

Bax Loss Impairs Myc-Induced Apoptosis and Circumvents the Selection of p53 Mutations during Myc-Mediated Lymphomagenesis

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Received 19 June 2001/Returned for modification 23 July 2001/Accepted 22 August 2001

The ARF and p53 tumor suppressors mediate Myc-induced apoptosis and suppress lymphoma development in E μ -myc transgenic mice. Here we report that the proapoptotic Bcl-2 family member Bax also mediates apoptosis triggered by Myc and inhibits Myc-induced lymphomagenesis. Bax-deficient primary pre-B cells are resistant to the apoptotic effects of Myc, and Bax loss accelerates lymphoma development in E μ -myc transgenics in a dose-dependent fashion. Eighty percent of lymphomas arising in wild-type E μ -myc transgenics have alterations in the ARF-Mdm2-p53 tumor suppressor pathway characterized by deletions in ARF, mutations or deletions of p53, and overexpression of Mdm2. The absence of Bax did not alter the frequency of biallelic deletion of ARF in lymphomas arising in E μ -myc transgenic mice or the rate of tumorigenesis in ARF-null mice. Furthermore, Mdm2 was overexpressed at the same frequency in lymphomas irrespective of Bax status, suggesting that Bax resides in a pathway separate from ARF and Mdm2. Strikingly, lymphomas from Bax-null E μ -myc transgenics lacked p53 alterations, whereas 27% of the tumors in Bax^{+/-} E μ -myc transgenic mice contained p53 mutations or deletions. Thus, the loss of Bax eliminates the selection of p53 mutations and deletions, but not ARF deletions or Mdm2 overexpression, during Myc-induced tumorigenesis, formally demonstrating that Myc-induced apoptotic signals through ARF/Mdm2 and p53 must bifurcate: p53 signals through Bax, whereas this is not necessarily the case for ARF and Mdm2.

The oncoprotein c-Myc, paradoxically, is an inducer of both cell proliferation and cell death, and the levels of Myc and/or the conditions in which it is expressed dictate cell fate (2, 7, 40). Most cancer cells that overexpress Myc, by translocation, amplification, or other means, harness the full growth potential of this oncogene by inactivating the apoptotic effectors of Myc, including the tumor suppressors ARF and p53 (5, 50). ARF is a nucleolar protein that binds to and sequesters Mdm2 (55, 59). Mdm2 is a p53 transcription target (3, 61) that inhibits p53's transactivation functions (37) and ubiquitinates p53 (12), leading to p53 degradation (48). Myc activation induces the sustained expression of both ARF and p53, and this triggers apoptosis; as a consequence, primary ARF- and p53-null hematopoietic and fibroblast cells are impaired in their apoptotic response to Myc (5, 63). Furthermore, deletion of ARF, mutation or deletion of p53, and Mdm2 overexpression occur in 24, 28, and 48%, respectively, of the lymphomas that arise in E μ -myc transgenic mice (80% overall [5]), and ARF- or p53-null E μ -myc transgenic mice have a markedly accelerated course of lymphoma (5, 17, 50).

Loss of the antiapoptotic protein Bcl-X_L or Bcl-2 compromises hematopoietic cell survival, whereas loss of ARF or p53 has no effect upon hematopoietic cell development (6, 38, 39,

41, 57). Bax is a proapoptotic Bcl-2 family member whose deletion has modest effects on lymphocyte numbers (22). However, the combined loss of Bax and Bak, another proapoptotic Bcl-2 family member, results in profound defects in both development and lymphocyte homeostasis (24). Bax normally resides in the cytosol of healthy cells, yet it relocalizes and inserts into the outer mitochondrial membrane after stimulation with a variety of apoptotic stimuli (reviewed in reference 9). In turn, this leads to mitochondrial dysfunction with alterations in the permeability transition pore, the release of cytochrome *c*, and the activation of Apaf-1 and caspases, which cleave intracellular targets required for cell survival (9). The balance of proapoptotic and antiapoptotic Bcl-2 family members regulates the susceptibility of cells to apoptosis (reviewed in reference 23). For example, an excess of Bax can overwhelm the cell and trigger an apoptotic response, whereas the antiapoptotic Bcl-2 family members Bcl-2 and Bcl-X_L inhibit the deleterious effects of Bax (23).

Bcl-2 and Bcl-X_L are overexpressed in many human malignancies (reviewed in reference 46), and Bcl-X_L expression is activated by retroviral insertions in some murine T-cell leukemias and lymphomas (41). Bcl-2 and Myc have been shown to cooperate in transformation (8, 56), and E μ -myc/E μ -bcl-2 double transgenic mice develop an aggressive and rapid lymphoma composed of primitive lymphoid cells (54). Although the cooperation between Bcl-2 and Myc and the regulation of Bax by Bcl-2 are well documented, the precise role that Bax plays in Myc functions is less clear.

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Bax-deficient mice manifest a modest lymphoid hyperplasia but are not prone to spontaneous tumor development (20, 22). However, mutations that inactivate *Bax* are found in a subset of human colon adenocarcinomas (45) and some human hematopoietic cancer cell lines (4, 30, 31), and *Bax* loss cooperates with simian immunodeficiency virus (SV40) large T antigen in transgenic mouse models of cancer (52, 62). Recently, *bax* has been suggested to be a direct transcriptional target of c-Myc in human tumor cell lines (32). However, it is unclear how *Bax* influences Myc-induced hematopoietic cell apoptosis and tumorigenesis and whether *Bax* expression influences the ARF-Mdm2-p53 tumor suppressor pathway. Here we report that, although Myc activation fails to regulate *Bax* levels in primary murine pre-B cells, *Bax*-deficient cells are markedly resistant to Myc-induced apoptosis. More importantly, *Bax* loss accelerates Myc-induced tumorigenesis in $E\mu$ -myc transgenic mice, and the lymphomas arising in *Bax*-null transgenics selectively lack mutations or deletions of *p53*. However, *Bax*-null $E\mu$ -myc transgenics still display the same frequency of alterations of ARF and Mdm2, indicating that *Bax* is not necessarily a target of ARF or Mdm2 even though both can function with p53 in this tumor suppressor pathway. The results support a model whereby *Bax* functions as a critical downstream effector of the p53 apoptotic pathway, and thus ARF and Mdm2 must have other mediators important for tumorigenesis.

MATERIALS AND METHODS

Transgenic and knockout mice. The inbred C57BL/6 $E\mu$ -myc transgenic mouse strain was kindly provided by Alan Harris (Walter & Eliza Hall Institute, Melbourne) and Charles Sidman (University of Cincinnati). *Bax*-null mice have been previously described and were C57BL/6 \times 129/svj (22). The *ARF*-null (C57BL/6 \times 129/svj) and p53-null (C57BL/6 \times 129/svej) mice were generously provided by Charles Sherr and Gerard Grosveld, respectively. $E\mu$ -myc transgenics were mated to *Bax*^{+/-} mice and the F₁ littermates were then mated to each other to obtain *Bax*^{+/+}, *Bax*^{+/-}, and *Bax*^{-/-} $E\mu$ -myc transgenics.

Primary B cells. Primary pre-B cell cultures were generated from the bone marrow of 6- to 8-week-old wild-type, *Bax*⁻, *ARF*⁻, *p53*⁻, and *ARF/p53*-double null mice as previously described (5). Briefly, culture of bone marrow in interleukin-7 (IL-7)-containing medium after 12 to 14 days established >98% pure population of pre-B cells as determined by phenotype analysis using B-cell-specific antibodies and fluorescence-activated cell sorting (FACS). The pre-B cells expressed CD19, B220, and CD24 and were negative for surface immunoglobulin M (IgM) and CD43 irrespective of genotype. IgM⁺/CD19⁺ B cells were sorted from spleens from age- and gender-matched mice: one wild-type and two precancerous $E\mu$ -myc transgenics. All antibodies used for phenotypic analyses were from PharMingen (San Diego, Calif.) or Southern Biotechnology (Birmingham, Ala.).

Virus infection. Virus was produced and used to infect primary pre-B cells as previously described (5). Briefly, MSCV-Myc-ER-IRES-GFP or control MSCV-IRES-GFP virus was cotransfected with helper virus into 293T cells, and live virus was then collected at intervals, pooled, and filtered (49). Viral stocks, MSCV-Myc-ER-IRES-GFP virus or the MSCV-IRES-GFP control virus, were used to infect primary pre-B cells in the presence of 8 μ g of Polybrene/ml. Green fluorescent protein (GFP)-positive infected cells were isolated 3 to 4 days postinfection by sterile sorting with a Cytomation MoFlo cell sorter (Fort Collins, Colo.). GFP-positive cells were expanded in IL-7-containing medium and analyzed for levels of Myc-ER (previously referred to as Myc-ERTM [5, 6]) protein and sensitivity to Myc-induced apoptosis. Myc-ER is a fusion protein of c-Myc linked to a modified estrogen receptor hormone binding domain (25) and is designed to hold Myc-ER in heat shock complexes in the cytosol. Upon addition of 1 μ M 4-hydroxytamoxifen (4-HT), which binds to the ER portion of Myc-ER, Myc-ER then translocates to the nucleus and activates transcription (25). As reported elsewhere (5), addition of 4-HT to uninfected or MSCV-IRES-GFP control virus-infected cells had no effect on pre-B cell growth or viability.

Viability and apoptosis assays. Cell viability was determined at specific intervals by trypan blue dye exclusion after the removal of IL-7 or the addition of 1 μ M 4-HT (Sigma, St. Louis, Mo.) to the culture medium to activate Myc-ER. For

the IL-7 deprivation experiments, wild-type and *Bax*^{-/-} pre-B cells were washed twice with phosphate-buffered saline and resuspended in medium lacking IL-7 but still containing 10% fetal calf serum. Apoptosis was measured by propidium iodide staining of DNA and quantitation of fragmented (sub-G₁) DNA.

Western blotting. Whole-cell protein extracts from primary pre-B cells or pre-B- or B-cell lymphomas from $E\mu$ -myc transgenic mice were isolated as previously described (5, 63). Briefly, ice-cold lysis buffer (50 mM HEPES, pH 7.5; 150 mM NaCl; 1 mM EDTA; 2.5 mM EGTA; 0.1% Tween 20; 1 mM phenylmethylsulfonyl fluoride; 0.4 U of aprotinin/ml; 1 mM NaF; 10 mM β -glycerophosphate; 0.1 mM sodium orthovanadate; 10 μ g of leupeptin/ml) was added to cells pellets or small (3- to 5-mm²) tumor chunks. Samples were then subjected twice to sonication for 8 s and centrifuged (4°C, 7 min, 14,000 rpm) to sediment the undissolved cellular material, and then the protein in the supernatant was quantified by using a Bio-Rad Protein Assay (Hercules, Calif.). Equal amounts of protein (200 μ g per lane) were separated by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) (10%), transferred to nitrocellulose membranes (Protran; Schleicher & Schuell, Dassel, Germany), and blotted with antibodies specific for the p19^{ARF} (44), p53 (Ab-7), and poly(ADP-ribose) polymerase (PARP; Ab-2) (both from, Calbiochem, La Jolla, Calif.), Mdm2 (C-18; Santa Cruz, Inc., Santa Cruz, Calif.), c-Myc (06-340; Upstate Biotechnology, New York, N.Y.), and *Bax* (13686E; PharMingen, San Diego, Calif.). Bound immunocomplexes were detected by enhanced chemiluminescence (Amersham, Piscataway, N.J.) or Supersignal (Pierce, Rockford, Ill.).

Southern blotting. Genomic DNA was isolated from lymphomas arising in *Bax*^{+/-} and *Bax*^{-/-} $E\mu$ -myc transgenic mice and digested with *Afl*III or *Bam*HI. Equal amounts of DNA were electrophoretically separated in agarose gels, transferred to nitrocellulose membranes, and then probed with cDNAs coding for *ARF* (exon 1 β) (*Afl*III digested) and *p53* (exons 2 to 10) and the joining region of immunoglobulin heavy chain (J_H) (both *Bam*HI digested). Genomic DNA isolated from the spleen of a wild-type littermate was used as a control.

Northern blotting. Total RNA was isolated by using TRIzol Reagent according to the manufacturer's directions (Life Technologies, Grand Island, N.Y.) at intervals (0, 1, 3, or 6 h) from primary pre-B cells after addition of 1 μ M 4-HT after a 30-min pretreatment with 10 μ g of cycloheximide or vehicle control (100% ethyl alcohol)/ml. Northern blotting with 20 μ g of total RNA per lane was performed using conventional techniques and probed with the coding portion of murine *bax* cDNA (kindly provided by John Reed, The Burnham Institute).

RESULTS

Bax loss impairs Myc-induced apoptosis. *Bax*-null mice have modest increases in B- and T-lymphocyte numbers, presumably due to decreased apoptosis (22). To determine whether *Bax*-deficient B lymphocytes were intrinsically more resistant to apoptosis than wild-type lymphocytes, we harvested bone marrow cells and expanded pre-B cells in IL-7-containing medium and measured proliferation rates and viability. The *Bax*-null pre-B cells grew at a rate similar to wild-type pre-B cells (data not shown) and showed no difference in viability (Fig. 1A, open symbols). Moreover, deprivation of IL-7 induced apoptosis in *Bax*-null pre-B cells with kinetics virtually identical to that of wild-type pre-B cells (Fig. 1A, closed symbols). Similar results were obtained when wild-type and *Bax*^{-/-} thymocytes were deprived of cytokines (22). Therefore, *Bax* deficiency does not confer a growth or survival advantage to lymphocytes during ex vivo culture.

To address whether *Bax* influences Myc-induced apoptosis, we infected primary wild-type and *Bax*-deficient pre-B cells with a Myc-ER-GFP (previously referred to as Myc-ERTM-GFP [5, 6]) expressing retrovirus or with a control GFP-only expressing retrovirus and then sorted for virus-infected cells by FACS. There was a modest decrease in the viability in wild-type pre-B cells infected with the Myc-ER encoding retrovirus compared to *Bax*-deficient pre-B cells infected with the same virus (Fig. 1B). This is most likely due to the somewhat leaky nature of Myc-ER expression system (5, 63). Activation of Myc-ER with 4-HT led to rapid apoptosis in the wild-type

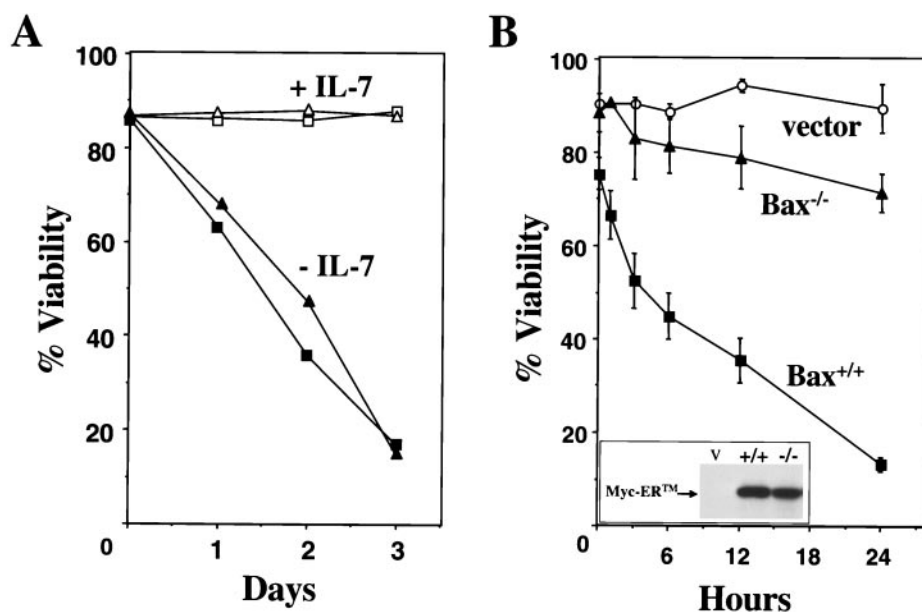


FIG. 1. Bax does not influence cytokine deprivation-induced apoptosis but does mediate c-Myc-induced apoptosis. (A) $Bax^{+/+}$ (squares) and $Bax^{-/-}$ (triangles) pre-B cells were cultured in medium with (open symbols) or without (solid symbols) IL-7, and their viability was determined at intervals by trypan blue dye exclusion. The data are representative of two independent experiments. (B) 4-HT was added to the indicated primary pre-B-cell cultures to activate Myc-ER, and their viability was determined at intervals thereafter by trypan blue dye exclusion. Apoptosis was confirmed by analysis of subdiploid DNA content after staining with propidium iodide. Steady-state levels of apoptosis in the wild-type primary pre-B cells are indicated at the zero hour time point. (Inset) The protein levels of Myc-ER in $Bax^{-/-}$ (-/-) and $Bax^{+/+}$ (+/+) pre-B cells infected with a retrovirus encoding Myc-ER-GFP and pre-B cells infected with the GFP vector control (V) retrovirus were determined by immunoblotting with an antibody for Myc. The data are the mean of three independent experiments, and error bars represent one standard deviation.

pre-B cells cultured in IL-7-containing medium, whereas the Bax -null cells were very resistant to Myc-induced apoptosis (Fig. 1B). Few wild-type pre-B cells (<10%) were alive after 24 h of Myc activation, whereas Bax -null pre-B cells were greater than 60% viable at this interval. Primary pre-B cells died by apoptosis upon Myc-ER activation, as determined by DNA fragmentation analysis (data not shown) and cleavage of caspase targets such as PARP (Fig. 2A). Thus, Bax is an important mediator of Myc-induced apoptosis in primary pre-B cells.

bax has been suggested to be a direct transcriptional target of c-Myc in immortal human tumor cell lines (32). However, Myc activation in primary pre-B cells was not associated with changes in Bax protein (Fig. 2A) whereas, as expected (5), p53 expression was increased upon Myc activation. Moreover, Bax levels were unaltered in IgM⁺ splenic B cells from precancerous $E\mu$ -myc transgenic mice compared to wild-type littermate controls (Fig. 2B). Therefore, Myc activation or overexpression does not alter Bax protein levels in B cells ex vivo or in vivo. Only a very slight increase in *bax* RNA levels was observed following Myc activation in pre-B cells, and this was prevented by pretreatment of the cells with cycloheximide (Fig. 2C). Since cycloheximide blocks new protein synthesis, the modest changes in *bax* RNA induced by Myc activation are indirect. Furthermore, the modest upregulation of *bax* RNA by Myc did not result in any increase in Bax protein levels (Fig. 2A).

Immortal cell lines, such as those used by Mitchell et al. (32), generally inactivate p53 or ARF to become established in vitro (11, 19), and *bax* has been reported to be a transcriptional

target of p53 (34, 35). Therefore, it was possible that the loss of p53 and/or ARF influences Bax expression independent of Myc and/or could alter the response of Bax to Myc activation. To address this issue, primary pre-B cells lacking p53 and/or ARF were infected with the Myc-ER encoding retrovirus. Loss of ARF and/or p53 did not significantly alter the steady-state levels of Bax protein (Fig. 2D). Moreover, activation of Myc-ER with 4-HT did not result in alteration of Bax protein levels in ARF-, p53-, or ARF/p53-double null primary pre-B cells (Fig. 2D). Therefore, loss of p53 and/or ARF does not influence Bax expression, even when Myc is activated.

Bax loss accelerates Myc-induced lymphomagenesis. Loss of ARF or p53 impairs Myc-mediated apoptosis and consequently accelerates Myc-induced lymphomagenesis (5, 50, 63). To test the genetic contribution of Bax to Myc-induced lymphomagenesis, we crossed $E\mu$ -myc transgenic mice onto the Bax -null background. Congenic C57BL/6 $E\mu$ -myc transgenic mice were mated to C57BL/6 \times 129/svj $Bax^{+/-}$ mice, since $Bax^{-/-}$ males and females have fertility problems (22, 43). F₁ littermates were intercrossed to obtain $Bax^{+/+}$, $Bax^{+/-}$, and $Bax^{-/-}$ $E\mu$ -myc transgenic mice, and these transgenics were carefully monitored for disease development. Notably, Bax loss accelerated the course of lymphoma development, decreasing the average age of survival from 21.7 weeks in $Bax^{+/+}$ $E\mu$ -myc transgenics to 12.6 weeks in Bax -null $E\mu$ -myc transgenics (Fig. 3). None of the $Bax^{-/-}$ $E\mu$ -myc transgenic mice survived past 30 weeks, whereas 22% (12 of 54) of the $Bax^{+/+}$ $E\mu$ -myc transgenics lived longer than 30 weeks. Bax haploinsufficiency also accelerated tumor development, since $Bax^{+/-}$ $E\mu$ -myc transgenic mice had a mean life span of 16.0 weeks (Fig. 3).

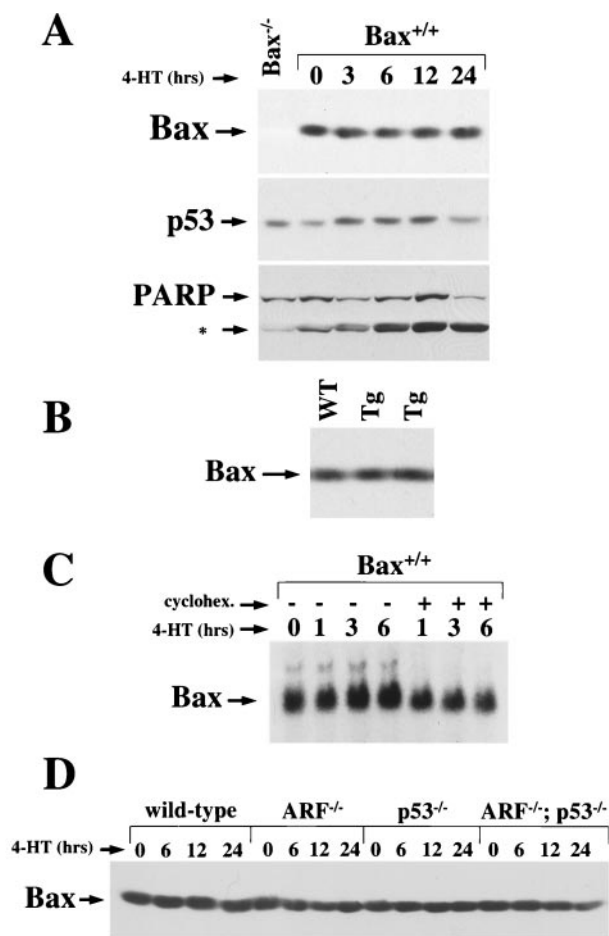


FIG. 2. Myc does not upregulate Bax protein expression in B cells. (A) 4-HT was added to wild-type pre-B-cell cultures infected with the Myc-ER encoding retrovirus to activate Myc-ER. At the indicated intervals cells were collected and protein lysates were made. Equal quantities of protein were assessed by immunoblotting with antibodies specific for Bax, p53, or PARP. The 85-kDa caspase cleavage fragment of PARP is denoted by an asterisk. (B) Equal quantities of protein from FACS sorted IgM⁺/CD19⁺ splenic B cells from one wild-type (WT) and two precancerous *Eμ-myc* transgenics (Tg) were assessed by immunoblotting with an antibody specific for Bax. (C) Total RNA was isolated from Myc-ER-infected wild-type pre-B cells activated with 4-HT for the indicated intervals. Pre-B cells pretreated with cycloheximide are indicated by a plus sign. The expression of *bax* transcripts was assessed by Northern blot analyses utilizing *bax* cDNA. (D) 4-HT was added to wild-type, *ARF*^{-/-}, *p53*^{-/-}, and *ARF*^{-/-}; *p53*^{-/-} pre-B-cell cultures infected with the Myc-ER-encoding retrovirus to activate Myc-ER. At the indicated intervals, cells were collected and protein lysates were prepared. Equal quantities of protein were evident by immunoblotting with antibodies specific for Bax, and the levels of Myc-ER protein expressed in the four genotypes were equivalent (5).

Therefore, Bax impairs Myc-induced lymphomagenesis. FACS analysis with lymphoid-specific antibodies showed that the *Bax*-null and *Bax*^{+/-} *Eμ-myc* transgenics develop pre-B- and B-cell lymphoma typical of wild-type *Eμ-myc* transgenics (data not shown) and not the primitive lymphoid tumor described in the *Eμ-myc/Eμ-bcl-2* double-transgenic mice (54). Predictably, Southern blot analysis revealed that all but one of the lymphomas that arose in *Bax*-null *Eμ-myc* transgenics were clonal

(data not shown), which is characteristic of the lymphomas that develop in *Eμ-myc* transgenics (1).

Inactivation of *p53* or *ARF* occurs in a mutually exclusive fashion in over half of all *Eμ-myc* lymphomas (5). Bax appears to function as a tumor suppressor in some scenarios (45), although *Bax*-null mice do not spontaneously develop cancer (20, 22). If Bax functioned as a bona fide tumor suppressor in *Eμ-myc* transgenic mice, one would predict that *Bax* would be inactivated in a subset of lymphomas and that lymphomas arising in *Bax*^{+/-} *Eμ-myc* transgenics would suffer inactivating mutations of the remaining wild-type *Bax* allele. However, we failed to detect loss of heterozygosity of *Bax* in the tumors analyzed from *Bax*^{+/-} *Eμ-myc* transgenics ($n = 15$), nor did we observe deletion of *Bax* in any lymphomas from *Bax*^{+/+} *Eμ-myc* transgenics ($n > 50$) (data not shown). Furthermore, all tumors derived from wild-type and *Bax*^{+/-} *Eμ-myc* transgenics expressed Bax protein (Fig. 4A and data not shown). In previous studies Bax has been shown to be inactivated in tumor cells by frameshift and missense point mutations (4, 30, 31, 45). However, sequencing full-length *Bax* cDNA derived from 16 tumors from *Bax*^{+/+} and *Bax*^{+/-} *Eμ-myc* transgenics failed to reveal any tumor-specific changes in *Bax* sequence. All tissue derived from these mice displayed a single nucleotide change (213T to C) in the BH3 domain of Bax, yet this change is silent and maintains aspartate at codon 71. Thus, inactivating mutations of *Bax* either do not occur or are rare in pre-B- and B-cell lymphomas arising in *Eμ-myc* transgenics, even though *Eμ-myc* transgenics that lack *Bax* develop lymphomas at an accelerated rate. Therefore, Bax does not function as a classic tumor suppressor but rather appears to act as a modifier of lymphoma development in *Eμ-myc* transgenic mice.

Bax loss selectively bypasses p53 mutations that arise during Myc-induced lymphomagenesis. *ARF*-null animals are tumor prone and spontaneously develop sarcomas and lymphomas within 8 months of age (19). *ARF* is upregulated after Myc activation, and loss of *ARF* impairs Myc-induced apoptosis and accelerates lymphomagenesis in *Eμ-myc* transgenic mice (5, 50). To determine whether the loss of *Bax* influences tumorigenesis initiated in *ARF*-deficient mice, we crossed *ARF*- and *Bax*-deficient mice, and F₁ mice were then mated to generate *ARF/Bax*-double null mice. The *ARF*^{-/-}*Bax*^{-/-} mice were monitored for tumor development and compared with the tumor latency in *ARF*^{-/-}*Bax*^{+/+} littermates. We found that Bax deficiency does not alter the survival of *ARF*-null mice, since the average age of survival for *Bax*^{+/+} *ARF*^{-/-} (48.9 weeks, $n = 37$) and *Bax*^{-/-} *ARF*^{-/-} (47.6 weeks, $n = 39$) mice was essentially equivalent. Therefore, loss of Bax does not influence the overall survival of *ARF*-null mice. At face value this could suggest that Bax is in the same pathway as *ARF*. On the other hand, the results could indicate that *ARF* and Bax exist in separate pathways that function independently of each other. In support of the latter concept, biallelic deletion of *ARF* occurred in lymphomas from both *Bax*^{-/-} *Eμ-myc* transgenics (12%) and *Bax*^{+/-} *Eμ-myc* transgenic mice (20%) (Fig. 5; Table 1), indicating that *Bax* loss does not prevent inactivation of *ARF*. The percentage of tumors with *ARF* deletions was slightly lower than previously reported (5), but this could be due to experimental variation or (more likely) to the different background of this cross from the one previously reported. Indeed, genetic background effects are evident when the dif-

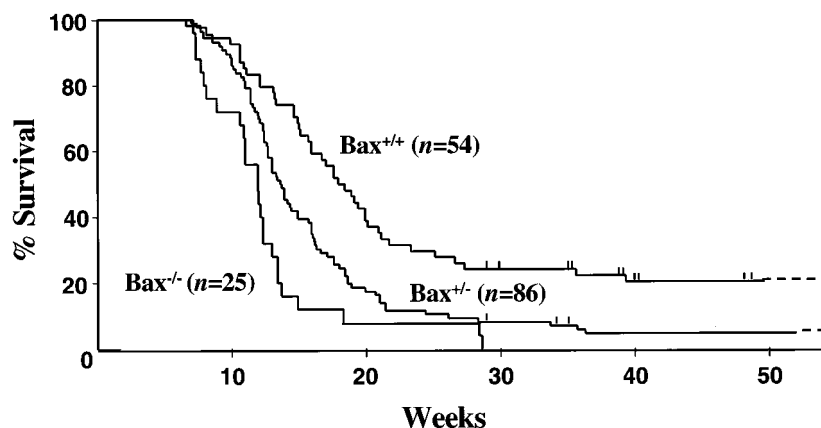


FIG. 3. Myc-induced lymphomagenesis is accelerated by *Bax* loss. The genotypes of the mice are indicated next to the Kaplan-Meier survival curves, and the numbers of mice in each group are denoted by the *n* values. Vertical lines indicate ages of surviving mice: 0 *Bax*^{-/-}, 3 *Bax*^{+/-}, and 10 *Bax*^{+/+} mice. The average life spans of *Bax*^{+/+}, *Bax*^{+/-}, and *Bax*^{-/-} Eμ-*myc* transgenics were 21.7, 16.0, and 12.6 weeks, respectively. Pre-B- and/or B-cell lymphoma was documented in all of the animals.

ferences in average survival of wild-type Eμ-*myc* transgenics, 22 weeks in the *Bax* background (Fig. 3) and 33 weeks in the *ARF* background, are compared (5).

The frequency of *p53* alterations in *Bax*^{+/-} Eμ-*myc* transgenics was similar to that reported for wild-type Eμ-*myc* transgenic mice (5), since approximately one-quarter of the lymphomas arising in *Bax*^{+/-} Eμ-*myc* transgenics sustained mutations or deletions in *p53* (Fig. 4B and 5A; Table 1). As a consequence of *p53* mutations, these tumors (CM201, CM271, and CM696) displayed high levels of p53 protein and concomitant increases in ARF protein (Fig. 4B and data not shown), presumably due to the loss of feedback control of ARF expres-

sion by *p53* (47). One tumor (CM622) from a *Bax*^{+/-} Eμ-*myc* transgenic had deleted both alleles of *p53*, as determined by Southern blot analysis (Fig. 5A). Strikingly, not a single lymphoma arising in *Bax*-null Eμ-*myc* transgenics contained mutant *p53*, nor was *p53* deleted in any of these tumors (Fig. 4B and 5B; Table 1). Therefore, *Bax* loss selectively circumvents the requirement for *p53* mutations and deletions during Myc-induced tumorigenesis but does not alter the frequency of alterations in *ARF*.

Normally, Mdm2 protein is expressed at very low levels. However, half of all lymphomas arising in Eμ-*myc* transgenics overexpress Mdm2 protein, and this also occurs in tumors

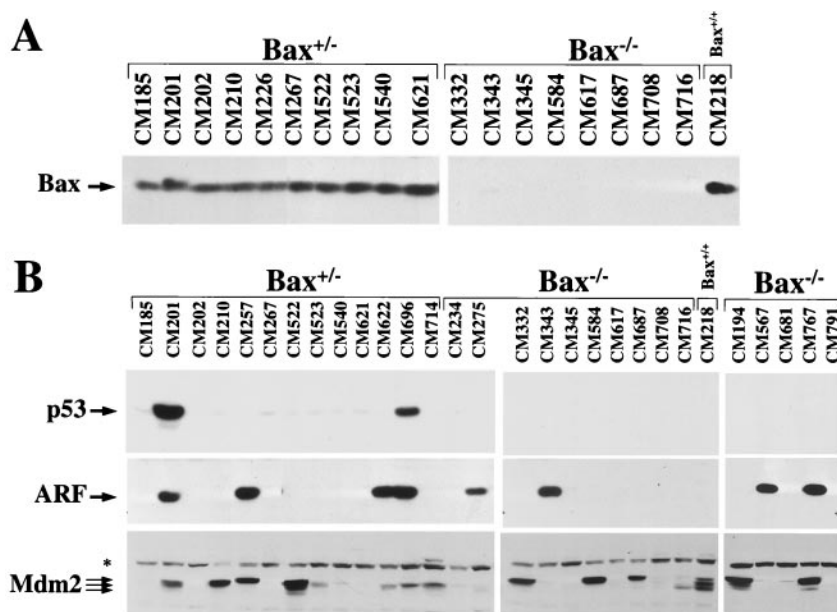


FIG. 4. Western blot analysis of lymphomas arising in *Bax*^{+/-} and *Bax*^{-/-} Eμ-*myc* transgenic mice. Levels of Bax (A), p53 (B, top), p19^{ARF} (B, middle), and Mdm2 (B, bottom) protein in whole-cell extracts of tumors from *Bax*^{+/-} and *Bax*^{-/-} Eμ-*myc* transgenic mice were assessed by immunoblotting with antibodies specific for each protein. Protein extracts from a tumor arising in a *Bax*^{+/+} Eμ-*myc* transgenic mouse that contains the p92, p90, and p85 Mdm2 isoforms were run to show the location of these isoforms in panel B and as a blotting control for Bax expression in panel A. The asterisk in panel B marks the position of a nonspecific background band detected with the Mdm2 antibody.

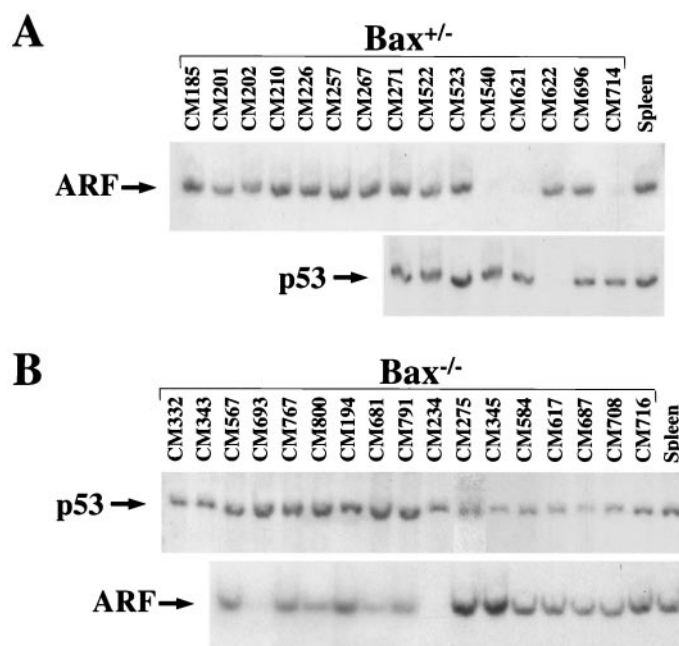


FIG. 5. Southern blot analysis of *Bax*^{+/-} and *Bax*^{-/-} E μ -myc lymphomas. *A*fIII and *B*amHI restriction fragments containing *ARF* exon 1 β and *p53* exons 2 to 10, respectively, from genomic DNA isolated from lymphomas arising in *Bax*^{+/-} (A) and *Bax*^{-/-} (B) E μ -myc transgenic mice. Genomic DNA from the spleen of a wild-type littermate was used as a control in both panels A and B. Lack of a band denotes biallelic deletion of that gene.

bearing deletions of *ARF* or mutations or deletions of *p53* (5). Mdm2 was also overexpressed in approximately half (56%) of all lymphomas arising in *Bax*-null and *Bax*^{+/-} E μ -myc transgenics, regardless of their *ARF* or *p53* status (Fig. 4B and Table 1). The frequency of Mdm2 overexpression in tumors lacking alterations in *ARF* or *p53* was somewhat higher in *Bax*^{-/-} (35%) and *Bax*^{+/-} (27%) E μ -myc transgenics (Table 1) compared to lymphomas arising in wild-type (16%) E μ -myc transgenic mice (5). This difference may be due to the lack of *p53* alterations in *Bax*-deficient E μ -myc transgenic mice. Overall, lymphomas from *Bax*^{-/-} E μ -myc transgenics showed a frequency of alterations in the ARF-Mdm2-*p53* pathway (71%) similar to that of *Bax*^{+/-} (80%) (Table 1) and wild-type (80%) (5) E μ -myc transgenics. Therefore, *Bax* loss selectively eliminates the requirement for *p53* mutations or deletions during lymphomagenesis, without significantly influencing the frequency of alterations in *ARF* and Mdm2 (Fig. 6).

DISCUSSION

B cells lacking mediators of Myc-induced apoptosis have an accelerated course of lymphoma development in E μ -myc transgenic mice (5, 17, 50). For example, deleting *ARF* or *p53*, both mediators of Myc-induced apoptosis, accelerates lymphomagenesis in E μ -myc transgenic mice (5, 50). Here, by using in vivo models, we extend these observations to the proapoptotic Bcl-2 family member *Bax* and show that intersecting apoptotic pathways play a crucial role in Myc-induced lymphomagenesis. Loss of *Bax* in pre-B cells confers resistance to Myc-induced apoptosis and accelerates pre-B- and B-cell lymphoma development in E μ -myc transgenic mice. This is consistent with the finding that *Bax*-null mouse embryo fibro-

blasts (MEFs) are more resistant to Myc-induced apoptosis (32). Therefore, *Bax* is a mediator of Myc-induced apoptosis and inhibits Myc-initiated tumorigenesis.

The balance of proapoptotic and antiapoptotic Bcl-2 family members regulates the susceptibility of cells to apoptosis (reviewed in reference 23). An excess of *Bax* induces cell death, whereas overexpression of Bcl-2 or Bcl-X_L suppresses apoptosis induced by a variety of apoptotic stimuli. In immortal human cells *bax* has been reported to be a transcriptional target of both *p53* (34, 35) and Myc (32), yet we failed to detect any direct or significant increase in *Bax* expression upon Myc activation in primary murine pre-B cells. Nevertheless, activation of *p53* can induce *bax* and suppress *bcl-2* expression in certain cell types (33–35). Myc, on the other hand, upregulates *p53* and ARF (5, 63) and suppresses Bcl-X_L expression, and the latter is independent of either *p53* or ARF in primary murine hematopoietic cells (6). Thus, Myc activation alone is sufficient to alter the ratio of pro- and antiapoptotic Bcl-2 family members with the net result being an excess of *Bax*, which leads to apoptosis. *Bax* loss short-circuits this response and confers survival to cells overexpressing Myc.

p53 is a mediator of Myc-induced apoptosis (5, 63), and *Bax* plays an important role in *p53*-dependent apoptosis in some cell types in vitro (28, 35) and in vivo (52, 62). This study confirms and extends these results by linking Myc with *p53* and *Bax* in vivo. Lymphomas arising in *Bax*-deficient E μ -myc transgenic mice lack *p53* mutations and deletions, whereas 28% of tumors from wild-type E μ -myc transgenics (5) and 27% of lymphomas from *Bax*^{+/-} E μ -myc transgenic mice sustain mutations or deletions in *p53*. Therefore, under selective pressure from Myc, *Bax*-deficient B cells differ from their wild-type counterparts by sustaining wild-type *p53* expression. These re-

TABLE 1. p53, ARF, and Mdm2 protein expression in lymphomas from *Bax*^{+/-} and *Bax*^{-/-} E μ -myc transgenics

E μ -myc transgenic (no. of tumors analyzed)	Finding (% tumors analyzed)	Mouse	Expression of:			
			p53	p19ARF	Mdm2	
<i>Bax</i> ^{+/-} (15)	ARF inactivation (20)	CM540	Basal	Undetected (deleted)	Low	
		CM621	Basal	Undetected (deleted)	Undetected	
		CM714	Low	Undetected (deleted)	Moderately overexpressed	
	p53 inactivation (26)	CM201	Mutant	Overexpressed	Overexpressed	
		CM271	Mutant	Overexpressed	Overexpressed	
		CM622	Deleted	Overexpressed	Moderately overexpressed	
		CM696	Mutant	Overexpressed	Moderately overexpressed	
	ARF overexpressed, p53 wild type (7)	CM257	Low	Overexpressed	Overexpressed	
	Mdm2 overexpression only (27)	CM210	Basal	Undetected	Overexpressed	
		CM226	Low	Undetected	Moderately overexpressed	
		CM522	Basal	Undetected	Overexpressed	
		CM523	Basal	Undetected	Moderately overexpressed	
	No detectable alteration (20)	CM185	Basal	Undetected	Undetected	
		CM202	Low	Undetected	Undetected	
		CM267	Basal	Undetected	Undetected	
	<i>Bax</i> ^{-/-} (17)	ARF inactivation (12)	CM234	Basal	Undetected (deleted)	Low
			CM693	Basal	Undetected (deleted)	Overexpressed
		p53 inactivation (0)				
		ARF overexpressed, p53 wild type (24)	CM275	Low	Overexpressed	Low
CM343			Low	Overexpressed	Undetected	
CM567			Low	Overexpressed	Low	
CM767			Low	Overexpressed	Overexpressed	
Mdm2 overexpression only (35)		CM194	Basal	Undetected	Overexpressed	
		CM332	Basal	Undetected	Overexpressed	
		CM584	Basal	Undetected	Overexpressed	
		CM687	Basal	Undetected	Overexpressed	
		CM716	Basal	Undetected	Moderately overexpressed	
		CM800	Basal	Undetected	Moderately overexpressed	
No detectable alteration (29)		CM345	Basal	Undetected	Undetected	
		CM617	Basal	Undetected	Undetected	
		CM681	Basal	Undetected	Low	
		CM708	Basal	Undetected	Undetected	
	CM791	Basal	Undetected	Undetected		

sults imply that during transformation mutation of *p53* is unnecessary when *Bax* is absent, supporting the observations that *Bax* is downstream from *p53* (10). This is consistent with the observation that there is no cooperative effect on the rate of tumorigenesis in mice lacking both *p53* and *Bax* compared to mice deficient in *p53* alone (20). Moreover, when the statuses of *ARF* and *p53* were analyzed in lymphomas that arise in E μ -myc transgenic mice, biallelic deletion of *ARF* or *p53* deletion or mutation occurred in a mutually exclusive fashion (5).

Thus, although *ARF* and *p53* can function in the same tumor suppressor pathway, our results demonstrate that this pathway must bifurcate, since only *Bax* and *p53* are in the same Myc-induced pathway (Fig. 6). Indeed, this study provides formal genetic proof that *ARF*, *Mdm2*, and *p53* have different targets.

One of the most intriguing outcomes of these studies is the finding that that *Bax* loss influences *p53* status independent of *ARF* (Fig. 6). *Bax* deficiency did not affect the frequency of *ARF* deletions in E μ -myc lymphomas nor tumor latency in

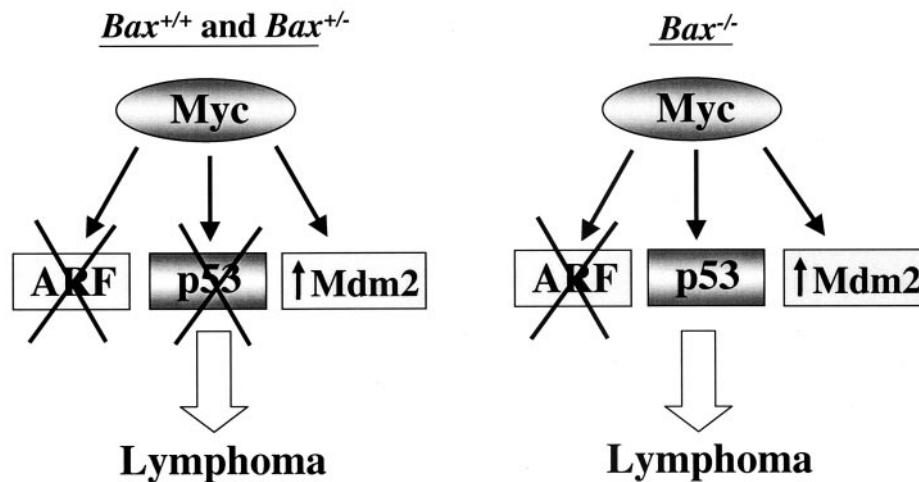


FIG. 6. Schematic describing the outcome of molecular events that occur in lymphomas in *Bax*^{+/+}, *Bax*^{+/-}, and *Bax*^{-/-} *Eμ-myc* transgenic mice. On the left, the majority of lymphomas that arise in *Bax*^{+/+} and *Bax*^{+/-} *Eμ-myc* transgenic mice have alterations in *ARF* (deletion, X) or *p53* (mutation or deletion, X) and/or *Mdm2* (overexpression, ↑) (Fig. 4 and 5 and Table 1; see also reference 5). On right, a similar frequency of alterations in *ARF* and *Mdm2* still occurs in lymphomas from *Bax*-null *Eμ-myc* transgenic mice; however, no *p53* mutations or deletions are observed in these lymphomas (Fig. 4 and 5, Table 1). Therefore, *Myc* targets *ARF* and *Mdm2* but not *p53* in the absence of *Bax* during *Myc*-induced lymphomagenesis.

ARF-null mice, suggesting that *Bax* and *ARF* are not in the same pathway, or that *Bax* resides in a position in the pathway that does not influence *ARF*. However, further analysis has demonstrated that *Bax* loss does affect the tumor spectrum in *ARF*-null mice (C. M. Eischen and J. L. Cleveland, unpublished data). Thus, there is cooperativity at least at some level, and *ARF* and *Bax* must function in separate pathways.

Even though *ARF* and *p53* function in the same tumor suppressor pathway, *p53* has been reported to function independently of *ARF* in certain situations and vice versa. For example, gamma irradiation-induced apoptosis is *p53* dependent and still occurs in *ARF*-null cells (19), and *ARF* can still induce cell cycle arrest in fibroblasts lacking *p53* and *Mdm2* (58). Our data from *Bax*-null *Eμ-myc* transgenic mice reveals a role for *Bax* that is dependent on *p53* but independent of *ARF*. *Myc* thus affects the *p53* pathway in two ways: by upstream activation through *ARF* and by downstream activation of *Bax*. However, the loss of *Bax* does seem to disrupt the *ARF*-*Mdm2*-*p53* pathway by other means. The increased percentage of lymphomas in *Bax*-null *Eμ-myc* transgenics that overexpressed *ARF* (Table 1) suggests that *Bax* expression could influence the *ARF*-*Mdm2*-*p53* pathway by somehow targeting proteins that regulate *ARF* expression, such as *Bmi-1* (16), *Dmp-1* (13), *JunD* (60), *Tbx2* (15), and *Twist* (27). Alternatively, *Bax* status could disrupt the delicate feedback control mechanisms that regulate the expression of *ARF*, *Mdm2*, and *p53* (47, 53).

Mdm2 is a negative regulator of *p53*, and we therefore predicted that, since the loss of *Bax* bypassed requirements for inactivating *p53*, then the frequency of *Mdm2* overexpression would be decreased as well. Surprisingly, *Mdm2* was overexpressed in 50% (16 of 32) of all of the lymphomas analyzed, as shown in wild-type *Eμ-myc* transgenics (5), regardless of *Bax* status. *Mdm2* has many targets other than *p53* (e.g., *E2F-1*, *DP-1*, *p300*, and *pRb*) (reviewed in reference 36) and appears

to function independently of the *p53* pathway in certain scenarios. For example, *Mdm2* is overexpressed in a third of all lymphomas that had mutated or deleted *p53* (5), and haploinsufficiency of *Mdm2* alters the tumor spectrum in *p53*-null mice (29). Moreover, *Mdm2* transgene overexpression resulted in altered mammary gland development (26) and tumorigenesis (18) in *p53*^{-/-} mice. Therefore, selection for *Mdm2* overexpression in *Eμ-myc* lymphomas is not influenced by *Bax* status and is also not necessarily linked to alterations in *p53* or *ARF* (Fig. 6).

Bax does not function as a classic tumor suppressor in *Eμ-myc*-induced lymphomas, as do *ARF* and *p53* (reviewed in reference 51). However, *Bax* tumor suppressor function has been reported in some scenarios. First, a *Bax* frameshift mutation occurs in a subset of colon adenocarcinomas (45), and cells with this mutation display a survival advantage when transplanted into nude mice (14). Second, *Bax* deficiency accelerates brain and breast tumor development in SV40 large T antigen-transgenic mice (52, 62). Finally, there is increased foci formation in transformation assays by using *Bax*-deficient MEFs (28). In contrast, *Bax* is not mutated in any of the *Bax*^{+/+} or *Bax*^{+/-} *Eμ-myc* tumors analyzed. Additionally, there was no loss of heterozygosity of *Bax* in mammary carcinomas from *Bax*^{+/-} C3 (1)/SV40 large T antigen-transgenic mice (52) or in lymphomas from *Bax*^{+/-} *Eμ-myc* transgenics (Fig. 4A). These latter findings are consistent with the observation that *Bax* is infrequently mutated in most types of human B-cell lymphoma (42). Moreover, *Bax*-null mice do not spontaneously develop cancer (22), and loss of *Bax* did not influence the survival of *ARF*-null mice. Therefore, *Bax* may function as a classic tumor suppressor under very specific circumstances but acts as a modifier in most situations, such as *Myc*-induced lymphomas. Our observations also indicate that targets in addition to *Bax* must contribute to *p53*-dependent tumor suppression.

It has been known for over a decade that Bcl-2 and Myc can cooperate in transformation. The malignancy in $E\mu$ -myc/ $E\mu$ -bcl-2 double-transgenic mice is composed of primitive lymphoid cells (54), rather than the pre-B and/or mature B cells typical of $E\mu$ -myc lymphomas (1). Although loss of *Bax* also accelerates lymphomagenesis in $E\mu$ -myc transgenics, flow cytometric analysis clearly indicates that these lymphomas are of pre-B- and/or mature B-cell origin. Thus, overexpression of Bcl-2 blocks Myc-induced apoptosis and alters the differentiation of the lymphoid cell, while *Bax* loss alters the sensitivity to Myc-induced apoptosis without overtly affecting B-cell differentiation. Thus, Bcl-2 and *Bax* appear to provide different developmental roles when B-cell precursors are forced to proliferate by Myc expression. Although Bcl-2 can inhibit the apoptotic effects of *Bax* (reviewed in reference 23), Bcl-2 and *Bax* can regulate apoptosis independently of each other (21). Moreover, Bcl-2 is overexpressed at the same frequency in $Bax^{-/-}$ and $Bax^{+/+}$ $E\mu$ -myc lymphomas (Eischen and Cleveland, unpublished). Therefore, it will be interesting to evaluate the status of *p53*, *ARF*, and Mdm2 in the tumors from $E\mu$ -myc/ $E\mu$ -bcl-2 double transgenics in order to determine whether Bcl-2 and *Bax* function in common or distinct pathway(s) in relationship to *p53*.

ACKNOWLEDGMENTS

We thank Gerard Zambetti for many helpful discussions and for critical review of the manuscript, Robert Hawley and Derek Persons for retroviral vectors, Alan Harris and Charles Sidman for providing breeders for $E\mu$ -myc transgenic mice, Richard Cross for superb assistance with FACS, and Cynthia Wetmore for assistance with *p53* sequencing. We also appreciate the outstanding technical support of Chunying Yang, Elsie White, and Rose Mathew.

This work was supported in part by National Institutes of Health grants CA76379 and DK44158 (J.L.C.), CA71907 and CA56819 (M.F.R.), Cancer Center Core grant CA21765, NIH Postdoctoral Grant CA81695 (C.M.E.), and by the American Lebanese Syrian Associated Charities of St. Jude Children's Research Hospital.

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