with 10 mM N-ethylmaleimide, 5 μg/mL aprotinin, 5 μg/mL leupeptin, 1 mM NaF, and 0.5 mM Na3VO4. Immunoprecipitation and immunoblotting were carried out as previously described.(23) Briefly, whole cell lysates were immunoprecipitated with the indicated antibody, and the immunoprecipitates were washed with RIPA buffer. Proteins were separated by SDS-PAGE and transferred to nitrocellulose membranes. Immunoblot signals were detected by ECL. Prime Western blotting detection reagent and ImageQuant LAS4000 mini system (GE Healthcare, Buckinghamshire, UK), and the band intensity was quantified using ImageQuant TL software (GE Healthcare).

For immunostaining, HEK293 cells were transfected with pCGT-FIP1L1-PDGFRA-FL or pCGT-PDGFRA-C. After 2 days, the cells were fixed with 3.7% formaldehyde and incubated with anti-PIAS1 antibody (ab32219) and anti-T7 antibody (Novagen) as primary antibodies and then incubated with Alexa Fluor 488 anti-mouse antibody and Alexa Fluor 594 anti-rabbit antibody (Life Technologies, Palo Alto, CA, USA). For DNA staining, fixed cells were stained with DAPI. Fluorescent images were acquired with an FV-10i confocal microscope (Olympus, Tokyo, Japan) and analyzed with Metamorph software (Universal Imaging, Downingtown, PA, USA).

Apoptosis assay. BAF-derived cells were treated with imatinib and/or ginkgolic acid at the indicated concentrations for 24 h. Induction of apoptosis was quantitated using the MEB-CYTO Apoptosis Kit (Medical and Biological Laboratories). Briefly, the cells (2 × 10^5) were collected, washed with PBS, and suspended in 90 μL binding buffer (containing 10 μL annexin V–FITC and 1 μL of 100 μg/mL DAPI). The samples were incubated in the dark for 15 min at room temperature and then analyzed by FACSCanto II (Beckton Dickinson, Franklin Lakes, NJ, USA) after addition of 400 μL binding buffer.

Results

FIP1L1-PDGFRA associates with PIAS1. To identify an intracellular protein that interacts with FIP1L1-PDGFRA, yeast two-hybrid screening was initially carried out, and 18 colonies were obtained from 3 × 10^6 library transformants. One of them was found to encode murine PIAS1. First, we examined whether PIAS1 could associate with FIP1L1-PDGFRA in mammalian cells. We transfected the FLAG-tagged expression vector of FIP1L1-PDGFRA-FL or PDGFRA-C into HEK293 cells. As shown in Figure 1(a), FIP1L1-PDGFRA-FL associated with a limited amount of endogenous PIAS1, with less than 1% of input PIAS1 being co-immunoprecipitated with FIP1L1-PDGFRA-FL. PDGFRA-C also associated with PIAS1, but the amount of PIAS1 associated with PDGFRA-C was much less than that with FIP1L1-PDGFRA-FL. These results suggest that the FIP1L1 portion is required for efficient association between FIP1L1-PDGFRA and PIAS1. Therefore, we examined the intracellular localization of FIP1L1-PDGFRA and PIAS1 by using confocal microscopy, as previous studies showed that PIAS1 is a nuclear protein and that FIP1L1-PDGFRA accumulates in the nucleus.(16,21) FIP1L1-PDGFRA-FL efficiently colocalized with PIAS1 in the nucleus, whereas PDGFRA-C predominantly localized in the cytoplasm.
(Fig. 1b). These results suggest that FIP1L1-PDGFRA associated with PIAS1 through the PDGFRA portion but that the FIP1L1 portion is necessary for efficient association with PIAS1 because of the nuclear accumulation of FIP1L1-PDGFRA directed by the FIP1L1 portion.

FIP1L1-PDGFRA phosphorylates PIAS1 on tyrosine residues and increases the stability of PIAS1. Immunoblotting of PIAS1 associated with FIP1L1-PDGFRA-FL resulted in slow migration of PIAS1 (Fig. 1a). Therefore, we next examined whether kinase activity of FIP1L1-PDGFRA is required for association between FIP1L1-PDGFRA and PIAS1 and whether FIP1L1-PDGFRA phosphorylates PIAS1. As shown in Figure 2(a), both FIP1L1-PDGFRA-FL and FIP1L1-PDGFRA-KD associated with PIAS1, and PIAS1 that associated with FIP1L1-PDGFRA-FL migrated more slowly than PIAS1 that associated with FIP1L1-PDGFRA-KD. These results raise the possibility that FIP1L1-PDGFRA phosphorylates PIAS1 on tyrosine residues.

To examine this possibility, Myc-tagged PIAS1 was coexpressed with FIP1L1-PDGFRA or its mutants in HEK293 cells, and phosphorylation of PIAS1 on tyrosine residues was analyzed using an anti-phosphotyrosine antibody. As a result, PIAS1 was phosphorylated on tyrosine residues by FIP1L1-PDGFRA-FL but not by FIP1L1-PDGFRA-KD or PDGFRA-C (Fig. 2b). Although PDGFRA-C is kinase-active and weakly associated with PIAS1 (Fig. 1a), tyrosine phosphorylation of PIAS1 was not detected (Fig. 2b, lane 3). This result suggests that the FIP1L1 portion is required not only for efficient association between FIP1L1-PDGFRA and PIAS1 but also for tyrosine phosphorylation of PIAS1 by FIP1L1-PDGFRA.

While examining the association between FIP1L1-PDGFRA and PIAS1, we noticed that the amount of PIAS1 associated with FIP1L1-PDGFRA was greater in cells expressing FIP1L1-PDGFRA-FL than in cells expressing FIP1L1-PDGFRA-KD. Moreover, transient expression experiments, in which expression vectors of FIP1L1-PDGFRA and PIAS1 were transfected, showed that the expression level of PIAS1 tended to be higher in cells cotransfected with FIP1L1-PDGFRA-FL than in cells cotransfected with FIP1L1-PDGFRA-KD. These results indicate the possibility that...
**Fig. 3.** Small ubiquitin-like modifier E3 ligase PIAS1 sumoylates and stabilizes leukemogenic kinase FIP1L1-PDGFRA. (a) FIP1L1-PDGRA is sumoylated by PIAS1. HEK293 cells were transfected with a combination of pCI-6xMyc-PIAS1, pFLAG-FIP1L1-PDGFRA-FL, and pCGT-SUMO-1. The total amount of transfected vectors was 6 μg, with 2 μg each vector used and empty vector used as a mock. FLAG-FIP1L1-PDGFRA was detected by anti-PDGFRA antibody and Myc-PIAS1 was detected by anti-Myc antibody. FIP1L1-PDGFRA was immunoprecipitated with anti-FLAG M2 antibody and subsequently analyzed by immunoblotting. Sumoylation of FIP1L1-PDGFRA was detected by anti-T7 antibody. (b) Knockdown of PIAS1 by siRNA attenuated sumoylation of FIP1L1-PDGFRA. HEK293 cells were transfected with pFLAG-FIP1L1-PDGFRA-FL and/or pCGT-SUMO-1 and/or human PIAS1-specific siRNA. Decreased expression of endogenous PIAS1 by siRNA was confirmed by anti-PIAS1 antibody. Decreased expression of FIP1L1-PDGFRA was observed in transfected cells that did not express exogenous PIAS1 or expressed PIAS1-C351S instead of wild-type PIAS1 (Fig. 3a, lane 5). Sumoylation of FIP1L1-PDGFRA was observed when ligase-mutant PIAS1-C351S was expressed (Fig. 3a, lane 4). This effect was not observed when ligase-mutant PIAS1-C351S was expressed instead of wild-type PIAS1 (Fig. 3a, lane 5). Sumoylation of FIP1L1-PDGFRA was observed in transfected cells that did not express exogenous PIAS1 or expressed PIAS1-C351S (Fig. 3a, lanes 3 and 5). To examine the effect of endogenous PIAS1, we undertook a knockdown experiment. When the expression of PIAS1 was suppressed by PIAS1-specific siRNA, sumoylation of FIP1L1-PDGFRA-FL decreased (Fig. 3b), indicating that PIAS1 acts as a SUMO E3 ligase of FIP1L1-PDGFRA.

As one of the physiological roles of sumoylation is regulation of protein stability, we hypothesized that PIAS1 regulates the stability of FIP1L1-PDGFRA. To prove this hypothesis, we inhibited the expression of PIAS1 in BAF-FIP1L1-PDGFRA-FL cells by transfecting PIAS1-specific siRNA. As a consequence of the inhibition of PIAS1, the expression level of FIP1L1-PDGFRA was decreased (Fig. 3c, left panel, lanes 2 and 3). Based on this result, the downregulation of FIP1L1-PDGFRA may also affect the expression level of PIAS1 in imatinib-resistant BAF-FIP1L1-PDGFRA-KD cells, which were cultured in the presence of IL-3, was not affected by treatment with imatinib. Moreover, the expression level of PIAS1 in imatinib-resistant BAF-FIP1L1-PDGFRA-KD cells was also not changed by treatment with imatinib. Collectively, the results suggest that FIP1L1-PDGFRA stabilizes PIAS1 through its kinase activity.

**PIAS1 sumoylates and stabilizes FIP1L1-PDGFRA.** As PIAS1 is a SUMO E3 ligase, we next examined whether PIAS1 sumoylates FIP1L1-PDGFRA. When PIAS1, FIP1L1-PDGFRA, and SUMO1 expression vectors were cotransfected into HEK293 cells, FIP1L1-PDGFRA was efficiently sumoylated (Fig. 3a). Enforced expression of PIAS1 enhanced sumoylation of FIP1L1-PDGFRA (Fig. 3a, lane 4). This effect was not observed when ligase-mutant PIAS1-C351S was expressed instead of wild-type PIAS1 (Fig. 3a, lane 5). Sumoylation of FIP1L1-PDGFRA was observed in transfected cells that did not express exogenous PIAS1 or expressed PIAS1-C351S (Fig. 3a, lanes 3 and 5). To examine the effect of endogenous PIAS1, we undertook a knockdown experiment. When the expression of PIAS1 was suppressed by PIAS1-specific siRNA, sumoylation of FIP1L1-PDGFRA-FL decreased (Fig. 3b), indicating that PIAS1 acts as a SUMO E3 ligase of FIP1L1-PDGFRA. As a consequence of the inhibition of PIAS1, the expression level of FIP1L1-PDGFRA was decreased (Fig. 3c, left panel, lanes 2 and 3). Based on this result, the downregulation of FIP1L1-PDGFRA may also affect the expression level of PIAS1 in imatinib-resistant BAF-FIP1L1-PDGFRA-KD cells, which were cultured in the presence of IL-3, was not affected by treatment with imatinib. Moreover, the expression level of PIAS1 in imatinib-resistant BAF-FIP1L1-PDGFRA-KD cells was also not changed by treatment with imatinib. Collectively, the results suggest that FIP1L1-PDGFRA stabilizes PIAS1 through its kinase activity.

FIP1L1-PDGFRA stabilizes PIAS1 through its kinase activity. To analyze the stability of PIAS1, we used a tetracycline-inducible expression system. After induction of PIAS1 by doxycycline, the culture medium was changed to a fresh medium without doxycycline in the presence or absence of imatinib, a tyrosine kinase inhibitor (Fig. 2c). The expression of PIAS1 was efficiently induced when FIP1L1-PDGFRA-FL was coexpressed (Fig. 2c, left panel); however, the kinase activity was suppressed and the expression level of PIAS1 was rapidly decreased by the addition of imatinib. In addition, the expression level of PIAS1 was not affected by imatinib when PIAS1 was coexpressed with FIP1L1-PDGFRA-FL, BAF-FIP1L1-PDGFRA-KD, and BAF-FIP1L1-PDGFRA-T674I, with imatinib (Fig. 2d). As previously described, parental BAF-B03 cells are IL-3-dependent pro-B cells, which become IL-3-independent following the introduction of a kinase-active FIP1L1-PDGFRA. Thus, BAF-FIP1L1-PDGFRA-FL and BAF-FIP1L1-PDGFRA-T674I cells proliferate in the absence of IL-3. By treatment with imatinib, kinase activity of FIP1L1-PDGFRA-FL was suppressed, resulting in a decrease of PIAS1 expression. In contrast, the expression level of PIAS1 in BAF-FIP1L1-PDGFRA-KD cells, which were cultured in the presence of IL-3, was not affected by treatment with imatinib. Moreover, the expression level of PIAS1 in imatinib-resistant BAF-FIP1L1-PDGFRA-KD cells was also not changed by treatment with imatinib. Collectively, the results suggest that FIP1L1-PDGFRA stabilizes PIAS1 through its kinase activity.
PDGFRA was decreased by knockdown of PIAS1 (Fig. 3c, right panel, lanes 2 and 3). These results support our notion that PIAS1 regulates the expression level of FIP1L1-PDGFRA.

Collectively, the results suggest that PIAS1 sumoylates and stabilizes FIP1L1-PDGFRA.

**PIAS1 is a potential therapeutic target for CEL treatment.** Our results suggest that sumolation regulates the expression level of FIP1L1-PDGFRA, and we therefore assumed that inhibition of sumolation or PIAS1 activity is a potential target in the treatment of CEL. Recently, it has been reported that ginkgolic acid acts as an inhibitor of a SUMO E1-activating enzyme,(24) so we examined the effect of ginkgolic acid on FIP1L1-PDGFRA expression. To analyze the effect of ginkgolic acid on FIP1L1-PDGFRA-dependent cell growth, we treated BAF-FIP1L1-PDGFRA-FL cells with different concentrations of ginkgolic acid and examined the expression levels of ginkgolic acid decreased the expression levels of FIP1L1-PDGFRA in both BAF-FIP1L1-PDGFRA-FL cells and BAF-FIP1L1-PDGFRA-KD cells (Fig. 4a). Treatment of BAF-FIP1L1-PDGFRA-FL cells with 20 μM ginkgolic acid alone had a minimal effect in inducing apoptosis, whereas BAF-FIP1L1-PDGFRA-FL cells underwent apoptosis following inhibition of FIP1L1-PDGFRA kinase activity by imatinib. We then examined whether the combination of ginkgolic acid and imatinib had a synergistic effect to induce apoptosis in BAF-FIP1L1-PDGFRA-FL cells. When BAF-FIP1L1-PDGFRA-FL cells were treated with a combination of 20 nM imatinib and 20 μM ginkgolic acid, ginkgolic acid augmented the effect of imatinib (Fig. 4b, left panel). This effect seemed to be mediated by suppression of the kinase activity of FIP1L1-PDGFRA, because these compounds had little effect on BAF-FIP1L1-PDGFRA-KD cells that manifest IL-3-dependent growth (Fig. 4b, right panel).

Moreover, we examined whether knockdown of PIAS1 augments the effect of imatinib on BAF-FIP1L1-PDGFRA-FL cells. The expression of PIAS1 in BAF-FIP1L1-PDGFRA-FL cells was inhibited by transfecting PIAS1-specific siRNA as described in the legend of Figure 3(c), and subsequently the cells were treated with imatinib. The knockdown of PIAS1 in the transfected cells was confirmed by immunoblotting (data...
not shown). In the treatment with 20 nM imatinib, apoptosis was similarly induced in cells transfected with a negative control and cells transfected with PIAS1-specific siRNAs. However, in the treatment with 10 nM imatinib, induction of apoptosis was significantly greater in the cells transfected with PIAS1-specific siRNAs than in cells transfected with a negative control (Fig. 4c, left panel). There was no effect of PIAS1-specific siRNAs on induction of apoptosis in BAF-FIP1L1-PDGFRA-FL cells (Fig. 4c, right panel). These results indicate that downregulation of PIAS1 sensitizes BAF-FIP1L1-PDGFRA-FL cells to a low concentration of imatinib.

Taken together, the results indicate that the sumoylation system by PIAS1 regulates the expression level of FIP1L1-PDGFRα and is a potential target for FIP1L1-PDGFRα-positive CEL treatment.

**Discussion**

To understand the mechanisms by which FIP1L1-PDGFRα exerts its transforming activity through the FIP1L1 portion, we identified PIAS1 as a FIP1L1-PDGFRα associating molecule and showed a positive cross-talk between FIP1L1-PDGFRα and PIAS1 for phosphorylation and sumoylation.

We found that PIAS1 associates with FIP1L1-PDGFRα and that the FIP1L1 portion is necessary for efficient association. Some molecules have been reported to directly associate with FIP1L1-PDGFRα. The lymphocyte adaptor protein Lnk binds to both PDGFRα and FIP1L1-PDGFRα and acts as a negative regulator of these molecules (25) c-Cbl is phosphorylated by both PDGFRα and FIP1L1-PDGFRα, but it efficiently ubiquitinates and destabilizes only PDGFRα. The association of Lnk and c-Cbl with FIP1L1-PDGFRα seems to be mediated by the PDGFRα portion, as these molecules associate with the full length of PDGFRα. However, efficient association between PIAS1 and FIP1L1-PDGFRα required the FIP1L1 portion, because the FIP1L1 portion directs FIP1L1-PDGFRα into the nucleus, where PIAS1 is localized. As a kinase, FIP1L1-PDGFRα phosphorylated PIAS1 on tyrosine residues and this phosphorylation also required the FIP1L1 portion. Moreover, the kinase activity of FIP1L1-PDGFRα stabilized PIAS1. It has been reported that the function of PIAS1 is regulated by the phosphorylation of serine residues. (27,28) Our results suggest a novel mechanism of PIAS1 being regulated by tyrosine phosphorylation. It has not yet been determined whether stabilization of PIAS1 by FIP1L1-PDGFRα is mediated by phosphorylation of PIAS1. Identification of tyrosine residues that are phosphorylated by FIP1L1-PDGFRα is necessary for further characterization of the underlying mechanism for PIAS1 regulation.

The kinase activity of FIP1L1-PDGFRα activates many downstream molecules by way of FIP1L1-dependent or -independent pathways. It has been reported that the FIP1L1 portion is necessary for activation of PKB/c-akt by FIP1L1-PDGFRα and that PIAS1 sumoylates and activates PKB/c-akt. (15,29) Our results suggest the presence of a potential signaling pathway by which PIAS1 can be upregulated by FIP1L1-PDGFRα and subsequently activate PKB/c-akt.

Moreover, PIAS1 sumoylated FIP1L1-PDGFRα and regulated its stability as a consequence of the association between FIP1L1-PDGFRα and PIAS1. Although imatinib is highly effective against FIP1L1-PDGFRα-positive CEL, drug resistance occasionally develops and relapse often occurs after discontinuation of imatinib treatment. (6,12,30,31) Inhibition of sumoylation by siRNA of PIAS1 or treatment with ginkgolic acid destabilized FIP1L1-PDGFRα. As a consequence, treatment of BAF-FIP1L1-PDGFRA-FL cells with ginkgolic acid and siRNA of PIAS1 augmented the effect of imatinib. These results suggest that PIAS1-targeted therapy may be effective in treating FIP1L1-PDGFRα-positive leukemia. Very recently, it has been reported that PIAS1 plays a crucial role in the maintenance of hematopoietic stem cells. (32) Based on our results, the positive cross-talk between FIP1L1-PDGFRα and PIAS1 may be associated with maintenance of leukemia stem cells in FIP1L1-PDGFRα-positive leukemia.

**Acknowledgments**

The authors thank Dr. M. Seto for providing BAF-B03 cells. The authors also acknowledge Ms. M. Yamane, Ms. M. Mayanagi, Ms. I. Sato, and Ms. R. Sekiguchi for technical assistance. This work was supported by Japan Society for the Promotion of Science (Kakenhi grant nos. 25461404 [to T.K.] and 26890001 [to M.O.]) and by a research fund from the North Japan Hematology Study Group.

**Disclosure Statement**

The authors have no conflict of interest.

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