

Regulation of annexin II by cytokine-initiated signaling pathways and E2A-HLF oncoprotein

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In pro-B cell acute lymphoblastic leukemia (ALL), expression of the E2A-HLF fusion gene as a result of t(17;19)(q22;p13) is associated with poor prognosis, hypercalcemia, and hemorrhagic complications. We previously reported that the E2A-HLF fusion protein protects interleukin-3 (IL-3)-dependent lymphoid cells from apoptosis caused by cytokine starvation. Here, we report that annexin II, a surface phospholipid-binding protein and

one of the proposed causes of the hemorrhagic complications of acute promyelocytic leukemia (APL), is also implicated in t(17;19)⁺ ALL. Annexin II was expressed at high levels in APL cells and in each of 4 t(17;19)⁺ leukemia cell lines, and annexin II expression was induced by enforced expression of E2A-HLF in leukemia cells. In IL-3-dependent cells, we found that annexin II expression was regulated by IL-3 mainly by Ras pathways, including

Ras/phosphatidylinositol 3-kinase pathways. Moreover, E2A-HLF increased annexin II expression in IL-3-dependent cells in the absence of the cytokine. These findings indicate that E2A-HLF induces annexin II by substituting for cytokines that activate downstream pathways of Ras. (Blood. 2004;103:3185-3191)

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Introduction

The E2A-HLF fusion transcription factor, which is generated by the t(17;19)(q22;p13) translocation, is found in some cases of pro-B cell acute lymphoblastic leukemia (ALL) that occur in older children and adolescents.^{1,2} In this chimeric molecule, the *trans*-activation domain of E2A is fused to the basic region and the leucine zipper (bZIP) domain of HLF, which mediate DNA binding and dimerization. Two distinct types of genomic rearrangements resulting in E2A-HLF fusion have been described in t(17;19)⁺ ALL.^{1,4} In type 1 rearrangements, an insertion that codes for a portion of the chimera not found in either wild-type protein occurs between E2A exon 13 and HLF exon 4. This insertion, derived from a cryptic exon spanning the 17;19 breakpoint, contains E2A intronic sequences at its 5' end, HLF intronic sequences at its 3' end, and various numbers of nontemplated nucleotides in the middle. The type 2 rearrangements arise from more 5' breakpoints in E2A and result in a fusion with E2A exon 12 spliced directly to HLF exon 4. The leukemias associated with the E2A-HLF fusion protein do not respond well to intensive chemotherapy, not even the aggressive conditioning for bone marrow transplantation. Moreover, these leukemias frequently manifest with intravascular coagulopathy and hypercalcemia, which are generally rare complications in children with pro-B ALL.^{3,5} Table 1⁶⁻⁹ summarizes the features of all reported t(17;19)⁺ ALLs that have been molecularly analyzed to date. Although the DNA-binding activities and the transcriptional activation properties of the type 1 and type 2 E2A-HLF

fusion proteins appear to be similar, coagulopathy develops more frequently among patients with a type 1 rearrangement than among those with type 2.^{4,10}

We previously demonstrated that E2A-HLF blocks apoptosis in cytokine-deprived murine interleukin-3 (IL-3)-dependent B precursor cells, suggesting that this fusion protein contributes to leukemogenesis by substituting for the antiapoptotic function of cytokines.^{11,12} IL-3 supports cell survival through 2 distinct signaling pathways. One pathway acts through the proximal portion of the common β (β_c) chain, a subunit shared between the receptor for IL-3 and the receptor for granulocyte-macrophage colony-stimulating factor (GM-CSF); the β_c chain proximal portion activates Janus kinase/signal transducer and activator of transcription (JAK/STAT) pathways to induce Bcl-x_L.¹³ In the other pathway, the β_c chain distal portion activates Ras pathways.¹⁴⁻¹⁶ E2A-HLF likely protects lymphoid progenitors from apoptosis by activating the latter because its physiologic counterpart, E4BP4/NFIL3, a related bZIP factor with antiapoptotic function, is induced by IL-3 through signals mainly from the β_c chain distal portion,¹⁷ especially through Ras-phosphoinositide 3-kinase (Ras-PI3-K) and Ras-Raf-mitogen-activated protein kinase (Ras-Raf-MAPK) pathways.¹⁵ We also identified several downstream targets of E2A-HLF, namely, SLUG, a zinc finger transcription factor implicated in the antiapoptotic function of E2A-HLF¹⁸; groucho-related genes that suppress RUNX1¹⁹; and annexin VIII and SRPUL (sushi-repeat protein up-regulated in

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Table 1. Clinical and molecular characteristics of t(17;19)⁺ ALL

Patient	Identification	Cell line	Age, y/sex	E2A-HLF type	Coagulopathy	Hypercalcemia	Outcome, mo*	Reference
1	—	UOC-B1	15/F	1	+	+	23	1,6
2	—	—	15/F	1	+	+	NA	1
3	—	HAL-O1	17/F	1 (variant)	+	—	2.5	2
4	DEN-R	—	NA	2	—	NA	NA	4
5	RFH-N	—	NA	2	—	NA	NA	4
6	Pt 1	—	17/F	2	—	—	56	7
7	Pt 2	—	11/M	2	—	+	8.5	7
8	Pt 3	—	13/M	1 + 2	—	+	NA	7
9	—	YCUB-2	4/M	2	—	+	NA	8
10	—	—	12/F	1	—	NA	8	9
11	—	Endo-kun	14/F	2	—	+	9	This paper
12	—	—	12/F	2	+	+	NA	This paper

Pt indicates patient; —, not available; and NA, not applicable.

*All 12 patients died.

leukemia), which are postulated to play paraneoplastic roles in this type of pro-B cell leukemia.²⁰

Leukemia patients with the E2A-HLF fusion product and a tendency to bleed have laboratory data similar to those of patients with t(15;17)⁺ acute promyelocytic leukemia (APL).²¹ Major determinants for the pathogenesis of APL-associated coagulopathy have been investigated for the past decade, and factors expressed in leukemia cells that affect procoagulant or fibrinolytic activities have been identified (for a review, see Falanga et al²¹). These factors include tissue factor, inflammatory cytokines such as interleukin-1 β (IL-1 β) and tumor necrosis factor- α (TNF- α), and members of the annexin family.^{22,23} One of these, annexin II, is reported to be a cause of the coagulopathy associated with APL.²⁴ Annexin II is a 36-kDa protein that forms a complex with the annexin II light chain, a member of the S100 family. Annexin II is a calcium-regulated, phospholipid-binding protein expressed on the surfaces of endothelial cells, macrophages, and some tumor cells; it has been implicated in cell-cell adhesion and in plasminogen activation, and it may function as a cell surface receptor (for reviews, see Hajjar et al^{25,26}). Surface localization of annexin II is absolutely dependent on micromolar-free Ca²⁺; the protein is stripped from the cell surface by EGTA (ethyleneglycotetraacetic acid).²⁷ Annexin II is translocated to the endothelial cell surface within 16 hours of biosynthesis, and cell surface annexin II comprises approximately 4% of the total pool of annexin II in endothelial cells.²⁷ The presence of the t(15;17) translocation is correlated with overexpression of annexin II, and annexin II mRNA expression is known to be down-regulated by treatment with all-*trans* retinoic acid (ATRA). Thus, the anomalous expression of annexin II on the surfaces of circulating APL cells may result in primary (annexin II-dependent) hyperfibrinolysis, thereby shifting the hemostatic balance toward excessive bleeding.²⁴ It has not, however, been clearly demonstrated that annexin II is a downstream target for the promyelocytic leukemia-retinoic acid receptor α (PML-RAR α) chimeric transcription factor that results from the t(15;17) translocation.²⁴ Moreover, it is controversial whether annexin II is the real cause of coagulopathy associated with APL, because laboratory findings in APL, such as elevation of the D-dimer level, suggest the occurrence of secondary hyperfibrinolysis rather than annexin II-dependent primary hyperfibrinolysis.²¹

Here, we show that annexin II is expressed at high levels in leukemia cells expressing E2A-HLF and that enforced expression of E2A-HLF in leukemia cells increases the expression of annexin II. We also demonstrate that annexin II in IL-3-dependent cells is regulated by IL-3 mainly through Ras pathways and that ectopic expression of E2A-HLF in these cells induces it in the absence of

IL-3. These findings indicate that annexin II is a downstream target of the E2A-HLF oncoprotein. However, surface expression levels of annexin II among leukemia cells with t(17;19) varied in a manner that suggests annexin II plays a role in the hypercalcemia or in the leukemic invasion rather than in the coagulopathy associated with this type of ALL.

Materials and methods

Cell culture and cell survival assay

Murine IL-3-dependent FL5.12 and Baf-3 pro-B lymphoid cells were cultured in RPMI 1640 medium supplemented with 10% fetal calf serum (FCS) and 0.3% 10T1/2-conditioned medium as a source of IL-3. Cell density was maintained below 10⁶/mL to avoid IL-3-independent growth. Establishment of FL5.12 cells expressing zinc-inducible E2A-HLF (FL5.12/E2A-HLF) or annexin II (FL5.12/annexin II) using the pMT-CB6+ eukaryotic expression vector (a gift from Dr F. Rauscher III, Wistar Institute, Philadelphia, PA) has been described previously.¹¹ Stable transfectants of a truncated form of the human GM-CSF (hGM-CSF) receptor (β 544 cells) and Ras mutants were described previously.^{14,28} Transfectants were maintained in medium containing either 0.6 μ g/mL G418 or 200 μ g/mL hygromycin. Human ALL cell lines that express E2A-HLF (UOC-B1, HAL-O1, YCUB-2, and Endo-kun) and other leukemia cell lines (Sup-B2, RS4;11, REH, 697, Jurkat, and NB-4) were cultured in RPMI 1640 medium containing 10% FCS; 697/E2A-HLF and 697/pMT cells that were transfected with the pMT/E2A-HLF vector or the empty pMT-CB6+ vector were described previously.²⁰ For cell survival assays, annexin II or E2A-HLF expression was induced in FL5.12 cells by adding 100 μ M ZnCl₂ for 16 hours before growth factor deprivation. IL-3 was removed by repeated centrifugation in fresh media, the cells were adjusted to 5 \times 10⁵/mL on day 0, and culture continued without IL-3. Viable cell numbers were determined by trypan blue dye exclusion. Wortmannin and LY294002 were purchased from Sigma-Aldrich (St Louis, MO).

Cloning of annexin II full-length cDNA and Northern blot analysis

The annexin II cDNA was cloned from UOC-B1 cells by reverse transcription-polymerase chain reaction (RT-PCR) using upstream and downstream primers (5'-TCTCAGCTCTCGGCGCACGG-3' and 5'-TTTCTAGACCTGTTAGCT-3'). RT-PCR was performed with a cDNA Cycle Kit (Invitrogen, Carlsbad, CA). DNA sequencing confirmed that the insert sequence was identical to that of the annexin II cDNA.²⁹ Total cellular or poly(A)-selected RNA was isolated using RNeasy kits (Qiagen, Hilden, Germany) or Fast Track kits (Invitrogen), respectively, according to the manufacturers' instructions. One microgram of messenger RNA or 20 μ g total RNA was separated by electrophoresis in 1% agarose gels

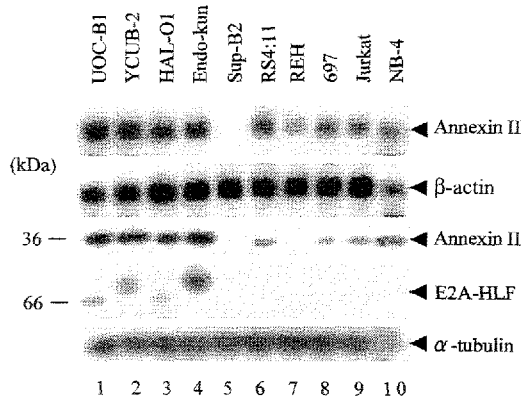


Figure 1. Expression of annexin II in human leukemia cell lines. (Top 2 panels) Northern blot analysis of poly(A)⁺ RNA (1 µg per lane) isolated from human leukemia cell lines. The blot was hybridized with an annexin II cDNA probe and then rehybridized with a β-actin probe. (Lower 3 panels) Immunoblot analysis using whole-cell lysates. Annexin II, E2A-HLF, and α-tubulin proteins were detected with specific antibodies. Lanes 1 to 4: UOC-B1, YCUB-2, HAL-O1, and Endo-kun t(17;19)-positive pro-B ALL cell lines. Lanes 5 to 8: Sup-B2, RS4;11, REH, and 697 pro-B ALL cell lines without t(17;19). Lane 9: Jurkat T-ALL cell line. Lane 10: NB-4 APL cell line.

containing 2.2 M formaldehyde, transferred to nylon membranes, and hybridized with an appropriate probe according to standard procedures.

Immunoblot analysis

Cells were solubilized in Nonidet P-40 lysis buffer (150 mM NaCl, 1.0% Nonidet P-40, 50 mM Tris, pH 8.0), and total cellular proteins were separated by sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS-PAGE). After wet electrotransfer onto nitrocellulose membranes, the proteins were detected using appropriate antibodies and following standard procedures. Blots were then stained with primary antibodies followed by horseradish peroxidase–conjugated antirabbit immunoglobulin secondary antibodies and were subjected to chemiluminescent detection according to the manufacturer’s instructions (Amersham Pharmacia Biotech, Buckinghamshire, England). Anti-annexin II polyclonal antibody was purchased from BD Transduction Laboratories (Lexington, KY). Anti-HLF(C) antibody for the detection of the E2A-HLF chimeric protein was described previously.³⁰ For immunoblot analysis of cell surface eluates, cells (1 × 10⁸) were washed 3 times with either Hanks balanced salt solution (HBSS; Invitrogen) alone or HBSS containing 4 mM CaCl₂ (HBSS/Ca) and were treated with either HBSS alone or HBSS/Ca for 30 minutes on ice. Elutes were collected and were solubilized in Laemmli lysis buffer (10% glycerol, 2% SDS, 50 mM Tris, pH 8.0) and were separated using SDS-PAGE. Assays for eluted lactate dehydrogenase were performed as previously described.²⁷

Results

Annexin II is induced by E2A-HLF

We performed Northern blot and immunoblot analyses to test the expression of annexin II in human leukemia cell lines. Because t(17;19)⁺ ALLs constitute only approximately 1% of childhood B-precursor ALLs,³ we used cell lines instead of primary patient samples. Four cell lines harboring the E2A-HLF chimeric protein (UOC-B1, HAL-O1, YCUB-2, and Endo-kun) uniformly expressed annexin II mRNA and protein at higher levels than NB-4, a t(15;17)-positive APL cell line used as a positive control (Figure 1, lanes 1-4, 10).

Sup-B2, a non-t(17;19) pro-B ALL cell line, lacked expression of annexin II (lane 5). Although annexin II mRNA was detected in other lymphoid leukemia cell lines (RS4;11, REH, 697, and Jurkat)

that lack E2A-HLF expression, annexin II protein was less abundant in these cells than in cells expressing E2A-HLF (lanes 6-9). The E2A-HLF fusion protein from each of the t(17;19)⁺ pro-B ALL cell lines migrated differently because the joining region at the fusion junction contains different numbers of inserted nucleotides, as described previously (fourth panel).^{1,2}

Next, we tested whether E2A-HLF induces the expression of annexin II. For these experiments, 697 cells were transfected with a pMT-CB6+/E2A-HLF construct (see “Materials and methods”) to generate clones that express zinc-inducible E2A-HLF. Ectopic expression of E2A-HLF in 697 cells induced annexin II (Figure 2). However, 697/E2A-HLF cells grown without zinc showed a low (baseline) level of annexin II expression that was not observed in 697/pMT cells, possibly because of the leaky expression of E2A-HLF (Figure 2, lanes 1 and 7).

In control 697/pMT cells, which contain the empty vector, annexin II expression levels were unaffected by zinc, confirming that the observed changes in gene expression were induced by E2A-HLF, not by zinc (Figure 2, lanes 7-8). A comparison of the magnitude of induction of annexin II mRNA and protein suggested that E2A-HLF-induced annexin II not only by affecting mRNA levels but also through posttranscriptional mechanisms.

Annexin II is regulated by IL-3-initiated signaling pathways

We previously reported that E2A-HLF reverses apoptosis caused by cytokine starvation in murine IL-3-dependent lymphoid cells, such as Baf-3 and FL5.12 cells, indicating that the chimeric transcriptional factor at least partially substitutes for cytokine-initiated signaling.¹¹ These findings prompted us to test whether expression of annexin II is under the control of cytokines. A marked decline in annexin II mRNA levels was observed within 8 hours or 4 hours of IL-3 deprivation in Baf-3 or FL5.12 cells, respectively (Figure 3). Similarly, annexin II protein expression declined, as shown by immunoblot analysis (Figure 3A-B, each third panel).

To identify the signaling pathways regulating the expression of annexin II, we used Baf-3 cells expressing a truncated form (residues 1-544) of the human βc chain (β544 cells).¹⁴ In β544 cells, stimulation with hGM-CSF activates pathways emanating from the βc chain proximal region, such as JAK2/STAT5, but it does not activate signaling pathways from the βc chain distal region, including Ras pathways.¹⁴ As expected, Bcl-x_L mRNA, which is known to be regulated by JAK/STAT pathways,^{13,15}

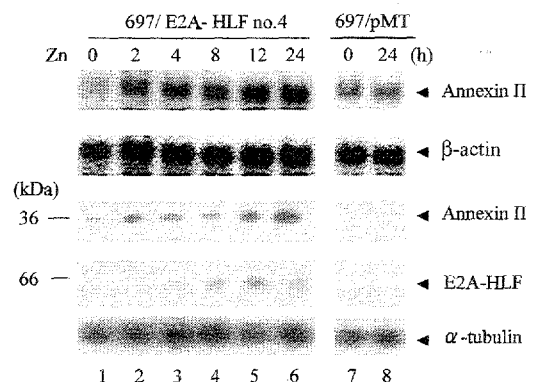


Figure 2. Induction of annexin II by enforced expression of E2A-HLF in human ALL cells. 697 cells inducibly expressing E2A-HLF (697/E2A-HLF cells) and control 697/pMT cells were cultured in medium containing 100 µM Zn²⁺ for the indicated times. (Top 2 panels) Northern blot analysis of poly(A)⁺ RNA (1 µg). The blot was hybridized with an annexin II cDNA probe and then rehybridized with a β-actin probe. (Lower 3 panels) Immunoblot analysis detecting annexin II, E2A-HLF, and α-tubulin proteins.

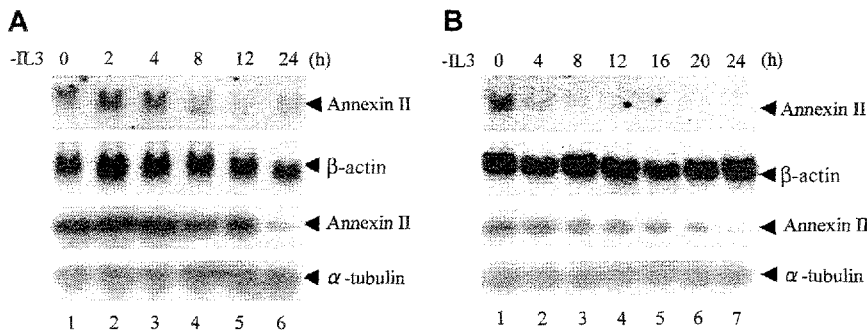


Figure 3. IL-3-dependent expression of annexin II. Baf-3 cells (A) or FL5.12 cells (B) were cultured in IL-3-free medium for the indicated times. (Top 2 panels) Northern blot analysis of total RNA (20 µg). The blot was hybridized with an annexin II cDNA probe and then rehybridized with a β -actin probe. (Lower 2 panels) Immunoblot analysis to detect annexin II and α -tubulin proteins.

returned rapidly to its original level after the addition of hGM-CSF (Figure 4A, bottom panel). In contrast, annexin II mRNA was barely detectable 8 hours after IL-3 deprivation (Figure 4A, upper panel, lane 2) and remained low after the addition of hGM-CSF (lanes 3-10). These results suggest that signals originating from the β c chain proximal region are not important for the stable expression of annexin II but that signals from the β c chain distal region are indispensable for annexin II gene expression.

Oncogenic RAS and E2A-HLF induce annexin II expression in mouse pro-B lymphocytes

To further identify the pathways regulating annexin II gene expression, we used Baf-3 cells with dexamethasone (Dex)-inducible expression of a constitutively active form of Ras (Ras^{G12V}).¹⁴ The level of annexin II mRNA declined by 4 hours after IL-3 deprivation and Dex treatment, but it was restored after 24 hours (Figure 4B). These effects appeared to be induced by Ras^{G12V}, not by Dex itself, because annexin II mRNA was not induced in wild-type Baf-3 cells after the addition of Dex (data not shown). Induction of annexin II by Ras^{G12V} was partially reversed by the PI3-K inhibitor wortmannin (right panel), suggesting that PI3-K pathways are important for annexin II expression.

Indeed, the Ras^{G12V/V45E} mutant, which activates PI3-K but not Raf-MAPK pathways,¹⁴ induced annexin II at levels similar to those induced by Ras^{G12V}, and this effect was almost completely reversed by wortmannin (Figure 4C). These results were confirmed by the use of another PI3-K inhibitor, LY294002 (data not shown), suggesting that Ras/PI3-K is an important pathway in the regulation of annexin II gene expression under the control of cytokines.

Next, we tested whether enforced expression of the E2A-HLF chimera can induce the expression of annexin II in FL5.12 cells in the absence of IL-3. For these experiments, we established FL5.12 cells expressing zinc-inducible E2A-HLF. Annexin II mRNA and protein expression persisted up to 32 hours after IL-3 starvation

(Figure 4D), in contrast to the rapid decline in wild-type FL5.12 cells (Figure 3B), suggesting that E2A-HLF partially substitutes for the function of cytokine-initiated signaling pathways that induce annexin II expression.

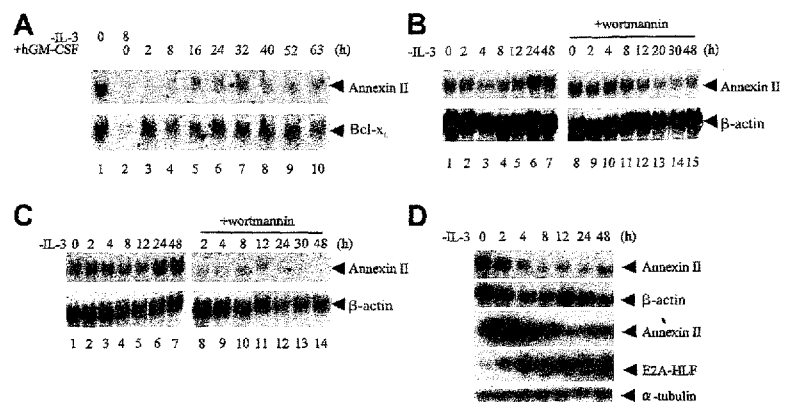
Induction of cell-surface annexin II by E2A-HLF

To gain insight into the roles of annexin II overexpressed in leukemia cells with t(17;19), we quantified cell-surface annexin II by eluting it with calcium-free HBSS, which disrupts the calcium-dependent binding of annexin II to the cell surface (see "Materials and methods").³¹ The eluate was then tested for annexin II by immunoblot analysis. As expected, no annexin II was detected when cells were treated with HBSS containing 4 mM CaCl₂ (Figure 5A, even-numbered lanes). Of 4 cell lines harboring the E2A-HLF chimeric protein, 3 showed high levels of surface annexin II, similar to that of NB-4 (lanes 1, 3, 7, and 19).²⁴ In the third E2A-HLF-expressing cell line, HAL-O1, surface expression of annexin II was much less, though clearly, detectable (lane 5). Surface expression of annexin II was barely detectable from cells without E2A-HLF or PML-RAR α (lanes 9, 11, 13, 15, and 17).

As a control, the eluates were also assayed for lactate dehydrogenase (LDH) activity. LDH activity was uniformly low in calcium-free and calcium-containing eluates (data not shown), suggesting that annexin II protein detected in this assay originated from the cell surface, not from the cytoplasm. Two cell lines with high levels of surface annexin II, YCUB-2 and Endo-kun, were derived from patients without hemorrhagic complications at onset, whereas HAL-O1, which expressed less surface annexin II, was established from a patient with coagulopathy (Table 1). These results thus suggested that levels of surface annexin II are not related to coagulopathy.

Annexin II mRNA and protein were quantified by densitometry; Figure 5B shows levels of mRNA and total and surface protein relative to those of NB-4 cells as positive control. The magnitude of

Figure 4. Pathways regulating annexin II expression in IL-3-dependent cells. (A) β 544 cells were cultured in cytokine-free medium for 8 hours (lane 2) and then in medium containing hGM-CSF for the indicated times (lanes 3-10). The Northern blot was hybridized with an annexin II cDNA probe and then rehybridized with a mouse Bcl-x_L cDNA probe. (B-C) Baf-3 cells expressing Ras^{G12V} (B) or Ras^{G12V/V45E} (C) under the regulation of Dex were cultured in IL-3-free medium containing 10⁻⁷ M Dex in the absence (left blots) or presence (right blots) of wortmannin (0.5 µM) for the indicated times. The Northern blots were hybridized with an annexin II cDNA probe and then rehybridized with a β -actin probe. (D) FL5.12 cells inducibly expressing E2A-HLF were cultured in IL-3-free medium containing 100 µM Zn²⁺ for the indicated times. (Top 2 panels) The Northern blot was hybridized with an annexin II cDNA probe and then rehybridized with a β -actin probe. (Lower 2 panels) Immunoblot analysis to detect annexin II, E2A-HLF, and α -tubulin using specific antibodies.



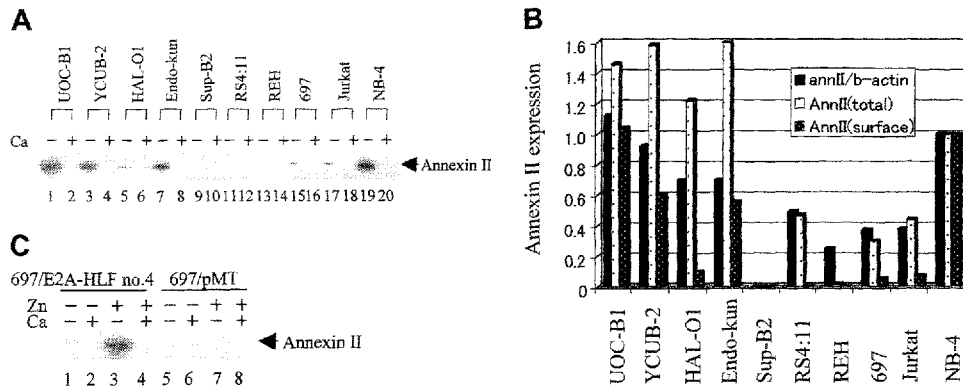


Figure 5. Immunodetection of annexin II from the cell surface of human leukemic cell lines. (A) Human leukemia cell lines were treated with either HBSS alone (lanes with a minus sign) or HBSS containing 4 mM CaCl₂ (lanes with a plus sign) for 30 minutes. Annexin II proteins were detected with specific antibodies. (B) The levels of mRNA and total and surface annexin II were determined by the band intensity of autoradiograms from Figures 1 and 5A. Amounts shown are relative to levels in the NB-4 APL cell line. AnnII/b-actin indicates ratio of annexin II mRNA to β-actin mRNA; annII(total), total annexin II protein; and annII(surface), surface annexin II protein. (C) 697/E2A-HLF cells and 697/pMT cells were cultured in medium with or without 100 μM Zn²⁺ as indicated for 16 hours before treatment with either HBSS alone (lanes with a Ca²⁺ minus sign) or HBSS/Ca (lanes with a Ca²⁺ plus sign). Annexin II proteins were detected using specific antibodies.

total annexin II protein induction was greater than that of mRNA, suggesting that E2A-HLF induces annexin II not only at the mRNA level but also through posttranscriptional mechanisms, in accordance with the results from enforced expression of E2A-HLF (Figure 2). In contrast, a comparison of the magnitude of induction of total annexin II protein with surface annexin II suggests that E2A-HLF does not selectively induce surface annexin II.

Next, we tested whether ectopic expression of E2A-HLF induces the surface expression of annexin II. Following zinc-induced overexpression of E2A-HLF in 697/E2A-HLF cells, levels of surface annexin II were increased (Figure 5C, lanes 1-4). Surface annexin II levels were unaffected by zinc in control 697/pMT cells, confirming that the observed changes in gene expression were induced by E2A-HLF and not by zinc (lanes 5-8).

Lack of antiapoptotic activity of annexin II

Because E2A-HLF protects IL-3-dependent lymphoid cells from apoptosis caused by IL-3 deprivation,¹¹ we tested whether annexin II is involved in the regulation of cell survival (Figure 6A). FL5.12 cells expressing E2A-HLF survived more than 4 days in IL-3-free medium, as we previously reported (Figure 6B).¹¹ In contrast, cells with zinc-induced overexpression of annexin II did not survive without the cytokine (Figure 6B),

suggesting that annexin II does not contribute to the survival of hematopoietic progenitors.

Discussion

In this study, we demonstrated that annexin II expression is regulated by IL-3 in murine IL-3-dependent Baf-3 and FL5.12 cells (Figure 3). Using β544 cells and cells expressing constitutively active Ras mutants, Ras pathways, including Ras/PI3-K pathways, were shown to be major regulators of annexin II expression (Figure 4). On the other hand, enforced expression of E2A-HLF induced annexin II in these lymphoid cells in the absence of IL-3 (Figure 4D) and in human leukemia cell lines (Figure 2), indicating that annexin II is a downstream target of E2A-HLF. E2A-HLF induced annexin II not only by affecting mRNA levels but also through posttranscriptional mechanisms (Figures 2, 5B).

In earlier studies, we reported that inhibition of the DNA-binding ability of E2A-HLF by a dominant-negative form of this chimeric transcription factor induces apoptosis in UOC-B1 cells but does not affect the cell cycle.¹¹ We also demonstrated that E2A-HLF protects Baf-3 and FL5.12 cells from apoptosis caused

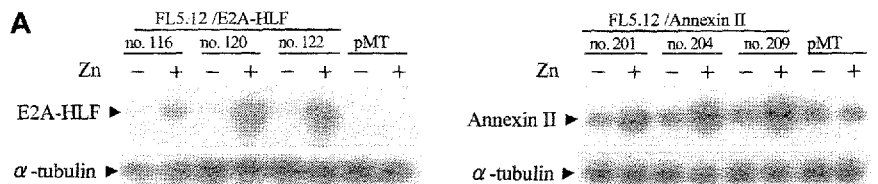
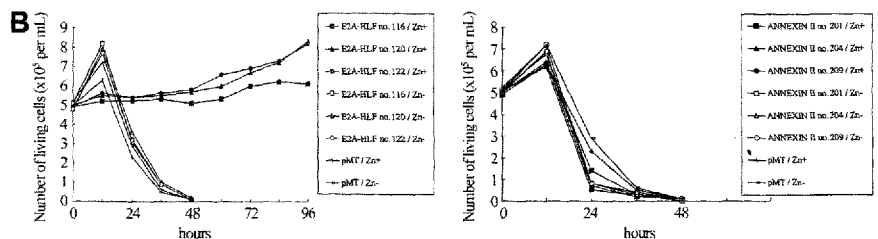


Figure 6. Effect of E2A-HLF and annexin II on the survival of FL 5.12 cells deprived of IL-3. (A) Immunoblot analysis of 3 independently established clones of G418-resistant FL5.12 cells stably transfected with pMT/E2A-HLF (left blot) or pMT/annexin II (right blot) and control cells that received the empty pMT vector. Cells were cultured in the presence or absence of zinc. E2A-HLF (left blot, top row) and annexin II (right blot, top row) and α-tubulin (both blots, bottom row) proteins were detected using specific antibodies. (B) Survival of the transfected FL5.12 cells in the absence of IL-3. Cells growing exponentially in IL-3-containing medium in the presence or absence of 100 μM Zn²⁺ for 16 hours were adjusted to 5 × 10⁵ cells/mL at hour 0, and viable cell numbers were determined at the indicated times after the removal of IL-3.



by IL-3 starvation,^{11,12} suggesting that E2A-HLF contributes to leukemogenesis through dysregulation of the cytokine-initiated cell survival system in hematopoietic progenitors. Consequently, we have postulated that a transcription factor acts as a physiologic counterpart of E2A-HLF in these IL-3-initiated cell survival systems. We identified a related bZIP factor, E4BP4/NFIL3, as a candidate, because E4BP4 avidly binds to the consensus DNA-binding sequence of E2A-HLF and because E4BP4 is induced by IL-3 through signals mainly from the β chain distal portion,¹⁷ especially through Ras-PI3-K and Ras-Raf-MAPK pathways.¹⁵ Moreover, the enforced expression of E4BP4 in IL-3-starved Baf-3 and FL5.12 cells delays apoptosis.¹⁷

Annexin II expression is unlikely to be controlled by antiapoptotic pathways regulated by E4BP4 because the overexpression of annexin II did not protect FL5.12 cells from apoptosis caused by IL-3 starvation (Figure 6B) and because we observed that the enforced expression of E4BP4 in IL-3-deprived FL5.12 cells did not induce annexin II (data not shown). Obviously, downstream targets of E4BP4 are not the only pathway that E2A-HLF aberrantly activates in B-precursor cells. E2A-HLF almost completely blocks apoptosis caused by cytokine deprivation of FL5.12 cells (Figure 6B), but E4BP4 has limited antiapoptotic effects.^{15,17} Therefore, annexin II appears to be regulated by another unidentified pathway under the control of IL-3 through Ras pathways in B-progenitor cells, and E2A-HLF constitutively activates this pathway to induce annexin II in t(17;19)-positive leukemia cells.

The proportion of annexin II on the cell surface compared with the total cellular expression levels varied among the cell lines. For instance, the total annexin II level in RS4;11 cells was nearly half that in NB-4 (Figure 1), but the cell surface annexin II of RS4;11 was barely detectable (Figure 5A), suggesting that translocation of this protein from the cytosol to the cell surface may be regulated in a manner dependent on cell lineage or maturation stage. The cell surface annexin II levels of 4 cell lines expressing E2A-HLF also diverged, in spite of the similar total annexin II levels of these 4 cell lines (Figures 1 and 5A-B). These results might be explained by the differences in E2A-HLF expressed in these 4 cell lines—that is, UOC-B1 expresses type 1, YCUB-2 and Endo-kun express type 2, and HAL-O1 expresses type 1 with a mutation in the leucine zipper region of HLF that alters the fusion protein's DNA-binding properties.¹⁰

The surface expression of annexin II is unlikely to be related to coagulopathy as an initial symptom, because HAL-O1 cells, which have low surface expression of annexin II, were derived from a patient with coagulopathy, whereas YCUB-2 and Endo-kun showed high expression of surface annexin II but derive from patients without coagulopathy (Table 1; Figure 5A). Surface annexin II could be correlated with hypercalcemia at onset, the other rare complication in pro-B ALL, because HAL-O1 is the only t(17;19)⁺ cell line that was derived from a patient without hypercalcemia. The biologic significance of cytokine-dependent annexin II expression in lymphoid cells is unclear, but it was recently reported that in rat adrenal pheochromocytoma (PC-12) cells, nerve growth factor (NGF) induces annexin II, which contributes to NGF-induced neuritogenesis in the differentiating PC-12 cells through the generation of plasmin.³² On the other hand, annexin II has been implicated in the proliferation of hepatocytes and neurons^{33,34} and in the invasion and metastasis of various tumors, including glioblastoma multiforme, pancreatic cancer, lung cancer, and gastric cancer.³⁴⁻³⁷ Annexin II interacts with procathepsin B on the surfaces of tumor cells and is involved in extracellular proteolysis, facilitating tumor invasion and metastasis.³⁸ It has also been suggested that annexin II may play a critical role in the tissue plasminogen activator-dependent, plasmin-mediated invasion of malignant glioma cells.³⁹ Although overexpressed annexin II lacked antiapoptotic activity in IL-3-dependent cells (Figure 6B), E2A-HLF-positive leukemia is characterized by bone invasion and hypercalcemia, which are paraneoplastic syndromes that are rare complications in other types of childhood acute B-lineage leukemia.^{7,11} Based on the results of this study, we postulate that annexin II overexpression is a general feature of E2A-HLF-positive pro-B cell ALL and that it may have a causative role in one or more of the unique paraneoplastic syndromes associated with the expression of this oncogenic transcription factor.

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Roles of Bim in Apoptosis of Normal and Bcr-Abl-Expressing Hematopoietic Progenitors

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Bcr-Abl kinase is known to reverse apoptosis of cytokine-dependent cells due to cytokine deprivation, although it has been controversial whether chronic myeloid leukemia (CML) progenitors have the potential to survive under conditions in which there are limited amounts of cytokines. Here we demonstrate that early hematopoietic progenitors (Sca-1⁺ c-Kit⁺ Lin⁻) isolated from normal mice rapidly undergo apoptosis in the absence of cytokines. In these cells, the expression of Bim, a proapoptotic relative of Bcl-2 which plays a key role in the cytokine-mediated survival system, is induced. In contrast, those cells isolated from our previously established CML model mice resist apoptosis in cytokine-free medium without the induction of Bim expression, and these effects are reversed by the Abl-specific kinase inhibitor imatinib mesylate. In addition, the expression levels of Bim are uniformly low in cell lines established from patients in the blast crisis phase of CML, and imatinib induced Bim in these cells. Moreover, small interfering RNA that reduces the expression level of Bim effectively rescues CML cells from apoptosis caused by imatinib. These findings suggest that Bim plays an important role in the apoptosis of early hematopoietic progenitors and that Bcr-Abl supports cell survival in part through downregulation of this cell death activator.

In the chronic phase, chronic myeloid leukemia (CML) is characterized by massive proliferation of granulocytes in the peripheral blood and their progenitors in the bone marrow. Abnormal hematopoietic stem cells harboring the *Bcr-Abl* chimeric gene still differentiate into mature granulocytes with apparently normal function but gradually come to occupy the hematopoietic space. They subvert the system controlling their homeostasis in the body and thus accumulate in large numbers. Because cytokines are considered to play critical roles in this homeostasis, dysregulation of cytokine-mediated cell death, cell survival, or cell division by Bcr-Abl may be responsible for leukemogenesis. Indeed, among multiple systems regulating diverse cell functions, including cell proliferation, differentiation, and apoptosis, which are dysregulated by Bcr-Abl, the reversal of apoptosis caused by cytokine deprivation is one of the most consistently observed effects (reviewed in references 15 and 23). This finding has been repeatedly demonstrated by use of different experimental systems that include murine interleukin-3 (IL-3)-dependent Baf-3 and 32D cells (8, 9, 11, 22, 28, 32, 37, 39).

We and others have investigated this cytokine-dependent cell survival system in hematopoietic progenitors by using IL-3-dependent cells and demonstrated that two distinct signaling

pathways support cell survival. One pathway emanates from the membrane-proximal region of the common receptor chain (β c chain) shared by IL-3 and granulocyte-macrophage colony-stimulating factor, which activates JAK-STAT pathways and transcriptionally upregulates Bcl-x_L expression (14, 45, 46). The other pathway functions via the distal portion of the β c chain and activates Ras pathways (26, 27, 30). Because experiments using Baf-3 cells expressing truncated forms of the β c chain revealed that signals from its proximal portion support cell survival only transiently, signals from its distal region, especially the activation of Ras pathways, were considered to be indispensable for long-term cell survival supported by cytokines (26; also reviewed in reference 35).

Recent progress has revealed that cell death decisions are implemented through an evolutionarily conserved mechanism (or general apoptosis program) in which members of the Bcl-2 superfamily play the central roles (reviewed in references 1 and 7). The anti- or proapoptotic family members regulate the translocation of cytochrome *c* from mitochondria to the cytosol, an event that ultimately activates the caspase cascade, while members of the BH3-only subfamily of cell death activators inhibit the function of the antiapoptotic Bcl-2 family members by binding to them. In mammals, more than three factors have been identified to be members of each subfamily. Redundancy in each category of the Bcl-2 superfamily has been explained, at least partially, by the tissue- and/or stimulus-specific response of each family member. We therefore concentrated on identifying the major Bcl-2 superfamily mem-

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TABLE 1. Primers used in this study for real-time quantitative RT-PCR

Gene product	Product size (bp)	Forward primer	Reverse primer
A1	168	GGGAAGATGGCTGAGTCTGAGCTCATG	TGACTTCAGATTCTTTTCAACTTC
Bad	233	CCACCAACAGCTATCATGGAGGCGC	GCTCTTTGGCGAGGAAGTCCCTTG
Bax	162	AATATGGAGCTGCAGAGGATGATTG	GCACITTAGTGCACAGGGCCTTGAG
Bcl-2	261	GTGGTGGAGGAACTCTTCAGGGATG	GGTCTTCAGAGACAGCCAGGAGAAATC
Bcl-x _L	293	GTAAGTGAATGAACCTCTTCGGGATGG	ACCAGCCACAGTCATGCCCGTCAGG
BimEL	324	AGTGGGTATTTCTCTTTTGACACAG	TCAATGCCTTCTCCATACCAGACG
Bim(si)	119	AATGTCTGACTCTGACTCTCGGAC	TCTCCGACGGCTGCAATTGTCTAC
Mcl-1	259	GTAATGGTCCATGTTTCAAAGATG	AAGCCAGCAGCACATTTCTGATGCC
DP5/Hrk	189	AGACCCAGCCCGGACCGAGCAA	AATAGCACTGGGGTGGCTCT
28S rRNA	324	ACGCAGGTGTCTTAAGGCGAGCTC	CACGACGGTCTAAACCCAGCTCAC

ber that is regulated by signals from the distal portion of the β chain, especially via Ras pathways. We and others have found that mRNA and protein expression levels of Bim, a member of the BH3-only death activator subfamily, are downregulated by IL-3 through either the Ras/Raf/mitogen-activated protein kinase (MAPK) or the Ras/phosphatidylinositol 3-kinase (PI3-K) pathway in Baf-3 cells (13, 44). Bim was isolated independently by two groups that exploited its ability to bind Bcl-2 or Mcl1 (20, 36). Alternative splicing gives rise to three variants, BimEL, BimL, and BimS, each of which contains the BH3 domain and functions as a death inducer. It was shown that Bim was induced in Baf-3 cells by IL-3 deprivation but not by other apoptotic triggers, such as DNA damage or Fas, and that enforced expression (but not overexpression) of each form of Bim induced apoptosis in Baf-3 cells even in the presence of IL-3 (44). In addition to Bim induction in hematopoietic cells, the induction of Bim by deprivation of nerve growth factor (NGF) in primary cultures of rat sympathetic neurons, as well as in neuronally differentiated rat pheochromocytoma PC-12 cells, has been reported (5, 40, 49). These findings suggest that the level of Bim expression is a major determinant of cell fate regulated by cytokines.

In addition to its role as a key intracellular factor for cytokine-mediated cell survival, Bim was demonstrated to be an essential regulator of the total number of white blood cells by analysis of Bim-deficient mice (6). Bim-deficient mice have increased numbers of mature monocytes, granulocytes, and lymphocytes but not erythrocytes in the peripheral blood, with overgrowth of hematopoietic precursors in the bone marrow. This prompted us to investigate the roles of Bim as a possible downstream target of Bcr-Abl by using our previously established transgenic (tg) mice in addition to the conventional experimental systems for CML, such as cell lines established from patients in the blast crisis (BC) phase and cytokine-dependent cells expressing Bcr-Abl. In these tg mice, Bcr-Abl is expressed under the control of the *tec* tyrosine kinase promoter that is active in immature myeloid progenitors (16, 17, 33). Virtually all of these mice develop CML-like disease, namely, proliferation of mature myeloid precursors and megakaryocytes in the bone marrow with increased granulocytes and platelets in the peripheral blood and progressive anemia, within 8 months of birth. They generally die of the disease within 15 months (18). Moreover, when they are intercrossed with p53 haplo-deficient mice, they develop T-cell leukemia and lack functional p53 (19), indicating that this model mimics human CML in both the chronic and BC phases. Here

we show that Bim plays an important role in the apoptosis of early hematopoietic progenitors and that Bcr-Abl supports cell survival in part through the downregulation of this cell death activator.

MATERIALS AND METHODS

Mice. p210^{Bcr/Abl} tg (*BCR-ABL*^{tg}) mice were previously described (18). Because the founder mice were generated by using ova derived from (C57BL \times DBA)F₂ (BDF₂) mice and the tg progeny were generated by intercrossing the tg mice with BDF₂ mice, the genetic background of the *BCR-ABL*^{tg} mice was a mixture of C57BL/6 and DBA. We used the normal littermates of these mice (*BCR-ABL*^{-/-}) as controls in this study.

Primary culture and isolation of cytokine-dependent hematopoietic progenitors. Mice that were 8 to 12 weeks of age were sacrificed, and bone marrow cells were harvested by a standard procedure. Cells were cultured for 5 days in serum-free medium (SF-O2; Sanko Junyaku, Tokyo, Japan) containing 10 ng of thrombopoietin (TPO) per ml and 50 ng of stem cell factor (SCF) per ml. After Ficoll gradient centrifugation to separate dead cells and mature granulocytes, cells expressing lineage-specific markers (CD4, CD8, CD11b, CD41, or Gr-1) were eliminated by using magnetic beads conjugated with specific antibodies (Miltenyi Biotec, Bergisch Gladbach, Germany). More than 90% of lineage marker-negative (Lin⁻) cells obtained by this procedure were positive for c-Kit. These cells were further divided into Sca-1-enriched (Sca-1⁺ c-Kit⁺ Lin⁻) and Sca-1-depleted (Sca-1⁻ c-Kit⁺ Lin⁻) fractions by using magnetic beads conjugated with Sca-1 antibody. Viable cell counts were determined by trypan blue dye exclusion in triplicate assays. Morphology was determined by using cytospin preparations stained with May-Giemsa solution.

TUNEL analysis. Cells in the Sca-1-enriched fraction were cultured in cytokine-free medium for different periods. Cells were harvested and fixed with 4% paraformaldehyde for 20 min, and a terminal deoxynucleotidyltransferase-mediated nick end labeling (TUNEL) assay was performed with an apoptosis detection kit according to the manufacturer's directions (Promega, Madison, Wis.). Cells were then stained with 1 μ g of propidium iodide per ml. Cytospin preparations were made, and the incorporation of dUTP was analyzed with a laser cytoscan (Olympus, Tokyo, Japan).

Real-time quantitative RT-PCR. Total cellular RNA was isolated with an Isogen kit according to the manufacturer's instructions (Wako Pure Chemicals, Osaka, Japan). RNA was reverse transcribed with Superscript II reverse transcriptase (Invitrogen, Carlsbad, Calif.). Real-time PCR was carried out with an ABI 7700 instrument and SYBR green PCR master mix (Applied Biosystems, Weiterstadt, Germany), which allows real-time monitoring of the increase in PCR product concentration after every cycle based on the fluorescence of the double-stranded-DNA-specific dye SYBR green. The number of cycles required to produce a product detectable above background levels was measured for each sample and used to calculate differences (*n*-fold) in starting mRNA levels for each sample. Because we had observed that levels of β -actin and GAPDH (glyceraldehyde-3-phosphate dehydrogenase) mRNA, which are generally used for monitoring equal loading of RNA, were rapidly downregulated in the course of apoptosis by cytokine deprivation in murine IL-3-dependent cell lines (data not shown), we used 28S rRNA as an internal control. The gene primers, selected to cross introns, are listed in Table 1. The real-time reverse transcription (RT)-PCR products were resolved on a 2% agarose gel containing ethidium bromide to confirm that only single bands of the predicted size were visible.

RNA interference. K562 cells were cultured in medium containing 1 μ M imatinib for 24 h. Cells (2×10^6) were then transfected with 5 μ g of double-stranded Cy3-labeled Bim small interfering RNA (siRNA) or control siRNA by using a hemagglutinating virus of Japan (HVJ) envelope (GenomeONE; Ishihara Sangyo Kaisha, Osaka, Japan) according to the manufacturer's directions. Cell culture was continued in the presence of imatinib for 24 h, and then cells were harvested to isolate RNA and cell lysate. Cells were also stained with annexin V-fluorescein isothiocyanate (FITC) (Promega), followed by analysis with flow cytometry. The primers used were the following, according to Reginato et al. (42): control sense, 5'-(GGCUGAACUUACGUGUACUU)d(TT)-3'; control antisense, 5'-(AAGUACACGUAAGUUACAGCC)d(TT)-3'; Bim sense, 5'-(GACCGAGAAGGUAGACAAUUG)d(TT)-3'; Bim antisense, 5'-(CAAUUGUCUACCUUCUCGGUC)d(TT)-3'.

Immunoblot analysis. Cells were solubilized in Nonidet P-40 lysis buffer (150 mM NaCl, 1.0% Nonidet P-40, 50 mM Tris [pH 8.0]) containing protease inhibitor mixture (Complete; Roche Molecular Biochemicals, Mannheim, Germany); total cellular proteins were separated by sodium dodecyl sulfate-polyacrylamide gel electrophoresis. Cell lysates extracted from 10^7 living cells for hematopoietic progenitors isolated from primary culture or 10^6 living cells for Baf-3 or cell lines established from patients with leukemia were applied to each lane. After their wet electrotransfer onto polyvinylidene difluoride membranes, the proteins were detected with the appropriate antibodies by following standard procedures. The blots were then stained with primary antibodies followed by horseradish peroxidase-conjugated anti-rabbit or anti-mouse immunoglobulin secondary antibodies and subjected to chemiluminescence detection according to the manufacturer's instructions (Amersham, Little Chalfont, Buckinghamshire, United Kingdom). Bim-specific polyclonal antibodies were raised against glutathione S-transferase fusion proteins containing amino acids 9 to 53 of mouse BimL, as previously described (44). Bcl-2 and Bcl-x polyclonal antibodies were purchased from Transduction Laboratories (Lexington, Ky.), a monoclonal antibody against β -actin was purchased from Chemicon (Temecula, Calif.), and polyclonal antibodies against total and phosphorylated-specific Akt and MAPK were purchased from Cell Signaling Technology (Beverly, Mass.).

Experiments using Baf-3 cells. Murine IL-3-dependent cells were cultured in RPMI 1640 medium containing 10% fetal calf serum, 20 mM HEPES, 50 μ M 2-mercaptoethanol, and 0.5% conditioned medium of 10T1/2 cells as a source of murine IL-3. To deplete IL-3, we washed the cells twice with IL-3-free growth medium. Cell lines established from patients with leukemia were cultured in RPMI 1640 medium supplemented with 10% fetal calf serum. Cell viability was determined by trypan blue dye exclusion. For retrovirus-mediated gene expression, we constructed a control CD8-expressing vector plasmid (pMX/IRES-CD8) from the pMX retroviral vector (a gift of T. Kitamura) (38) by inserting an internal ribosomal entry site (IRES)-CD8 cassette in which the mouse CD8 cDNA was fused in frame to the IRES sequence. The *Bcr-Abl* gene was expressed by inserting the cDNA immediately after the 5' long terminal repeat sequence. The retrovirus was made by the method described by Onishi et al. (38), using BOSC23 cells. Retroviral infection of Baf-3 cells and the selection of CD8-positive cells with a CD8 monoclonal antibody and MACS separation columns (Miltenyi Biotec) were performed according to a method described previously (27). The selection procedure was repeated until more than 95% of the cells were positive for CD8 by flow cytometry.

Reagents and statistical analysis. A MAPK inhibitor, PD98059 (PD), and a PI3-K inhibitor, LY294002 (LY), were purchased from Wako Pure Chemicals and Sigma-Aldrich (St. Louis, Mo.), respectively. The 2-phenylamino-pyrimidine derivative imatinib mesylate was a kind gift of Elisabeth Buchdunger (Novartis, Basel, Switzerland). An analysis of variance and the post hoc method were used to compare viable cell counts in different culture conditions. Significant differences were defined as having a *P* value of <0.05.

RESULTS

Amplification and isolation of hematopoietic progenitors from mouse bone marrow. We initially tested the role of Bim in the regulation of cell survival by using cytokine-dependent undifferentiated hematopoietic progenitors isolated from primary cultures of bone marrow cells from normal mice. Cells from normal littermates of the *Bcr-Abl* tg mice (18) were cultured for 5 days in serum-free medium containing 10 ng of TPO per ml and 50 ng of SCF per ml. After the elimination of dead cells, mature granulocytes, and cells expressing lineage-

specific markers (CD4, CD8, CD11b, CD41, or Gr-1), more than 90% of the cells were negative for lineage markers and positive for c-Kit (c-Kit⁺ Lin⁻). These cells were further divided into Sca-1-enriched fractions (Sca-1⁺ c-Kit⁺ Lin⁻; typically more than 75% of cells were positive for Sca-1 immediately after separation) and Sca-1-depleted fractions (Sca-1⁻ c-Kit⁺ Lin⁻; less than 5% of cells were positive for Sca-1) by using magnetic beads coated with Sca-1 antibody. Figure 1A shows the morphology of Sca-1⁺ c-Kit⁺ Lin⁻ cells. Typical yields of Sca-1-enriched and Sca-1-depleted fractions were 5×10^5 and 2×10^7 cells, respectively, pooled from 10 mice.

Cells in both fractions proliferated and differentiated into mature granulocytes or monocytes when culture was continued in medium containing TPO and SCF (Fig. 1B). Cell numbers increased by around 10-fold by 5 days and then decreased, and cultures died out 10 days later. Although peak cell numbers of the progeny of Sca-1⁺ c-Kit⁺ Lin⁻ cells were always greater than those of Sca-1⁻ c-Kit⁺ Lin⁻ cells, the time courses were similar. When culture was continued in the absence of cytokines, Sca-1⁺ c-Kit⁺ Lin⁻ cells rapidly died within 24 h without maturation (Fig. 1C, left panel). Sca-1⁻ c-Kit⁺ Lin⁻ cells also died but did so more slowly than Sca-1⁺ c-Kit⁺ Lin⁻ cells, and nearly half differentiated into mature granulocytes or monocytes (Fig. 1C, right panel). To confirm that the cell death observed in these experiments was apoptotic, we performed TUNEL assays (Fig. 1D). When Sca-1⁺ c-Kit⁺ Lin⁻ cells were cultured in the presence of cytokines, there was a substantial number in S phase with few TUNEL-positive cells among them (Fig. 1D, left panel). In contrast, in the absence of cytokines, cells underwent G₀/G₁ arrest with many TUNEL-positive cells (Fig. 1D, center and right panels). These results indicated that the cell division and survival of Sca-1-positive early hematopoietic progenitors isolated by this method were cytokine dependent.

Upregulation of Bim and downregulation of Bcl-2 in cytokine-deprived hematopoietic progenitors. To elucidate the contribution of Bcl-2 superfamily members to cytokine-dependent cell survival in hematopoietic progenitors, expression levels of A1, Bad, Bax, Bcl-2, Bcl-x_L, BimEL, Mcl-1, and DP5/Hrk mRNA were assessed by using real-time quantitative RT-PCR technology. In both Sca-1⁺ c-Kit⁺ Lin⁻ and Sca-1⁻ c-Kit⁺ Lin⁻ cells from normal littermates, rapid downregulation of Bcl-2 and upregulation of BimEL were consistently observed in independent experiments (Fig. 2A), while mRNA expression of other Bcl-2 superfamily members did not change significantly upon cytokine deprivation (data not shown). Although downregulation of Bcl-x_L following cytokine deprivation has been observed in many cytokine-dependent cell lines, including Baf-3, FL5.12, and 32D (27, 28, 39), Bcl-x_L expression in hematopoietic progenitors isolated by this method was not affected by cytokine deprivation (Fig. 2A). These findings were further supported at the protein level by immunoblot analysis (Fig. 2B); simultaneous downregulation of Bcl-2 and upregulation of BimEL were observed, while Bcl-x_L remained unchanged in both Sca-1⁺ c-Kit⁺ Lin⁻ and Sca-1⁻ c-Kit⁺ Lin⁻ cells. Importantly, the levels of the two antiapoptotic Bcl-2 family members Bcl-x_L and Bcl-2 were 5- to 10-fold lower in Sca-1⁺ c-Kit⁺ Lin⁻ cells than in Sca-1⁻ c-Kit⁺ Lin⁻ cells, possibly explaining the rapid apoptosis observed in the former (Fig. 1C). These results suggest that the induction

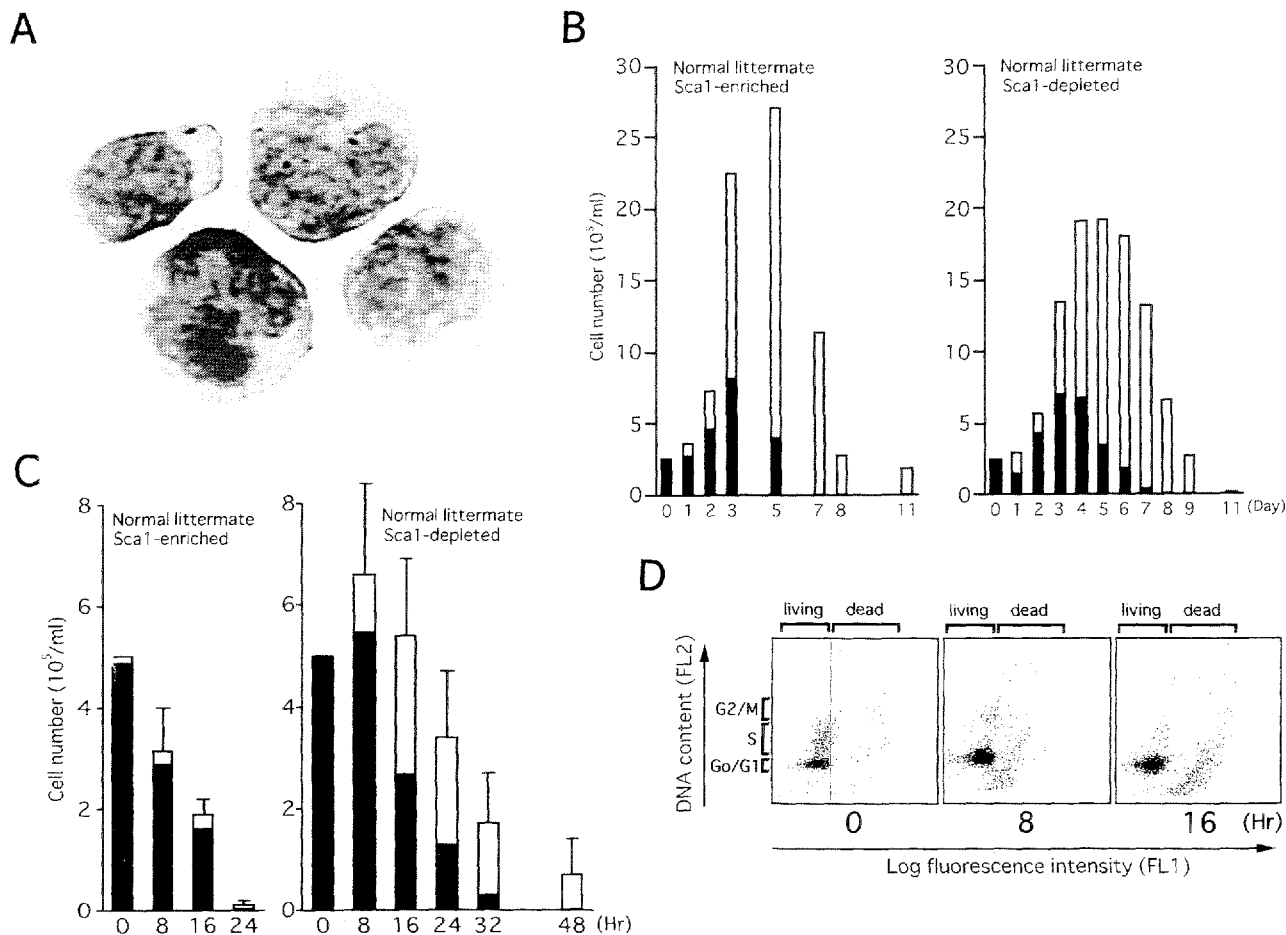


FIG. 1. Cytokine-dependent hematopoietic progenitors isolated from mouse bone marrow. (A) Cytopsin preparation showing the morphology of Sca-1-positive early hematopoietic progenitors ($Sca-1^+ c-Kit^+ Lin^-$) isolated from primary cultures of mouse bone marrow cells visualized by May-Giemsa staining. (B and C) Cultures of $Sca-1^+ c-Kit^+ Lin^-$ (left panels) and $Sca-1^- c-Kit^+ Lin^-$ cells (right panels) were continued in the presence (B) or absence (C) of SCF and TPO. The numbers of viable cells were determined by trypan blue dye exclusion. Blast cells (black bars) and terminally differentiated cells (open bars) were quantified by cytopsin centrifugation. Results from one representative study (B) and the means and standard errors of results from three independent experiments (C) are shown. (D) $Sca-1^+ c-Kit^+ Lin^-$ cells were cultured in cytokine-free medium for the indicated periods. Cells were harvested, the TUNEL assay was performed with fluorescein-dUTP, and cells were stained with propidium iodide. Cytopsin preparations were made and analyzed with a laser cytometer.

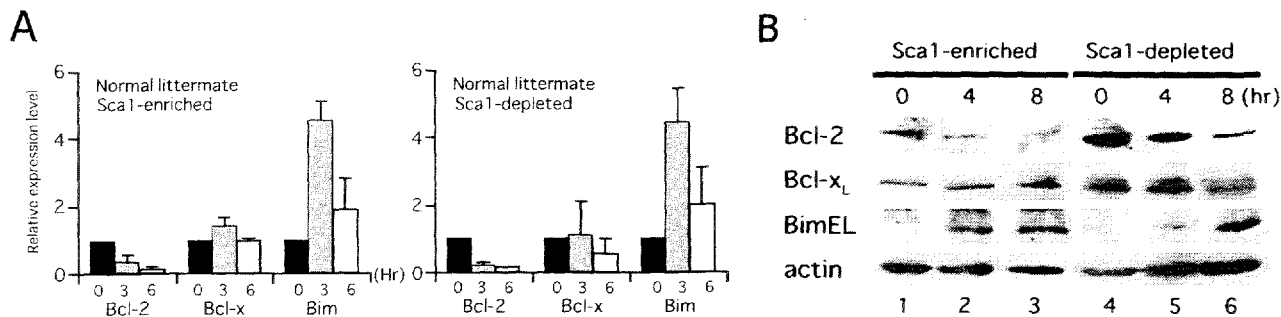


FIG. 2. Expression of Bcl-2, Bcl-x_L, and BimEL in $Sca-1^+ c-Kit^+ Lin^-$ and $Sca-1^- c-Kit^+ Lin^-$ cells from normal mice. Cells were cultured in the absence of cytokines for the indicated times. (A) Real-time quantitative PCR was carried out, and the numbers of cycles required to produce a detectable product were measured and used to calculate differences (n-fold) in starting mRNA levels for each sample by using 28S rRNA as an internal control. mRNA expression levels in cells cultured for 0 (black bars), 3 (gray bars), and 6 (open bars) h without cytokines relative to those in cells cultured in the presence of cytokines are shown. (B) Protein expression levels of the three Bcl-2 superfamily members, as well as β -actin as a control for equal loading, were analyzed by immunoblotting with specific antibodies for each protein.

of Bim by cytokine deprivation plays an important role in regulating cell fate in Sca-1-positive early progenitors.

Bcr-Abl reverses the upregulation of Bim by IL-3 deprivation in IL-3-dependent cells. To test whether Bcr-Abl downregulates Bim expression, we initially used Baf-3 cells expressing Bcr-Abl. Baf-3 cells were infected with retrovirus containing Bcr-Abl and mouse CD8 cDNA as a marker (pMX-Bcr-Abl/IRES-CD8; see Materials and Methods), and infected cells were selected with magnetic beads coated with CD8 antibodies. As reported by others (11, 28), these cells proliferated in IL-3-free medium at nearly the same rate as they did in IL-3-containing medium (data not shown). As previously reported (13, 44), the simultaneous downregulation of Bcl-x_L and upregulation of Bim were induced by IL-3 starvation in wild-type Baf-3 cells (Fig. 3A). In Baf-3 cells expressing Bcr-Abl, Bcl-x_L expression levels were unaffected, while Bim protein was induced for 12 h after IL-3 deprivation, and then the level of Bim declined and returned to its original level within 3 days (Fig. 3B). It was also reported previously that BimEL is phosphorylated by IL-3 signaling (44), shown here by slower migrating bands (Fig. 3A, lane 1, and C, top blot). Similar slower migrating bands were observed in Baf-3 cells expressing Bcr-Abl in the absence of IL-3 [Fig. 3B and C, blots labeled Bim and Baf-3 (Bcr-Abl)], suggesting that Bcr-Abl also phosphorylates BimEL.

In wild-type Baf-3 cells, it was demonstrated previously that signals from the distal portion of the β c chain independently downregulate Bim expression through both the classical Ras/Raf/MAPK and Ras/PI3-K pathways (44). To test whether Bcr-Abl downregulates Bim expression via the same signaling pathways in this particular cell system, Baf-3 cells expressing Bcr-Abl were cultured in the absence of IL-3 for 3 days, after which they were treated with the MAPK inhibitor PD, the PI3-K inhibitor LY, or both. The effects of these inhibitors were monitored by immunoblot analysis using antibodies recognizing phosphorylated Akt (pAkt) or phosphorylated MAPK. When cells were treated with PD, phosphorylated MAPK but not pAkt decreased, and viability was slightly reduced (Fig. 3D and E). When cells were treated with LY or both PD and LY together, levels of pAkt decreased, and massive cell death occurred. Immunoblot analysis revealed a mild enhancement of Bim expression in cells treated with PD, while a marked elevation was observed in cells treated with LY or both kinase inhibitors (Fig. 3F). These results suggest that, although both Raf/MAPK and PI3-K pathways contribute to cell survival and the downregulation of Bim by Bcr-Abl kinase, PI3-K pathways are more important than Raf/MAPK pathways in this particular cell system.

Bim expression is downregulated in cells expressing Bcr-Abl from patients with leukemia. To gain insight into the roles of Bim in the process of human leukemogenesis, we quantified the levels of Bim and Bcl-x_L proteins in cell lines established from patients in the BC phase of CML (CML/BC) and from patients with Philadelphia chromosome (Ph¹)-positive acute lymphoblastic leukemia (ALL) and compared them with the levels in patients with human acute myeloid leukemia (AML) and ALL cell lines that do not express the *Bcr-Abl* fusion gene. Levels of Bim in all six cell lines established from patients in CML/BC were low (Fig. 4A, lanes 1 to 6) compared with those in three control AML cell lines (Fig. 4A, lanes 7 to 9). Low

levels of Bim, especially BimEL, in Ph¹-positive cells were also observed in five cell lines established from patients with ALL (Fig. 4B, lanes 1 to 5). In contrast, levels of Bcl-x_L varied among cell lines established from patients in CML/BC and patients with AML (Fig. 4A), as expected based on results from previous studies reporting that Bcl-x_L expression levels differ among AML patients (43). The levels of Bcl-x_L in all ALL cell lines with or without Bcr-Abl expression seemed consistently low compared with those in AML cell lines (Fig. 4B).

To test whether the low level of Bim protein expression in Ph¹-positive leukemia cells was due to the potential of Bcr-Abl tyrosine kinase to downregulate it (as shown in Fig. 3B), we blocked Bcr-Abl function by using a specific inhibitor of Abl kinase, imatinib mesylate (formerly known as STI571). As previously reported (12, 24), apoptosis was induced by imatinib in five cell lines established from patients in CML/BC, and dephosphorylation of Akt and MAPK was observed in these cells (Fig. 5A and B). Increased levels of Bim proteins, especially BimEL and BimL, were induced by the addition of imatinib to KOPM30, K562, and BV173 cells (Fig. 5C). Moreover, dephosphorylation of BimEL was observed (Fig. 5C), suggesting that Bcr-Abl phosphorylates BimEL or BimL in human Ph¹-positive leukemia cells. Expression levels of Bcl-x_L were not altered in KOPM30 and were downregulated only transiently in K562 and BV173 cells (Fig. 5C). Similar results were obtained with KOPM28 and KOPM53 (data not shown).

To examine whether the upregulation of Bim expression contributes to apoptosis induced by imatinib, K562 cells were transfected with Cy3-labeled siRNA oligonucleotides homologous to the *Bim* sequence or control siRNA (42). The induction efficiency was judged to be around 60% based on observations with fluorescence microscopy (data not shown). Real-time quantitative RT-PCR analysis using a primer set to cross the cleavage site [Bim(si)] (Table 1) revealed a 45% reduction of Bim mRNA by the Bim siRNA when whole cells were analyzed (Fig. 5D, left panel). Immunoblot analysis revealed a greater-than-60% reduction of Bim protein, while Bcl-x_L analyzed as a control was reduced by less than 10% (Fig. 5D, right panel). The percentage of apoptotic cells was determined with annexin V-FITC. Cells transfected with Bim siRNA showed a significantly lower percentage of annexin V-positive cells (68.1% \pm 7.3% [average \pm standard deviation]) than those transfected with control siRNA (38.1% \pm 9.3%) (Fig. 5E). These data suggest that Bcr-Abl supports cell survival in cell lines established from patients in CML/BC through the downregulation of Bim, although it was not clear whether the magnitude of Bim induction in these cells was sufficient to account for all of the apoptosis caused by imatinib.

Prolonged survival of Sca-1-positive early progenitors from Bcr-Abl tg mice in cytokine-free medium. Cell lines established with cells in CML/BC harbor additional abnormalities that develop during progression to BC and/or during adaptation to the ex vivo artificial culture environment. To test whether Bcr-Abl downregulates Bim expression in cells from patients in the chronic phase of CML, we used progenitors expressing Bcr-Abl from primary cultures of bone marrow cells obtained from Bcr-Abl tg mice that always develop CML-like myeloproliferative disease (see the introduction). Their survival and

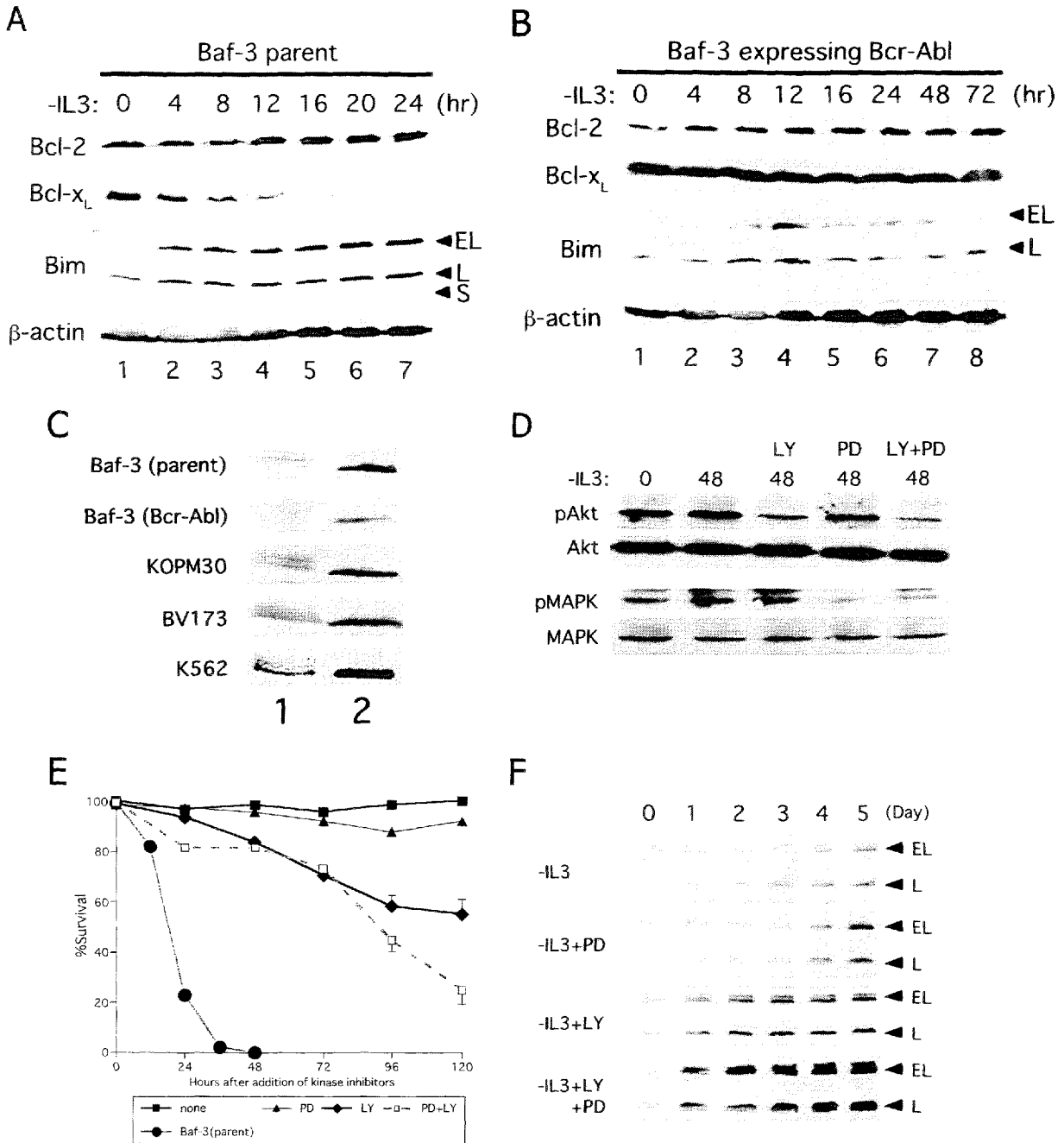


FIG. 3. Bim expression is regulated by IL-3 or Bcr-Abl through Raf/MAPK and/or PI3-K pathways in Baf-3 cells. EL, BimEL; L, BimL; S, BimS. (A and B) Expression of Bcl-2, Bcl-x_L, and Bim proteins in wild-type Baf-3 cells (A) and Baf-3 cells expressing Bcr-Abl after infection with a retrovirus vector (B). Cells were cultured in the absence of IL-3 for the indicated times. An immunoblot analysis using antibody specific for each protein was performed. A bracket in panel A indicates the phosphorylated forms of BimEL. (C) Phosphorylation of BimEL protein. Parental Baf-3 cells were cultured in the presence of IL-3 (lane 1) or in the absence of IL-3 (lane 2) for 4 h; IL-3-starved and Bcr-Abl expressing Baf-3, KOPM30, BV173, and K562 cells were cultured in the absence (lane 1) or presence (lane 2) of imatinib for 12 h. (D to F) Baf-3 cells expressing Bcr-Abl were cultured in IL-3-free medium for 72 h and then treated with PD, LY, or both (LY+PD) at a concentration of 50 μM for the indicated times (in hours). Immunoblot analyses using anti-phosphorylated form-specific Akt or MAPK, as well as antibodies recognizing total Akt or MAPK (D) or anti-Bim antibody (F), were performed. (E) Cell viability was determined by trypan blue dye exclusion. The survival curve of parental Baf-3 cells is shown as a control. Standard errors are shown when they were greater than 3%.

levels of Bcl-2 superfamily member expression were compared with those of their normal littermates.

Sca-1⁺ c-Kit⁺ Lin⁻ and Sca-1⁻ c-Kit⁺ Lin⁻ cells were isolated from primary cultures of bone marrow cells from the tg

mice. When these cells were cultured in the presence of cytokines, they proliferated with kinetics similar to those of cells from the normal littermates of the tg mice (Fig. 6A), although cell numbers from the tg mice were greater than those from

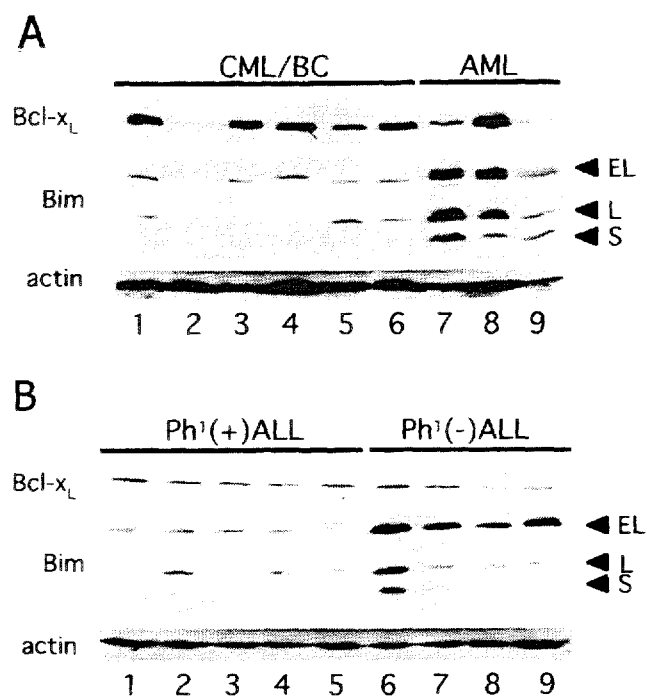


FIG. 4. Levels of Bcl-x_L and Bim protein in human leukemia cell lines. Immunoblot analysis using antibody specific for each protein was performed. EL, BimEL; L, BimL; S, BimS. (A) Lanes 1 to 6, the KOPM28, KOPM30, KOPM53, K562, BV173, and KU812 cell lines, respectively, established with CML/BC cells; lanes 7 to 9, the HL60 myeloid leukemia, HEL erythroid leukemia, and U937 monocytic leukemia cell lines, respectively, lacking Ph¹. (B) Lanes 1 to 5, the KOPN-55bi, KOPN-57bi, KOPN-66bi, KOPN-72bi, and KOPN-30bi Ph¹-positive pro-B ALL cell lines, respectively; lanes 6 to 9, the 920, 697, RS4;11, and UOC-B1 pro-B ALL cell lines, respectively, lacking Ph¹.

their normal littermates in both fractions (Fig. 1B). When Sca-1⁺ c-Kit⁺ Lin⁻ cells were cultured in cytokine-free medium, they survived for more than 3 days (Fig. 6B, left panel), much longer than those from normal littermates (Fig. 1C, left panel). Indeed, virtually no viable cells from normal littermates were observed 24 h after cytokine deprivation, while cells with immature and mature morphology from Bcr-Abl tg mice survived even after 48 h in repeated experiments. In contrast, Sca-1⁺ c-Kit⁺ Lin⁻ cells underwent apoptosis with kinetics similar to those of cells from the normal littermates (Fig. 1C, right panel). To confirm that Bcr-Abl prolongs the survival of Sca-1-positive early hematopoietic progenitors in cytokine-free medium, we added 1 μ M imatinib to the culture medium. Imatinib did not affect the survival of the Sca-1⁺ c-Kit⁺ Lin⁻ cells (Fig. 6C, middle panel). In contrast, Sca-1⁺ c-Kit⁺ Lin⁻ cells rapidly underwent apoptosis (Fig. 6C, left panel). A comparison of the numbers of living cells with those of Sca-1⁺ c-Kit⁺ Lin⁻ cells from normal mice (Fig. 1C) revealed that imatinib seemed not only to reverse the antiapoptotic effects of Bcr-Abl but even to enhance apoptosis at 8 and 16 h. This finding might be explained in part by the inhibitory effects of imatinib against c-Kit function, which could persist after the removal of SCF because imatinib also induced apoptosis in Sca-1⁺ c-Kit⁺ Lin⁻ cells from normal mice at 8 h (not statistically significant; $P = 0.14$) and 16 h ($P < 0.05$) after the

removal of the cytokines (Fig. 6C, right panel). These data suggest that Bcr-Abl protects Sca-1-positive early progenitors, but not Sca-1⁻ c-Kit⁺ Lin⁻ cells, from apoptosis caused by cytokine deprivation. Bcr-Abl mRNA expression was detected by RT-PCR in both fractions (data not shown).

Suppression of Bim induction in cytokine-deprived progenitors by Bcr-Abl. To clarify the mechanism through which Bcr-Abl prolongs survival of Sca-1-positive progenitors, we assessed the expression of Bcl-2 superfamily members in these cells. Real-time quantitative RT-PCR revealed that neither Bcl-2, Bcl-x_L, nor Bim mRNA expression was altered by cytokine deprivation in either Sca-1-positive or Sca-1-negative cells, except that Bim mRNA was induced twofold in Sca-1⁻ c-Kit⁺ Lin⁻ cells (Fig. 7A). These data were confirmed at the protein level by immunoblot analysis. Bcl-2 and Bcl-x_L levels were unchanged by cytokine deprivation, while Bim protein was barely detectable in either fraction (Fig. 7B), in contrast to a clear induction of Bim and downregulation of Bcl-2 in progenitors from normal littermates (Fig. 2B).

To further confirm that Bcr-Abl downregulates Bim, we analyzed the expression of the Bcl-2 superfamily members in cells cultured in cytokine-free medium in the presence of imatinib. Bim was markedly induced, while Bcl-2 was downregulated in Sca-1-positive and -negative progenitors isolated from Bcr-Abl tg mice (Fig. 7C, left and center panels). In contrast, induction levels of Bim in Sca-1-positive progenitors isolated from normal littermates were not changed by treatment with imatinib (Fig. 7C, right panel, and 2A, left panel), suggesting that the reduction of viable cells in progenitors from normal littermates by imatinib (Fig. 6C, right panel) was due to mechanisms other than Bim induction. Taken together, these data indicate that Bcr-Abl reverses the downregulation of Bcl-2 and upregulation of Bim that are observed in cytokine-starved normal hematopoietic progenitors.

DISCUSSION

In earlier studies, it was established that the induction of Bim is an important step in Baf-3 cells undergoing apoptosis due to IL-3 deprivation (44). Here we demonstrate that Bim was induced by cytokine starvation in early hematopoietic progenitors (Sca-1⁺ c-Kit⁺ Lin⁻) isolated by primary short-term culture of bone marrow cells from normal mice. In contrast, Bim was not induced by cytokine starvation in early progenitors from CML model mice that were more resistant to apoptosis than those from normal mice. We also found that Bcr-Abl downregulates Bim expression in Baf-3 cells and cell lines established with cells from patients with Ph¹-positive leukemia, suggesting that Bim is one of the key target factors downstream of Bcr-Abl that render CML progenitors resistant to apoptosis caused by cytokine deprivation.

The function of Bim is reported to be regulated by at least four different mechanisms. First, mRNA expression is downregulated by cytokines in mouse IL-3-dependent Baf-3, FL5.12, and 32D cells through the Ras/MAPK and PI3-K pathways, independently (13, 44). Moreover, NGF suppresses Bim mRNA expression through the inactivation of the c-jun NH₂-terminal kinase in NGF-dependent neuronal cells, including primary cultures of rat sympathetic neurons and neuronally differentiated PC-12 cells (5, 40, 49). In addition, serum deprivation

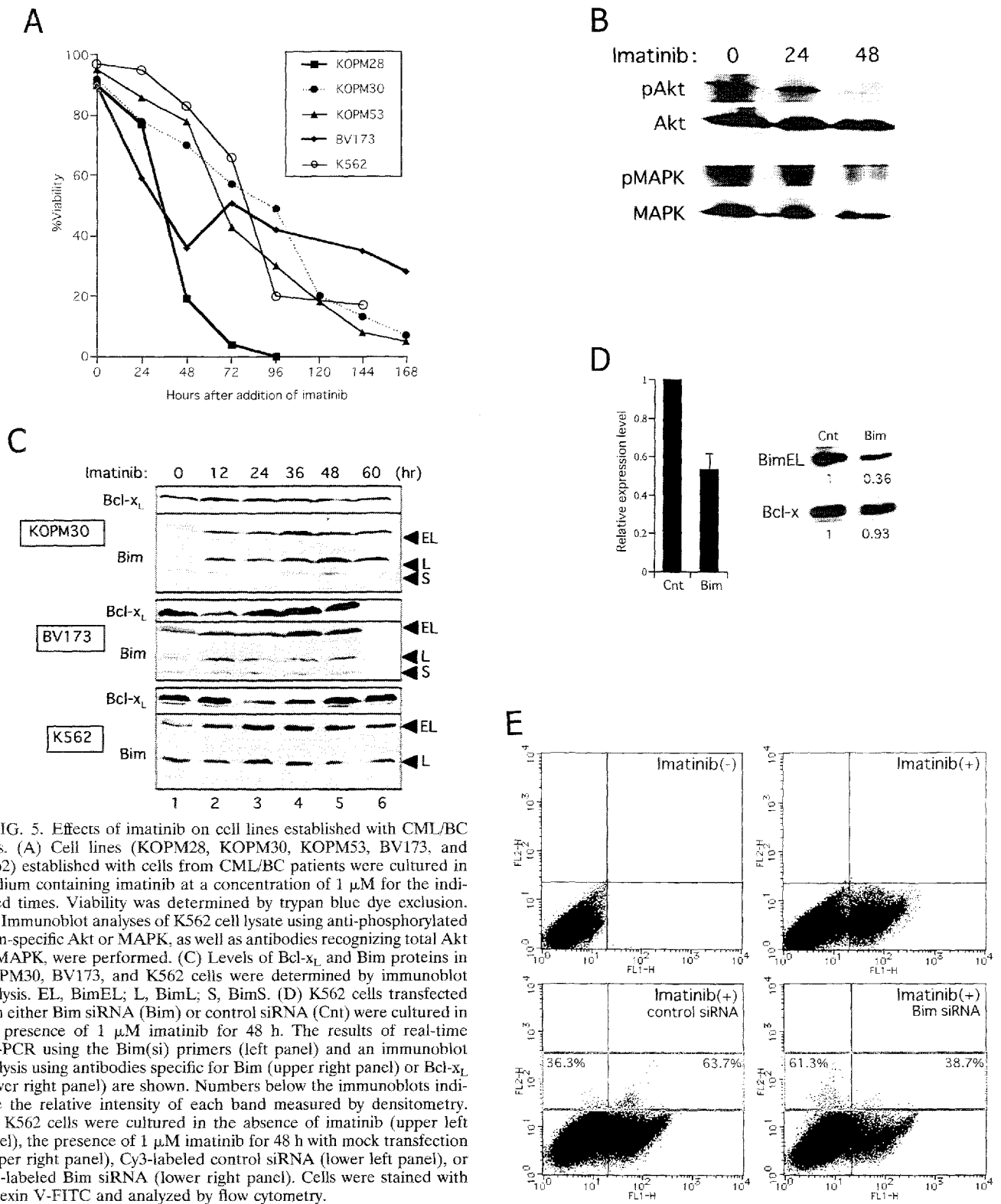


FIG. 5. Effects of imatinib on cell lines established with CML/BC cells. (A) Cell lines (KOPM28, KOPM30, KOPM53, BV173, and K562) established with cells from CML/BC patients were cultured in medium containing imatinib at a concentration of 1 μ M for the indicated times. Viability was determined by trypan blue dye exclusion. (B) Immunoblot analyses of K562 cell lysate using anti-phosphorylated form-specific Akt or MAPK, as well as antibodies recognizing total Akt or MAPK, were performed. (C) Levels of Bcl-x_L and Bim proteins in KOPM30, BV173, and K562 cells were determined by immunoblot analysis. EL, BimEL; L, BimL; S, BimS. (D) K562 cells transfected with either Bim siRNA (Bim) or control siRNA (Cnt) were cultured in the presence of 1 μ M imatinib for 48 h. The results of real-time RT-PCR using the Bim(si) primers (left panel) and an immunoblot analysis using antibodies specific for Bim (upper right panel) or Bcl-x_L (lower right panel) are shown. Numbers below the immunoblots indicate the relative intensity of each band measured by densitometry. (E) K562 cells were cultured in the absence of imatinib (upper left panel), the presence of 1 μ M imatinib for 48 h with mock transfection (upper right panel), Cy3-labeled control siRNA (lower left panel), or Cy3-labeled Bim siRNA (lower right panel). Cells were stained with annexin V-FITC and analyzed by flow cytometry.

vation of CC139 fibroblasts upregulates Bim mRNA via the classical MEK/extracellular signal-regulated kinase (ERK) pathway (48). Second, subcellular localization of Bim is controlled by IL-3 in FDC-P1 cells, another mouse IL-3-depend-

ent line, and by exposure to UV light in 293 cells (29, 41). BimEL and BimL, but not BimS, form complexes with an 8,000-molecular-weight dynein light chain, LC8 (also PIN or Dlc-1) (10, 21, 25). The Bim/LC8 complex in the presence of

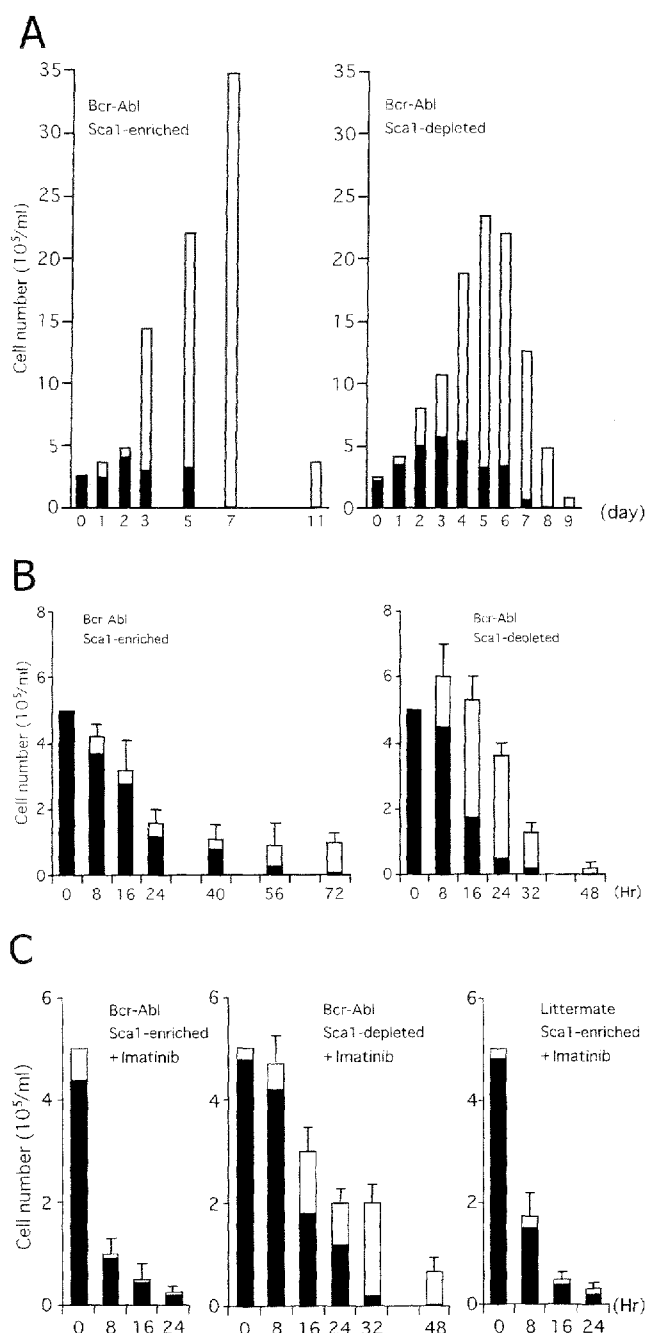


FIG. 6. (A and B) Sca-1⁺ c-Kit⁺ Lin⁻ cells (left panel) and Sca-1⁻ c-Kit⁻ Lin⁻ cells (right panel) amplified and isolated by primary cultures of bone marrow cells from Bcr-Abl tg mice were cultured in the presence (A) or absence (B) of SCF and TPO. (C) Sca-1⁻ c-Kit⁺ Lin⁻ cells (left and right panels) or Sca-1⁻ c-Kit⁺ Lin⁻ cells (middle panel) amplified and isolated by primary cultures of bone marrow cells from Bcr-Abl tg mice (left and middle panels) or their normal littermates (right panel) were cultured in the absence of SCF and TPO. Imatinib was added at a concentration of 1 μ M. The number of viable cells was determined by trypan blue dye exclusion. Blast cells (black bars) and terminally differentiated cells (open bars) were determined by cytospin centrifugation. The results from one representative study (A) or the means \pm standard errors of results from three independent experiments (B and C) are shown.

IL-3 binds to the intermediate chain of the dynein motor complex on the microtubules. IL-3 withdrawal releases the complex from sequestration in the cytoplasm by mechanisms not yet fully understood. In the case of 293 cells exposed to UV, phosphorylation at Thr-56 of (human) BimL by activated c-jun NH₂-terminal kinase was reported to play an important role in this process (29). Third, NGF phosphorylates BimEL and BimL but not BimS through the MEK/MAPK pathway in neuronally differentiated PC-12 cells. Phosphorylation of (rat) BimEL at Ser-109 and Thr-110, which are adjacent to but distinct from the phosphorylation residues in 293 cells exposed to UV as mentioned above, was reported to suppress the proapoptotic function of BimEL without affecting its binding potential to LC8 or its subcellular localization (5). Fourth, proteasome-dependent degradation is involved in the regulation of Bim expression in serum-deprived fibroblasts and macrophage colony-stimulating factor-dependent osteoclasts (2, 31). These somewhat confusing results suggest that the functions of BimEL and BimL on the one hand and BimS on the other may be regulated in different ways in certain situations and that the relative importance of these four mechanisms may differ between cell types. Indeed, it has been found that the enforced expression of either BimL or BimS readily induced apoptosis in Baf-3 and 293 cells, in contrast with five glioma cell lines, in which a massive amount of BimL did not induce apoptosis, in spite of the fact that a much lower amount of BimS easily killed these cells (44, 50).

In this paper, we demonstrated that Bim is downregulated at both the mRNA and protein levels by cytokines in hematopoietic progenitors isolated from primary cultures of bone marrow cells (Fig. 2). This finding indicates that the regulation of mRNA expression is the major mechanism for controlling Bim function in early hematopoiesis. We also demonstrated that Bcr-Abl reverses the induction of Bim mRNA caused by cytokine deprivation in these progenitors (Fig. 7). Among several pathways that are reported to regulate Bim mRNA, those involved in PI3-K are most likely the major pathways for the downregulation of Bim by Bcr-Abl (Fig. 3F). In addition, phosphorylation of Bim (as with the third mechanism mentioned in the previous paragraph) might contribute to the survival of hematopoietic cells. It was previously reported that BimEL and BimL are phosphorylated in Baf-3 cells by IL-3 signaling via the same pathways that control the expression of Bim, i.e., the Ras/Raf/MAPK and Ras/PI3-K pathways (44). In this study, although the phosphorylation of BimEL in early progenitors may not be convincing (Fig. 2B), it was clearly detected in Baf-3 cells expressing Bcr-Abl cultured in IL-3-free medium and in cell lines established from patients in CML/BC cultured in the absence of imatinib (Fig. 3C). We consider it unlikely that phosphorylation plays a major role in cytokine-deprived Baf-3 cells, because cells expressing hyperphosphorylated BimEL or BimL in the presence of IL-3 still underwent apoptosis (44). However, the possibility that phosphorylation of BimEL and BimL by cytokines or Bcr-Abl contributes to cell survival to some extent in early hematopoietic progenitors or leukemic cells cannot be excluded.

There are substantial differences between early (Sca-1⁺ c-Kit⁺ Lin⁻) and late (Sca-1⁻ c-Kit⁺ Lin⁻) progenitors in cytokine dependence and the effects of Bcr-Abl kinase. Early progenitors undergo rapid apoptosis without maturation in the

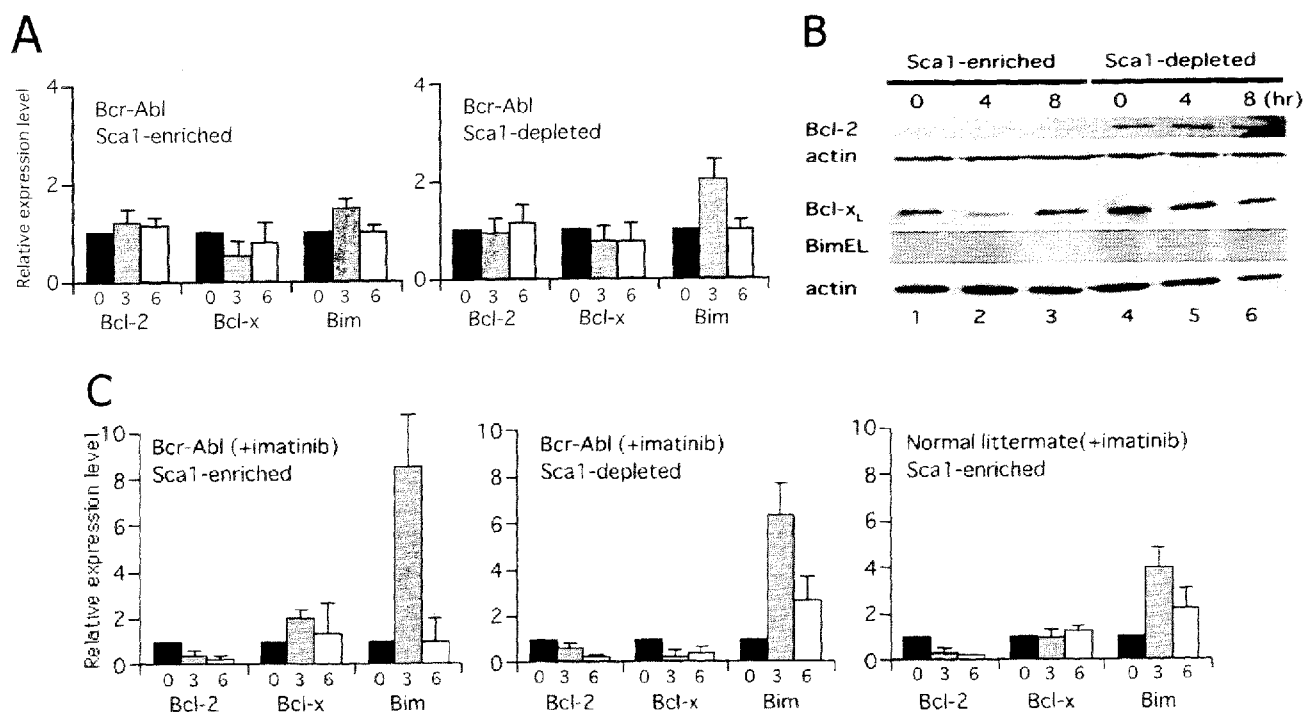


FIG. 7. Expression of Bcl-2, Bcl-x_L, and BimEL in Sca1⁺ c-Kit⁺ Lin⁻ and Sca1⁻ c-Kit⁺ Lin⁻ cells from Bcr-Abl tg mice and their normal littermates. Cells were cultured in cytokine-free medium in the absence (A and B) or presence (C) of imatinib at a concentration of 1 μM for the indicated times. (A and C) Real-time quantitative PCR was carried out, and the numbers of cycles required to produce a detectable product were measured and used to calculate the differences (*n*-fold) in starting mRNA levels for each sample by using 28S rRNA as an internal control. Levels of mRNA in cells cultured for 0 (black bars), 3 (gray bars), and 6 (open bars) h without cytokines relative to those in cells in the presence of cytokines are shown. (B) Levels of three Bcl-2 superfamily members, as well as β-actin proteins, as a control for equal loading were detected by specific antibodies.

absence of cytokines (Fig. 1C). This could be explained at least partially by relatively low levels of Bcl-2 and Bcl-x_L expression (Fig. 2B), because it is generally accepted that cell fate is determined by the balance between pro- and antiapoptotic members of the Bcl-2 superfamily (1). Although Bcl-2 levels were downregulated by cytokine deprivation in early progenitors, this downregulation is unlikely to be the major cause of rapid apoptosis, because levels of Bcl-2 in the presence of cytokines are very low and Bcl-2-deficient mice did not show apparent abnormalities in myeloid hematopoiesis (34, 47). Thus, Bim is considered to be the major determinant of cell fate in Sca1⁺ c-Kit⁺ Lin⁻ cells, and downregulation of Bim in cytokine-deprived Sca1-positive early progenitors isolated from Bcr-Abl tg mice may result in longer survival (Fig. 6B). On the other hand, Bim may not be the major determinant of cell fate in Sca1⁻ c-Kit⁺ Lin⁻ cells, which express Bcl-2 and Bcl-x_L at high levels (Fig. 2B). Moreover, half of these cells can differentiate before undergoing apoptosis (Fig. 1C). Additionally, late progenitors from the tg mice show virtually the same time course as those from normal littermates in the absence of cytokines (Fig. 1C and 6B, right panels) in spite of the fact that there was little induction of Bim in these cells, similar to Sca1-positive early progenitors (Fig. 7A and B).

Many reports have maintained that the growth and survival characteristics of CML progenitors in the chronic phase are similar to those in healthy bone marrow (reviewed in references 15 and 23). In spite of prominent antiapoptotic effects of

Bcr-Abl in cytokine-dependent cell lines such as Baf-3, resistance of CML progenitors to cytokine deprivation is controversial. Bedi et al. reported that CD34-positive CML progenitors live longer in serum- and cytokine-free medium than CML progenitors treated with Bcr-Abl junction-specific antisense oligonucleotides and normal CD34-positive cells (4), but Amos et al. did not observe a survival advantage of CML progenitors under cytokine-free conditions (3). In the present study, we isolated early hematopoietic progenitors by using Sca1, which is one of the most reliable markers for early progenitors, including stem cells, but is available only for the study of mouse hematopoiesis. Another advantage of our study is the use of progenitors isolated from young mice (8 to 12 weeks of age) whose peripheral blood and bone marrow are still indistinguishable from those of their normal littermates (18). Taking these advantages, we revealed a relatively small but distinct difference in apoptosis due to cytokine deprivation between normal and Bcr-Abl-expressing progenitors that correlated to the expression levels of Bim (Fig. 1, 2, 6, and 7). Moreover, Bim was induced by imatinib in CML cell lines undergoing apoptosis (Fig. 5C), and siRNA that reduced the expression level of Bim effectively rescued these cells (Fig. 5E). Taken together, these results suggest that Bim is an important downstream target that supports cell survival of Bcr-Abl-expressing hematopoietic cells. Further studies are necessary to clarify whether downregulation of Bim by Bcr-Abl contributes to the massive expansion of myeloid cells observed in CML.

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SPOTLIGHT CORRESPONDENCE

Interstitial pneumonia induced by imatinib mesylate: pathologic study demonstrates alveolar destruction and fibrosis with eosinophilic infiltration

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TO THE EDITOR

Imatinib mesylate (Gleevec, Glivec, formerly, STI571) is an inhibitor of the BCR-ABL tyrosine kinase that is central to the pathogenesis of chronic myelogenous leukemia (CML). A recent large-scale prospective randomized trial, comparing imatinib vs interferon plus cytarabine for chronic phase CML, demonstrated the impressive therapeutic superiority of imatinib.¹ The current therapeutic strategy for CML was reviewed by Hehlmann.² Although imatinib is a well-tolerated drug, various adverse events such as superficial edema, nausea, muscle cramps, and skin rash were reported. These events were grades 1–2 in most cases, and medical treatment appears to be feasible.³ With respect to the respiratory complications, dyspnea and cough have been reported to occur in 7–10 and 10–14% of patients receiving imatinib, respectively,^{1,3} although they were ascribed to pulmonary edema. Their causes have not been clearly described. We report a case of an imatinib-induced interstitial pneumonia and its pathologic findings obtained by transbronchial lung biopsy (TBLB) in a patient with CML.

The patient was a 64-year-old man who was first given a diagnosis of CML in June 2001. Thereafter, he received 1000 mg of hydroxycarbamide daily, which resulted in a complete hematological response. After 18 months, his white blood cell (WBC) count increased even though he was still receiving hydroxycarbamide. No hepatosplenomegaly was noted. The bone marrow findings showed a hypercellular marrow with 1.6% blasts, and interphase-FISH analysis revealed the BCR-ABL fusion gene in 89.8% of the bone marrow nucleated cells. Imatinib (400 mg/day) was started in January 2003, resulting in a complete hematological response. However, on the 78th day after initiation of imatinib, he started to suffer dyspnea (Hugh-Jones grade II). At that time, an interphase-FISH analysis revealed the BCR-ABL fusion gene to be present in 92.5% of peripheral neutrophils. Chest X-ray showed bilateral ground-glass opacities in the lower lung fields. Computed tomography (CT) revealed reticular and ground-glass opacities in the subpleural area (Figure 1). Arterial blood measurements showed a pH of 7.418, arterial oxygen pressure of 95.6 mmHg, and carbon dioxide pressure of 43.3 mmHg in room air. No other symptoms, including skin rash and edema, were noted. He did not take other medicines at that time. Laboratory studies revealed that the WBC count was $3.9 \times 10^6/l$ with 12.7% eosinophils, hemoglobin was 11.2 g/dl, and platelet count was $1.4 \times 10^8/l$. The erythrocyte sedimentation rate was 33 mm/h, C-reactive protein was 1.4 mg/l, LDH was 438 U/l (normal range: 224–454 U/l), and KL-6, which indicates an activity of interstitial

pneumonia, was 1360 U/ml (normal limit: less than 500 U/ml), respectively. Other biochemical data were all within normal ranges. Although a drug lymphocyte-stimulating test (DLST) for imatinib mesylate was negative, imatinib-induced interstitial pneumonia was suspected, because no other cause was evident. Imatinib was discontinued after a total dose of 31200 mg (400 mg \times 78 days). A TBLB revealed the destruction of alveolar septi and mixed intra-alveolar and interstitial fibrosis along with eosinophilic infiltration (Figure 2). Bronchoalveolar lavage fluid could not be collected at that time. After cessation of imatinib, the dyspnea improved within 10 days even without steroid therapy. Chest X-ray and CT on the 18th day after cessation of imatinib showed almost complete resolution of interstitial shadows. Since the WBC count re-elevated to $30 \times 10^6/l$ after discontinuation of imatinib, we began to give hydroxycarbamide, increasing the dosage to 1500 mg/day in May 2003. This resulted in a reduction of the WBC count.

Imatinib mesylate now has been estimated to be used in about 3200 cases in Japan. According to a recent postmarketing surveillance by Novartis Japan, 24 cases of interstitial pneumonia, apparently related to imatinib, have been registered (20 cases of CML, one of hypereosinophilic syndrome, and three cases of gastrointestinal stromal tumor) (Novartis Pharma KK, data on file). Only two of 24 cases had a past history of lung disease; one was interstitial pneumonia and the other was chronic bronchitis. The appearance of interstitial pneumonia ranged from 10 to 337 days (median 42 days) after initiation of imatinib administration. Among these cases, three received 600 mg/day of imatinib, 13 cases received 400 mg/day, and eight cases less than 300 mg/day. In 20 CML patients showing interstitial pneumonia, 35% were in the accelerated/blastic crisis phase and 65% in the chronic phase. In the 14 cases reporting complete blood cell count and WBC differentiation, eight patients (57%) showed eosinophilia, although they had achieved complete hematological response by imatinib at that time. Steroid therapy was carried out in all these cases, and 19 cases recovered; one case did not improve, and one patient died.

The mechanism of drug-induced pneumonia is unclear in the vast majority of cases; however, it is considered to consist of either idiosyncratic (= noncytotoxic type) or cytotoxic type. The latter is dose dependent with pathologic features of interstitial edema, lymphocytic infiltration, destruction of alveolar epithelium etcetera, for example, busulfan lung or bleomycin lung. In contrast, the noncytotoxic type resembles hypersensitivity pneumonia, bronchiolitis obliterans, or eosinophilic pneumonia. We found eosinophilic infiltration in the current case; however, we cannot completely rule out the possibility that the underlying disease (CML) may have modified the pathologic features. In the Novartis report, none of the seven cases of imatinib-induced interstitial pneumonia examined were DLST positive. In our case, the pathologic findings of TBLB showing prominent infiltration of eosinophils suggested an immunoallergic mechanism. There is one report showing a case of hypersensitivity pneumonitis related to imatinib, which may also support the immunoallergic background, but that study

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