Vav3 collaborates with p190-BCR-ABL in lymphoid progenitor leukemogenesis, proliferation, and survival

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Despite the introduction of tyrosine kinase inhibitor therapy, the prognosis for p190-BCR-ABL+ acute lymphoblastic leukemia remains poor. In the present study, we present the cellular and molecular roles of the Rho GTPase guanine nucleotide exchange factor Vav in lymphoid leukemogenesis and explore the roles of Vav proteins in BCR-ABL–dependent signaling. We show that genetic deficiency of the guanine nucleotide exchange factor Vav3 delays leukemogenesis by p190-BCR-ABL and phenocopies the effect of Rac2 deficiency, a downstream effector of Vav3. Compensatory up-regulation of expression and activation of Vav3 in Vav1/Vav2–deficient B-cell progenitors increases the transformation ability of p190-BCR-ABL. Vav3 deficiency induces apoptosis of murine and human leukemic lymphoid progenitors, decreases the activation of Rho GTPase family members and p21-activated kinase, and is associated with increased Bad phosphorylation and up-regulation of Bax, Bak, and Bik. Finally, Vav3 activation only partly depends on ABL TK activity, and Vav3 deficiency collaborates with tyrosine kinase inhibitors to inhibit CrkL activation and impair leukemogenesis in vitro and in vivo. We conclude that Vav3 represents a novel specific molecular leukemic effector for multitarget therapy in p190-BCR-ABL–expressing acute lymphoblastic leukemia. (Blood. 2012;120(4):800-811)

Introduction

Philadelphia chromosome–positive (Ph+) hematologic malignancies arise from the t(9;22) (q34;q11.2) mutation, which encodes the constitutively active tyrosine kinase oncprotein BCR-ABL. BCR-ABL is both necessary and sufficient to induce leukemia.1 Two types of BCR-ABL fusion proteins, associated with different break points in the BCR gene, have been identified in patients with Ph+ B-cell acute lymphoblastic leukemia (Ph+ B-ALL). A 190-kDa fusion protein, referred to as p190-BCR-ABL, is present in 60%-80% of Ph+ B-ALL cases. Leukemia induced by this BCR-ABL fusion protein arises from a transformed B–cell progenitor.2 A BCR-ABL isoform of 210 kDa, known as p210-BCR-ABL, is commonly expressed in patients with chronic myelogenous leukemia (CML) and in a minority of patients with Ph+ B-ALL. The transforming effect of BCR-ABL is dependent on the tyrosine kinase (TK) activity of the fusion protein that leads to autophosphorylation, recruitment of adaptor proteins, and subsequent activation of downstream signaling. The TK inhibitor (TKI) imatinib and the second-generation TKIs dasatinib and nilotinib have been used as frontline treatment for CML and Ph+ B-ALL patients.3 However, relapse is common in Ph+ B-ALL despite high rates of complete response with initial therapy,4,5 probably because of survival of leukemic progenitors. These BCR-ABL+ progenitors appear to accumulate additional genetic mutations that result in a proliferative advantage and differentiation arrest.6 Understanding the downstream signaling cascades activated by BCR-ABL may lead to the development of more effective therapeutic strategies that aim to prevent the development and/or selection of TKI-resistant clones.

Expression of p210-BCR-ABL activates the Rho-family GTPases Rac, RhoA, and Cdc42,7 possibly through the double homology (DH) domain of guanine exchange factors (GEFs).8 We demonstrated previously that the absence of Rac proteins, specifically Rac2 or the combination of Rac1 and Rac2, impairs myeloid leukemogenesis induced by p210-BCR-ABL expression in the hematopoietic stem and progenitor cell compartment.9,10 Activation of Rac GTPases, particularly Rac2, has been shown to regulate reactive oxygen species production by NADPH oxidase complexes11 and possibly to be responsible for DNA damage and genetic instability in BCR-ABL leukemias.12 Expression of p190-BCR-ABL also activates Rac GTPases7 despite a lack of the DH domain, suggesting that the activation of Rho-family GTPases by p190-BCR-ABL must depend on the expression and activation of alternative GEFs.

Vav proteins are GEFs for Rho-family GTPase members.13 The mammalian Vav family is made up of 3 members: Vav1, Vav2, and...
Vav3. Despite common functional domains and similar mechanism of phosphorylation-dependent activation,14 the sequence homology between the 3 Vav isoforms is only approximately 65%. In addition, Vav1 expression is restricted to hematopoietic cells, whereas Vav2 and Vav3 are expressed broadly in multiple tissues.15 Overexpression studies and various Vav gene knockout mice have revealed both unique and redundant roles of the 3 Vav family members in lymphoid cells.16 The phosphorylation of Vav proteins on specific tyrosine residues leads to conformational changes required for binding to GTPase effectors.13 Vav1 has been shown to exist as a complex with both p190- and p210-BCR-ABL,17 with uncertain significance. Whether other Vav proteins complex BCR-ABL is not known.

In the present study, we explored the upstream mechanism of p190-BCR-ABL–dependent Rac activation through the Vav GEF family members. We show that, although both Vav1 and Vav3 are hyperactivated in primary human and murine p190-BCR-ABL+ B-ALL, Vav3-deficient leukemogenesis induced by p190-BCR-ABL is delayed. The proliferation and survival of B-cell progenitors is impaired by genetic loss of Vav3 and can be reverted by its reintroduction, and compensatory Vav3 up-regulation induced by genetic combined deficiency of Vav1 and Vav2 translates into increased survival and expansion ex vivo. Vav3 deficiency reduces p190-BCR-ABL–induced Rac GTPase activation and decreases proliferation and Vav3-deficient p190-BCR-ABL+ murine and human B-cell progenitors have enhanced apoptosis associated with augmented expression of Bad and Bik and the downstream effectors Bak and Bax. Our results demonstrate that Vav3 is a critical GEF in p190-BCR-ABL–mediated activation of Rac GTPase and down-regulation of proapoptotic signals required for leukemogenesis. We also demonstrate that Vav3 deficiency collaborates with TKI in the inhibition of leukemogenesis in vivo. Therefore, the results of the present study suggest that Vav3 may be a useful therapeutic target in p190-BCR-ABL+ B-ALL.

Methods

Animals

Vav-deficient mice16 and Rac2-deficient mice18 have been described previously. Vav1−/−;Vav2−/− mice were generated by intercrossing. All mutant mice had been backcrossed 10 generations into C57Bl/10 or C57Bl/6 mice. Six- to 8-week-old female wild-type (WT) C57Bl/6 and C57Bl/10 mice were obtained commercially (The Jackson Laboratory and Harlan Laboratories) and used as donors and/or recipients of transduction/transplantation models. The Cincinnati Children’s Hospital Medical Center institutional animal care and use committee approved the protocol.

Human specimens

Umbilical cord blood (UCB) cells, normal BM, and B-ALL low-density bone marrow (LDBM; p190-BCR-ABL+ or TEL-AML1+) specimens were obtained through institutional review board-approved protocols and donor informed consent from Cincinnati Children’s Hospital Medical Center, Universidad de Navarra (Spain), or Shanghai Children’s Medical Center (China). All leukemic specimens contained a minimum of 80% blasts and were analyzed the level of Vav3 activation in human p190-BCR-ABL+ leukemia

Vav mediates the activity of protein TKs, including BCR-ABL,20 as a result of the phosphorylation of a specific tyrosine residue in the Vav DH domain. Vav1 has been shown to be activated in BCR-ABL–expressing leukemias,17 but the level of activation of Vav3 in BCR-ABL leukemias is unknown. In the present study, we analyzed the level of Vav3 activation in human p190-BCR-ABL+ B-lymphoblastic leukemias. All 7 LDBM samples from p190-BCR-ABL+ B-ALL patients showed markedly increased levels of expression and phosphorylation of Vav1 and Vav3 compared with LDBM cells (7- and 14.3-fold increase, P < .05 and P < .01, respectively) and CD34+ cells (6.3- and 3.9-fold, respectively,
expression of p190-BCR-ABL in Vav3-deficient mice. In these
murine models or WT mice were transduced with bicistronic
vectors expressing EGFP and p190-BCR-ABL (MSCV-p190-BCR-
ABL B-ALL cells (41-fold difference, 

effectors (supplemental Figure 1A-C). Expression of p190-BCR-ABL in
murine B-cell progenitors induced increased expression and activa-

We hypothesized that Vav3 activation plays an important and
nonredundant role in p190-BCR-ABL–mediated leukemogenesis. To
test this hypothesis, we used Vav gene-knockout mice in which
we transduced p190-BCR-ABL in LDBM cells. We first deter-

Vav3 is uniquely required for leukemia cell proliferation and
survival induced by p190-BCR-ABL, but not by p210-BCR-ABL

To assess the effects of Vav proteins on p190-BCR-ABL leukemo-
genesis, we analyzed whether the deficiency of these proteins
modulates the proliferation and/or survival of p190-BCR-ABL+ B-cell progenitors. Deficiency of Vav3 impaired the expansion of
p190-BCR-ABL+ CFU-proB cells, whereas, paradoxically, the
combined deficiency of Vav1 and Vav2 increased the cumulative expansion of B-cell progenitors (Figure 2A). Nontransformed
B-lymphoid progenitors showed limited expansion, which was
independent of their genotype (Figure 2A).

To analyze the cellular mechanism responsible for the different-
effect of Vav3 and Vav1/Vav2 deficiencies on the expansion of
leukemic B-cell progenitors, we determined the proliferation and
survival of leukemic-transformed and nonleukemic-transformed
B-cell progenitors in vitro. We found that the absence of Vav3 was
associated with decreased cell-cycle progression (Figure 2B and
supplemental Figure 2), in contrast, combined Vav1 and Vav2
deficiency did not affect the proliferation of p190-BCR-ABL+ B-cell progenitors significantly (Figure 2B). Interestingly, the
deficiency of Vav3 or Vav1/Vav2 did not modify cell-cycle entry of
mock-transduced B-cell progenitors significantly (Figure 2A-B and
supplemental Figure 2), suggesting that p190-BCR-ABL uses Vav3
as a signal mediator in cell proliferation. As expected, p190-BCR-
ABL expression enhanced survival of B-cell progenitors in culture
over 2 weeks (cell death in mock-transduced B-cell progenitors
> 95%, Figure 2A and supplemental Figure 3A). Vav3 deficiency
impaired survival of p190-BCR-ABL B-cell progenitors signifi-
cantly, as assessed in liquid culture (Figure 2C) and in CFU-proB
cultures (supplemental Figure 3B-D), whereas combined Vav1/
Vav2 deficiency was associated with significantly decreased leukem-
ic progenitor death (Figure 2C and supplemental Figure 3B-D).
These data indicate that Vav3 controls the proliferation and survival of
leukemic lymphoid progenitors and that the survival of leukemic
B-cell progenitors is inversely affected by the absence of Vav1/
Vav2 expression.

Because Vav function may be subject to compensatory regu-
lation by the other Vav proteins, as suggested by the up-regulation
of Vav1 and Vav2 expression in Vav3-deficient B-cell progenitors
(supplemental Figure 1A-C), we analyzed whether the combined
deficiency of Vav1 and Vav2 modified Vav3 expression and/or
activation significantly. We found that the combined deficiency
of Vav1 and Vav2 up-regulated Vav3 expression (supplemental Figure
3E) and tyrosine phosphorylation (Figure 2D), as assessed in
whole-cell lysates and Vav3-immunoprecipitated specimens, respec-
tively. These data imply that Vav3 activation is responsible for the
Inversely correlated with the level of expression of Vav3 (Figure 2A). Increased levels of apoptosis of ex vivo–cultured cells were observed compared to WT (red lines), Vav3−/− (green lines), and Vav3+/+. (B) S-phase fraction as assessed by bromodeoxyuridine incorporation of B-cell progenitors expressing either mock vector (hatched bars) or p190-BCR-ABL (solid bars) on day 6 of in vitro culture. (C) Apoptosis as assessed by annexin V binding of leukemic p190-BCR-ABL–B-cell progenitors on day 16 of in vitro culture. (D) Representative example of immunoprecipitation and Western blot of pTyr-Vav and total Vav3 in p190-BCR-ABL–B-cell progenitors from WT, Vav1−/−;Vav2−/−, and Vav3−/− mice. Lysates from 5 × 10^6 B-cell progenitors were immunoprecipitated, loaded, and blotted with Abs against phospho-tyrosine and Vav3. β-actin expression analysis from total lysate was used as a loading control (n = 3 independent experiments).

Changes in cell-cycle progression and survival and suggest that the increased survival observed in Vav1/Vav2-deficient, p190-BCR-ABL–transduced B-cell progenitors is due to compensatory overexpression and overactivation of Vav3. We also analyzed whether Vav3 and BCR-ABL coimmunoprecipitated in leukemic cells. Vav3 and c-Abl immunoprecipitates of Ba/F3 cells transduced with either p190- or p210-BCR-ABL did not show any significant binding of Vav3 and BCR-ABL (supplemental Figure 4A-B), suggesting that BCR-ABL–induced Vav3 activation does not depend on direct protein-protein interaction.

To confirm the functional role of Vav3 in survival of leukemic B-cell progenitors, we introduced Vav3 cDNA into Vav3−/−, p190-BCR-ABL+ B-cell progenitors. Transduction of Vav3−/− p190-BCR-ABL+ B-cell progenitors with a lentiviral vector expressing Vav3 (denoted Vav3+/−;Vav3 in Figure 3A) resulted in restoration of Vav3 activation. Reintroduction of Vav3 reversed the state of apoptosis induced by Vav3 deficiency significantly in p190-BCR-ABL+ B-cell progenitors to a level similar to that in WT leukemic cells (Figure 3B-C).

To verify the relevance of our findings in murine leukemic cells, human UCB CD34+ cells were retrovirally transduced with a p190-BCR-ABL–internal ribosomal entry site (IRES)-EYFP vector and 3 different Vav3 shRNA-IRESEGFPP-containing vectors and a nontargeting shRNA-IRESEGFPP–containing vector as a control. The level of interference of Vav3 expression was confirmed in sorted EGFP+/EYFP+/CD34+/CD19+ cells (Figure 4A). Increased levels of apoptosis of ex vivo–cultured cells were inversely correlated with the level of expression of Vav3 (Figure 4B-C). These data support the conclusion that Vav3 is required for p190-BCR-ABL+ murine and human leukemic cell survival and that its activation may not depend on direct protein-protein interaction.

**Vav3 is required for complete leukemogenesis induced by p190-BCR-ABL**

As a consequence of these results, we next determined the effect of Vav3 expression on p190-BCR-ABL+ B-ALL leukemogenesis in vivo. Because loss of Vav proteins has been associated with defective BCR signaling and defective naive B-cell survival,16 we first determined whether there were significant quantitative or functional defects in the BM B-cell progenitor content of Vav-deficient mice that may have impared the development of B-cell lymphopoiesis at an early stage of differentiation. Vav3−/− and Vav1−/−;Vav2−/− mice had a normal numbers of immunophenotypically defined B-cell progenitors (supplemental Figure 5A). Functional analysis also confirmed normal numbers of progenitors (supplemental Figure 5B). When mice were transplanted with LDBM cells transduced with a retrovirus vector expressing p190-BCR-ABL+, greater than 90% of recipient mice developed B-ALL. These mice maintained an expanded B220dim+; CD19+, CD43+dim B-cell progenitor population in circulation (Figure 5A). B-ALL mice showed both circulation and organ infiltration of p190-BCR-ABL+ lymphoid cells leading to splenomegaly, lymphadenopathy, and CNS manifestations characterized by limb palsies. The mean survival of congenic C57Bl/10 mice transplanted with
WT, p190-BCR-ABL+ LDBM was 36.5 ± 1.8 days. Survival was significantly extended to 49.4 ± 4.9 days in mice transplanted with Vav3−/−, p190-BCR-ABL+ LDBM (Figure 5B, log-rank test, \( P < .05 \)). In contrast, loss of Vav1 (supplemental Figure 6) or combined deletion of Vav1 and Vav2 did not prolong the survival of recipient mice (33.7 ± 2.3 days; Figure 5B, \( P = \) not significant.). All recipient mice maintained peripheral B220+/EGFP+ cells from day +21 after transplantation throughout the study, confirming sustained engraftment of p190-BCR-ABL–expressing B-lymphoid cells even in the absence of Vav proteins (Figure 5C).

Moreover, impaired leukemogenesis of sorted BM Vav3-deficient B-cell progenitors even in the absence of Vav proteins (Figure 5C). Among the Rho GTPases, we showed previously that Rac, especially Rac2, is critical in the proliferation and survival of p190-BCR-ABL expressing B-cell progenitors. We then analyzed whether Vav3 is required for activation of small GTPases by p190-BCR-ABL in vivo.9 To determine whether Vav3 plays a role as a GEF for Rac2 in p190-BCR-ABL+ leukemic B-cell progenitors (Figure 5F), this result is consistent with previous observations that Ras is not a direct substrate of Vav.22 These data also indicate that Vav3 is necessary for full activation of Rho GTpases by p190-BCR-ABL in B-lymphoid progenitors.

Vav3 deficiency impairs the Rac GTPase signaling pathway in vivo

Both p190 and p210 forms of BCR-ABL activate small GTpases, including Rac, Rho, and Ras GTpases (supplemental Figure 9). We then analyzed whether Vav3 is required for activation of small GTpases in p190-BCR-ABL expressing B-cell progenitors. We observed that the activation of total-Rac, Rac-2, Cdc42 and Rho were diminished in the absence of Vav3 in B-ALL cells harvested from murine leukemias (Figure 5E). On the other hand, the activation of Ras was not reduced in Vav3-deficient p190-BCR-ABL+ leukemic B-cell progenitors (Figure 5F). Among the Rho GTpases, we showed previously that Rac, especially Rac2, is critical in the proliferation and survival of p190-BCR-ABL+ CML leukemic stem cells,9,10 whereas the single deficiency of Rac1 did not impair their leukemogenic ability in vivo.9 To determine whether Vav3 plays a role as a GEF for Rac2 in p190-BCR-ABL+ B-cell progenitors, we performed an effector pull-down assay of GST-bound recombinant small GTpases. We found that Rac2 to a higher degree, Rac1, Rho, and Cdc42 only marginally bind Vav3 from lymphoblastic leukemic p190-BCR-ABL–expressing cells (Figure 5G). K-Ras did not bind Vav3 (Figure 5G). A dominant-negative mutant of Rac2 (Rac2D57N, nucleotide-free and with an ability to act as a GEF sink)23 has increased binding to Vav3 (Figure 5G). In combination with the small GTpase pull-down data (Figure 5E-F), these data strongly suggest that Rac/Rho, and specifically Rac2, bind and are activated by Vav3 in p190-BCR-ABL B-cell progenitors.

To determine the role of p190-BCR-ABL–induced Rac activation in leukemogenesis, we analyzed the role of Rac2, which strongly binds to Vav3 (Figure 5G), and Rac3, which has been implicated in BCR-ABL leukemia,24 in vivo leukemogenesis. Deficiency of Rac2, but not Rac3, delayed p190-BCR-ABL...
leukemogenesis and prolonged mean survival time (54.6 ± 3.0, 84.8 ± 18.2, and 54.9 ± 4.6 days for mice transplanted with WT, Rac2−/−, and Rac3−/− p190-BCR-ABL–transduced LDBM, respectively, P < .05 for comparison between mice engrafted with WT vs Rac2−/− LDBM; Figure 5H). Similar to previous data in a model of p210-BCR-ABL myeloproliferative disease,25 Rac2-deficient mice showed levels of EGFP/shRNA/B220+ cells in peripheral blood comparable with that in recipients of WT-transduced cells until their death (supplemental Figure 10). The contents of B-cell progenitors in BM of Rac2−/− donor mice was normal, suggesting that the lack of a target cell population was not responsible for the delayed latency of leukemia (supplemental Figure 11A-B). These data confirm the role of Rac2 in p190-BCR-ABL–induced leukemogenesis and phenocopy the survival advantage of Vav3-deficient leukemias.

Vav3 is required to maintain the balance between survival and death signals in p190-BCR-ABL+ B-ALL

To address the signaling pathways responsible for Vav3-dependent leukemic B-cell progenitor survival, we explored the molecular mechanism of increased apoptosis in Vav3−/− leukemic B-cell progenitors. Whereas activation of Akt was not consistently altered by Vav3 deficiency (Figure 6A), activation of p21-activated kinase (PAK), a direct effector of Rac GTPases, was decreased markedly in p190-BCR-ABL+ Vav3−/− B-cell progenitors (Figure 6A). In contrast, the activation of the adaptor protein CrkL, which binds ABL directly, was not changed in the absence of Vav3 (Figure 6A). BCR-ABL–dependent signals are known to modulate the prosurvival proteins of the Bcl-2 family. Bcl2 family members have been suggested as therapeutic targets in BCR-ABL leukemias.26 To determine whether Vav3-dependent survival of p190-BCR-ABL+ B-ALL cells was mediated by Bcl2 family proteins, we analyzed the effect of Vav3 deficiency on the expression of Bcl2 family in primary p190 BCR-ABL+ leukemic B-cell progenitors from B-ALL mice. There was a significant increase in the expression of death signals in Vav3-deficient, p190-BCR-ABL+ B-cell progenitors in vitro (supplemental Figure 12) and leukemic blasts in vivo (Figure 6B-C,E). Vav3−/− p190-BCR-ABL+ B-ALL cells showed increased expression of cleaved caspase-3, confirming apoptotic cell death associated with increased expression of the proapoptotic proteins Bax, Bak, and the BH3-only molecule Bik (Figure 6B,E). Although the level of expression of Bim, another BH3-only molecule, was not changed in Vav3-deficient B-ALL primary tumors (Figure 6B), the expression of all 3 isoforms of Bim was up-regulated significantly in cultured p190-BCR-ABL+ B-cell progenitors (supplemental Figure 12), suggesting that an interplay of in vivo signals may reverse Bim up-regulation induced by Vav3 loss of function. In addition, Bad mRNA and protein expression was increased markedly in Vav3-deficient, p190-BCR-ABL+ B-cell progenitors (Figure 6C,E and supplemental Figure 13). Bad inactivation prevents association of Bad with Bcl2/Bcl-xL and promotes cell survival. To address whether Vav3 deficiency is associated with inactivation of Bad, we analyzed 2 specific sites of Bad phosphorylation that result from alternative kinase pathways. The level of phospho(Ser136)-Bad, which is dependent on p90RSK28 and protein kinase A activation,29 was not changed (Figure 6C,E). The
from BCR-ABL–dependent activation of prosurvival Bcl-2 family members (Figure 6D). These data indicate Vav3 modulates the balance between pro- and antiapoptotic signals in p190-BCR-ABL–expressing leukemia cells. Moreover, these results suggest that the up-regulation of BH3-only molecules induced by the loss of Vav3 can counteract the increased survival of leukemic cells resulting from BCR-ABL–dependent activation of prosurvival Bcl-2 family members.

**Vav3 deficiency collaborates with TKIs to impaire survival of leukemic lymphoid progenitors in vitro and in vivo**

BCR-ABL TK activity is considered to be responsible for BCR-ABL transformation. However, TKIs targeting BCR-ABL have only shown a transient and modest effect on the long-term survival of BCR-ABL+ B-ALL patients. Therefore, we examined whether TK inhibition and deficiency of Vav proteins collaborated in terms of inhibition of p190-BCR-ABL+ leukemic cell proliferation while cultured in presence of SCF and IL-7. To allow similar numbers of starting CFU-proB cells in the original inocula, p190-BCR-ABL–transduced LDBM cells were cultured for 3 days (a selected period of time when Vav3 deficiency has not yet induced a loss of B-cell progenitor outgrowth (Figure 7C-D), suggesting that the Src family kinase inhibitory activity of dasatinib may antagonize the function of hyperactivated Vav3.
To understand mechanistically the signaling mechanisms of collaboration between Vav3 and the TK domain of ABL, we analyzed the activation of Pak and CrkL, which has been shown to be crucial in BCR-ABL–induced leukemogenesis.41 in TKI-treated, sorted leukemic B-cell progenitors. Both Vav3 deficiency and incubation with TKIs are highly effective in impairing Pak activation in lymphoblastic progenitors, and seem to have an additive effect (Figure 7E). Unlike TKIs37 or Vav3 deficiency alone, incubation with either imatinib or dasatinib synergized with Vav3 deficiency to completely abrogate activation of CrkL (Figure 7E). These data strongly suggest that the TK activity of p190-BCR-ABL and Vav3 activity collaborate in Pak activation and that they are functionally redundant for activation of CrkL.

Collaboration of Vav3 deficiency and administration of TKIs was also analyzed in vivo. Vav3 deficiency collaborated with administration of imatinib to extend the survival of mice transplanted with either WT or Vav3−/− p190-BCR-ABL–transduced LDBM cells (mean survivals times, 52.0 ± 6.8 days and 77.3 ± 5.7 days, respectively, P < .05; Figure 7F) compared with mice receiving no TKI administration (Figure 5B). Whereas dasatinib administration extended the survival of mice transplanted with WT, p190-BCR-ABL–transduced LDBM cells significantly (average survival time, 65.2 ± 5.2 days) compared with mice treated with imatinib (P < .05), the effect of Vav3 deficiency (average survival time, 72.3 ± 2.2 days) was more modest and did not reach statistical significance (Figure 7F). Analysis of Vav3 activation in leukemic EGFP+ BM cells from imatinib- and dasatinib-treated WT deceased animals demonstrated a modest inhibition of Vav3 activation, which was more significant for dasatinib-treated leukemias, albeit not abrogated (Figure 7G). Vav3 expression was not modified by imatinib or dasatinib treatment. These data suggest that Vav3 activation in vivo may depend on multiple signals, including the ABL TK of p190-BCR-ABL and Src kinase activity.

The results of the present study suggest that TKI therapy does not suffice to prevent Vav3 activation and that Vav3 deficiency collaborates with TKIs to inhibit Pak and CrkL to inhibit leukemogenesis in vitro and in vivo.

**Discussion**

Our previous studies have demonstrated that hyperactivation of Rac GTPases, and specifically Rac2, are key signals in BCR-ABL–induced transformation and leukemogenesis.9,10 Lymphoid transformation of BCR-ABL–expressing progenitors has been associated with genomic instability and mutagenesis through mechanisms that are not well characterized but in which Rac activation has been suggested to play a role through the generation of reactive oxygen species.12

In the present study, we explored the upstream mechanism of Rac activation by the short form of BCR-ABL, which lacks an activating DH domain. We found that Vav3 plays a crucial role in p190-BCR-ABL–mediated leukemogenesis, proliferation, and survival. Our data show that p190-BCR-ABL up-regulates both Vav1 and Vav3 expression and activation, but only the deficiency of Vav3 attenuates the transformation phenotype regarding progenitor proliferation, especially the survival of B-cell progenitors, the putative leukemia-initiating cells in this disease. Vav3 deficiency delays p190-BCR-ABL–induced but not p210-BCR-ABL–induced lymphoid leukemogenesis in vivo. The delay in lymphoid leukemogenesis induced by the loss of Vav3 phenocopies the deficiency of Rac2, indicating that whereas the functional relevance of Vav3 activation relates specifically to p190-BCR-ABL but not p210-BCR-ABL expression, the dependence on Rac2 activity seems to affect to both p210-BCR-ABL leukemia11,12 and p190-BCR-ABL leukemia (Figure 5H). Vav3 deficiency impairs cell-cycle progression and survival mediated by p190-BCR-ABL, unlike a combined deficiency of Vav1 and Vav2, which leads to increased Vav3 activation with either no effect or modest enhancement of leukemic transforming phenotypes. Moreover, the survival impairment induced by Vav3 deficiency can be rescued by exogenous expression of Vav3 in Vav3−/− lymphoid progenitors, ruling out a developmental defect associated with Vav3 deficiency in primary murine cells.

![Image](image-url)
To understand the role of Vav3 signaling in p190-BCR-ABL+ cell survival, we investigated whether Vav3 coimmunoprecipitated with BCR-ABL and the downstream pathways of Vav3, specifically the direct effector of Rac GTPase, and Ras activation. First, unlike Vav1,20 we found that Vav3 did not coimmunoprecipitate with either p190-BCR-ABL or p210-BCR-ABL, but as is the case with p210-BCR-ABL leukemia,5,11 Rac GTPases are activated in p190-BCR-ABL leukemia (supplemental Figure 9). Therefore, Vav3 activation seems not to depend on direct binding to BCR-ABL. Second, we found that whereas Ras activity was not affected by Vav3 deficiency, Rac activation was decreased significantly in Vav3-deficient, p190-BCR-ABL lymphoblastic leukemias. Biochemically, Vav3 strongly binds Rac2, Rac1, RhoA, and, marginally, Cdc42 in p190-BCR-ABL–expressing lymphoid leukemia cells. A dominant-negative mutant of Rac2 (Rac2D57N) with a markedly enhanced rate of GTP dissociation is able to pull down all significantly impaired GTP binding ability resulting from a marked loss of Rac2 activity in Vav3-deficient cells. Furthermore, Rac2 but not Rac3 deficiency phenocopies Vav3 deficiency in extending the survival of mice transplanted with p190-BCR-ABL–transduced LDBM cells. In agreement with our previously published data on the role of Rac proteins in p210-BCR-ABL+ myeloproliferative disease development9 and the role of Rac2 specifically in leukemic stem cell–initiated myeloproliferative disease,10 the results of the present study further strengthen our understanding of the crucial role of Rac proteins in the initiation and/or progression of BCR-ABL+ leukemias. Although we cannot rule out a non-GEF activity of Vav3 similar to that for Vav1 in other cell contexts,33 our data strongly suggest that Vav3 acts as a GEF of Rac2.

BCR-ABL induces cell proliferation and suppresses apoptosis through different mechanisms, including inhibition of proapoptotic molecules such as Bad.34 Bad controls the life-death switch and promotes apoptosis and cell-cycle arrest by antagonizing the prosurvival and cell-cycle progression activity of Bcl-2/Bcl-xL proteins35 or by activating proapoptotic Bax or Bak directly.36 Bad has been identified as an overexpressed gene in imatinib-resistant CML37 and in Rac2-null mast cells.38 Whereas the expression levels of Bad are important in the regulation of its function, Bad activity also depends on its regulation of its function, Bad activity also depends on its
phosphorylation state. Bad phosphorylation at Ser112 or Ser135/136 induces ubiquitination and protein degradation. Our data suggest that Vav3 deficiency regulates cell-cycle arrest and apoptosis that is altered in p190-BCR-ABL leukemogenesis. PAK proteins are major effectors of activated Rac and activated Pak has been shown to phosphorylate and inactivate Bad.40 Pak may also phosphorylate Bik, resulting in the survival of B-lineage lymphoid cells.41 This signal pathway has also shown to be responsible for cytoskeletal rearrangements and cell motility in B-lineage lymphoid cells.42 In the present study, diminished Rac (including Rac2) activation in Vav3-deficient B-ALL was correlated with decreased Pak activation, an increased Bad/pBad ratio, and a deficiency of Rac2 that phenocopied the increased survival of recipient mice of Vav3-deficient, p190-BCR-ABL leukemic cells. In contrast, we found that the expression of Bcl-2 and Bcl-xL was not altered in Vav3-deficient leukemic cells. These data suggest that Vav3 activation may use Rac2/Pak/pBad as a signaling pathway in p190-BCR-ABL leukemic cell survival.

Although the level of inactive phospho(Ser112)-Bad, a consequence of phosphorylation by p90RSK28 or protein kinase A,29 was maintained (Figure 6C,E), the level of phospho(Ser136)-Bad, a target of Pak and Akt kinase activities, was reduced to promote cell death.26 In the context of decreased Pak activation with unchanged Akt activation, these results strongly suggest that Pak/Bad are downstream signaling targets of Vav3 activity in the context of p190-BCR-ABL leukemogenesis. Increased expression of Bad, Bik, Bax, and Bak in Vav3-deficient cells represents additional negative regulation on lymphoid progenitor proliferation and survival. These data suggest that Vav3 deficiency regulates cell-cycle progression and survival negatively, which counteracts the survival signals induced by BCR-ABL.

Current therapeutic strategies in p190-BCR-ABL+ B-ALL are based on combination therapy regimens incorporating continuous imatinib treatment with intensive multigene chemotherapy, radiotherapy, and stem-cell transplantation in selected patients.43 A poor response and/or resistance to TKI therapy is believed to be due to mutations in ABL. For this reason, current efforts are focused on the development of new drugs with ABL TKI activity against BCR-ABL mutants.44 Dasatinib, a multigene kinase inhibitor with specificity for BCR-ABL, Src family kinases, and other TKs, has shown an advantage over classic ABL TKIs through binding to mutation-induced conformational dynamics of the ABL kinase domain.45 Dasatinib shows significant antileukemic activity and is increasingly used in the treatment of BCR-ABL+ B-ALL.46 Unfortunately, like imatinib, long-term durable responses are not observed with single-agent therapy47 and effects on survival largely depend on combinatorial therapies. With both imatinib and dasatinib, resistance to TKI therapy has been shown to occur in a significant number of patients. Among the downstream mechanisms found to be activated in TKI therapy resistance, Bcl-2 overexpression or loss of Bim and Bad expression48 and gene deletion of Cdkn2a and Cdkn2b in BCR-ABL+ leukemia cell–initiating cell subpopulations has been associated with aggres-
sive leukemic growth.6 These genetic alterations evolve even in the presence of effective TKI and are dependent on cytokine signaling,49 suggesting that signals independent of BCR-ABL TK activity may be responsible for cell transformation, proliferation, and survival in BCR-ABL+ leukemia.

The results of the present study show that the combination of Vav3 deficiency and imatinib extends animal survival in vivo and results in the inhibition of B-cell progenitor expansion in vitro, even in the presence of lymphoid cytokines. As expected from our previous data, which showed that combined Vav1/Vav2 deficiency induces overexpression and hyperactivation of Vav3, the combined deficiency of Vav1 and Vav2 showed an opposite effect, inducing B-cell progenitor expansion in vitro. Furthermore, the additive effect of imatinib or dasatinib and Vav3 deficiency strongly suggests that Vav3 controls the activation of BCR-ABL–signaling pathways, and loss of Vav3 collaborates with TK inhibition to revert leukemic progenitor transformation. The combined deficiency of Vav1 and Vav2 antagonizes the inhibitory effect of imatinib on B-cell progenitor proliferation, which may be explained by basal Vav3 up-regulation of Vav1/Vav2–deficient leukemic progenitors. Interestingly, dasatinib, an inhibitor of a much broader spectrum of kinase targets, collaborates with the combined deficiency of Vav1 and Vav2, suggesting that the inhibitory activity of dasatinib on targets other than the ABL TK domain may affect active pathways distinctly secondary to increased Vav3 activation. We have found that in vivo administration of imatinib or further dasatinib inhibits leukemic Vav3 activation, but does not abrogate it, indicating that Vav3 activation depends partly on ABL TK and Src kinase activities, but also on other in vivo signals. The unidentified signals may originate in the BM microenvironment because, as we have shown previously,50 the abrogation of the expression of the full BCR-ABL fusion protein induces B-ALL apoptosis and cures leukemia. The mechanism of collaboration between Vav3 and ABL TK signaling in p190-BCR-ABL B-cell progenitors may relate to their concerted action on Pak and CrkL activation. Whereas Vav3 deficiency impairs Pak activation significantly, the addition of TKI completely abrogates its activation. Similarly to incubation with TKIs,32 the isolated deficiency of Vav3 does not inhibit CrkL activation significantly. However, the combination of either imatinib or dasatinib with Vav3 deficiency abrogates CrkL activation completely. These data may provide an explanation for the clinical resistance to TKI observed in p190-BCR-ABL B-ALL.

In summary, the results of the present study show that Vav3 is a pivotal downstream target in p190-BCR-ABL signaling and acts as a critical determinant of leukemic cell survival. Deregulated expression and activation of Vav3 is associated with leukemic transformation. Loss of Vav3 alone resulted in increased leukemic cell death and impaired disease progression in vivo. Targeted specific inhibition of Vav3 activity may lead to the loss of leukemic cells through decreased survival and, together with TKI therapy, may improve the treatment of p190-BCR-ABL+ ALL.

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Vav3 collaborates with p190-BCR-ABL in lymphoid progenitor leukemogenesis, proliferation, and survival

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