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BCL-2 Cooperates with Promyelocytic Leukemia Retinoic Acid Receptor α Chimeric Protein (PMLRAR α) to Block Neutrophil Differentiation and Initiate Acute Leukemia

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Abstract

The promyelocytic leukemia retinoic acid receptor α (PMLRAR α) chimeric protein is associated with acute promyelocytic leukemia (APL). PMLRAR α transgenic mice develop leukemia only after several months, suggesting that PMLRAR α does not by itself confer a fully malignant phenotype. Suppression of apoptosis can have a central role in tumorigenesis; therefore, we assessed whether BCL-2 influenced the ability of PMLRAR α to initiate leukemia. Evaluation of preleukemic animals showed that whereas PMLRAR α alone modestly altered neutrophil maturation, the combination of PMLRAR α and BCL-2 caused a marked accumulation of immature myeloid cells in bone marrow. Leukemias developed more rapidly in mice coexpressing PMLRAR α and BCL-2 than in mice expressing PMLRAR α alone, and all mice expressing both transgenes succumbed to leukemia by 7 mo. Although both preleukemic, doubly transgenic mice and leukemic animals had abundant promyelocytes in the bone marrow, only leukemic mice exhibited thrombocytopenia and dissemination of immature cells. Recurrent gain of chromosomes 7, 8, 10, and 15 and recurrent loss of chromosome 2 were identified in the leukemias. These chromosomal changes may be responsible for the suppression of normal hematopoiesis and dissemination characteristic of the acute leukemias. Our results indicate that genetic changes that inhibit apoptosis can cooperate with PMLRAR α to initiate APL.

Key words: leukemia • myeloid/leukemia • promyelocytic • acute/leukopoiesis/PML protein/receptors • retinoic acid

Introduction

Many genetic alterations have been associated with acute myeloid leukemia (AML)¹ (1, 2). Nevertheless, our understanding of the combinations of changes sufficient to fully

transform myeloid cells remains limited. The t(15;17)(q22;q11.2) chromosomal translocation is closely associated with human acute promyelocytic leukemia (APL; reference 3). This translocation fuses the gene encoding promyelocytic leukemia (PML), a protein that limits proliferation and induces apoptosis, with the gene encoding the retinoic acid receptor α (RAR α), a hormone receptor that represses transcription in the absence of retinoic acid and activates transcription in response to this ligand. A PMLRAR α fusion protein is expressed in almost all cases of APL, and this protein can initiate acute leukemias with promyelocytic features when expressed in mice (4–6).

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¹Abbreviations used in this paper: 7-AAD, 7-amino actinomycin D; AML, acute myeloid leukemia; APL, acute promyelocytic leukemia; PML, promyelocytic leukemia; RAR α , retinoic acid receptor α ; tRA, all-trans retinoic acid.

PMLRAR α is thought to contribute to leukemogenesis primarily by inhibiting neutrophilic differentiation. Retinoids can induce differentiation of myeloid and other cell types (7). PMLRAR α inhibits differentiation of myeloid cell lines (8–11), and all-trans retinoic acid (tRA) binding to PMLRAR α results in transcriptional activation and neutrophilic differentiation (3, 12–14). Nevertheless, mice expressing PMLRAR α exhibited only mild abnormalities before the appearance of acute leukemia (which arises with limited penetrance only after several months; references 4–6), suggesting that additional genetic changes cooperate with PMLRAR α to block differentiation.

PMLRAR α may also contribute to leukemogenesis by enhancing the survival of immature myeloid cells. Whereas PMLRAR α induces apoptosis of nonhematopoietic and some hematopoietic cell lines (15), PMLRAR α confers increased resistance to apoptosis in myeloid cell lines in which its expression is tolerated (8, 16). PMLRAR α also enhances survival of primary myeloid CFU in response to proapoptotic stimuli (17) and hematopoietic progenitor cells after growth factor deprivation (18). PMLRAR α -mediated suppression of apoptosis might influence the ability of this fusion protein to initiate leukemia.

BCL-2 protects cells from apoptosis by inhibiting the activation of caspases necessary to execute a cell death program (19). In follicular lymphoma, BCL-2 is overexpressed as a result of a t(11;14)(q32;q21) chromosomal translocation. BCL-2 expression has also been observed in AMLs, including leukemic cells of some APL patients, and such expression has been associated with poor prognosis (20–26). Thus, BCL-2, or related proteins, may play a role in the pathogenesis of a subset of APL and might influence the response of patients to therapy.

Transgenic mice expressing PMLRAR α under the control of the *MRP8* promoter were bred with *MRP8-BCL-2* transgenic mice to assess whether BCL-2 could cooperate with PMLRAR α to initiate leukemia. We observed that coexpression of BCL-2 and PMLRAR α caused a marked accumulation of immature myeloid cells. Furthermore, BCL-2 accelerated the development of acute leukemia in mice that express PMLRAR α .

Materials and Methods

Mice. Mice were bred and maintained at the University of California at San Francisco and their care was in accordance with University of California at San Francisco guidelines. *MRP8-PMLRAR α* transgenic mice (4) were bred with *MRP8-BCL-2* transgenic mice (27) to generate the litters of control, singly transgenic, and doubly transgenic mice used for experiments.

Preparation of Tissues for Analysis. Blood was obtained from anesthetized animals by venipuncture of the retroorbital venous plexus. Bone marrow was obtained by flushing HBSS through mouse long bones. Blood smears and bone marrow smears were prepared according to standard hematological techniques. Sternums were decalcified for 2–3 h (formic acid 11%, formaldehyde 8%). Sternums, livers, spleens, and kidneys were fixed overnight in buffered formalin and embedded in paraffin before sectioning.

Peripheral Blood Counts and Bone Marrow Differential Counts.

Blood counts of nonleukemic, preleukemic, and some leukemic mice were obtained on automated hematology analyzers running veterinary software (Cell-Dyne3500, Abbott; Hemavet 850, CDC Technologies). Blood counts of leukemias that arose early in the study were obtained on a Technicon H-3 automated hematology analyzer running the standard software used for clinical analysis. Peripheral blood differential white blood cell counts (total of 200 cells each) and bone marrow differential counts (total of 400 cells each) were performed on stained smears as described (28).

Analysis of Proliferation. Bone marrow cells were fixed in ice-cold 70% ethanol for 30 min. After two washes in PBS, cells were resuspended in PBS containing 50 μ g/ml propidium iodide (Boehringer) and 10 μ g/ml RNase (Sigma-Aldrich). After a 30-min incubation, cells were analyzed using a FACScanTM flow cytometer (Becton Dickinson) and cell cycle distribution of 10,000 events was assessed using Modfit software (Becton Dickinson).

Analysis of Apoptosis. Immediately after harvest, bone marrow cells were washed twice in PBS with 2% heat-inactivated fetal bovine serum (wash buffer), and cells were then stained with FITC-conjugated antibodies to CD18 or an isotype control (BD PharMingen) for 20 min on ice. Then, cells were washed and stained for 30 min in the dark, on ice, with 20 μ g/ml 7-amino actinomycin D (7-AAD; Calbiochem). After being washed twice, cells were resuspended in wash buffer containing 10 μ g/ml actinomycin D (Calbiochem). Analysis was carried out using a FACScanTM flow cytometer within 1 h of staining. 50,000 events were analyzed using CELLQuestTM software (Becton Dickinson). CD18⁺ cells were gated and three populations were identified: 7-AAD^{low} live nonapoptotic cells; 7-AAD^{moderate} apoptotic cells; and 7-AAD^{bright} dead cells (29).

Methylcellulose Cultures of Bone Marrow. As described previously (28), bone marrow cells were cultured in duplicate in 35-mm petri dishes in Methocult M3230 methylcellulose medium (StemCell Technologies Inc.) supplemented with either 50 U/ml of G-CSF (Boehringer) or 20 ng/ml GM-CSF (StemCell Technologies Inc.). 1-ml cultures contained 50,000 viable bone marrow cells. Cultures were examined at 7 d. Colonies were counted on an inverted light microscope. Duplicate plates were averaged. Cells were harvested, pelleted, washed once in HBSS, and counted before preparation of cytopins. Differential cell counts (total of 200 cells each) were performed on stained cytopins to assess percentages and calculate absolute numbers of neutrophilic cells. To assess the effects of growth factor deprivation, cells were placed into methylcellulose medium with or without GM-CSF and incubated for 24 h before plating matched cultures in the presence of GM-CSF. Results were expressed as a percentage (CFU of growth factor-deprived culture/CFU of matched culture without growth factor deprivation \times 100).

Transplantation of Bone Marrow. Essentially as described previously (4), total bone marrow isolated from tibias and femurs of 4–6-wk-old mice was divided for intravenous injection into 6–10 recipient mice (\sim 1–3 \times 10⁶ nucleated marrow cells/recipient). 6–12-wk-old FVB/N mice were prepared for transplantation by cesium irradiation totaling 10 Gy, divided into two doses 3–6 h apart. The results shown in Fig. 3 include five recipients of *PMLRAR α /BCL-2* doubly transgenic marrow that was 0.75 FVB/N strain, 0.25 BA strain; six recipients of matched *PMLRAR α* singly transgenic marrow (0.75 FVB/N, 0.25 BA); eight recipients of *PMLRAR α /BCL-2* doubly transgenic marrow (0.98 FVB/N, 0.02 BA); and 21 recipients of *PMLRAR α* singly transgenic marrow (1.0 FVB/N). The difference in survival of recipients of doubly transgenic and singly transgenic marrow was statistically

significant whether the data were analyzed as a whole or as subgroups.

Comparative Genomic Hybridization. Comparative genomic hybridization was performed as described previously (30, 31) at the Molecular Cytogenetics Core Facility, Comprehensive Cancer Center, University of California at San Francisco.

Retinoic Acid/Arsenic Treatment. As described previously, mice were treated by subcutaneous implantation of a 21-d release pellet containing 5 mg tRA or placebo (Innovative Research of America; reference 4), and/or by daily intraperitoneal injection of As_2O_3 (arsenic) at a dose of 5 $\mu\text{g/g}$ body wt (32).

Statistical Analysis. The software program Statistica (v.4.1 for Macintosh) was used to prepare Kaplan-Meier curves and to compare survival using the Wilcoxon test. Other statistical analyses were performed with Excel (v.5.0/95) using the Student's *t* test, two-tailed distribution, and unequal variance. Comparisons are with control animals unless otherwise noted.

Results

BCL-2 Cooperates with PMLRAR α to Impair Neutrophil Maturation and Expand Myeloid Progenitors. Previously, we developed a mouse model of APL by expressing PML-

RAR α in the neutrophilic cells of transgenic mice (4). PMLRAR α had a modest effect on neutrophil differentiation but did not initially arrest maturation. Some of the PMLRAR α transgenic mice went on to develop acute leukemia with promyelocytic features. The latency and limited penetrance of the leukemic phenotype indicated that in this mouse model, additional events were required to cooperate with PMLRAR α in the genesis of acute leukemia. In our effort to identify genetic changes that can cooperate with PMLRAR α to induce leukemia, we considered previous studies indicating that PMLRAR α induces apoptosis of many cell lines (15) and evidence that apoptosis can be a critical regulator of malignant transformation in vivo (33).

To assess the hypothesis that suppression of apoptosis cooperates with PMLRAR α in leukemogenesis, we crossed MRP8-PMLRAR α transgenic mice with MRP8-BCL-2 transgenic mice (27). Previous studies of MRP8-BCL-2 transgenic mice indicated that (a) the BCL-2 transgene inhibited apoptosis of neutrophils but not their engulfment by macrophages (27), (b) the transgene inhibited apoptosis of monocytes as well as rescued macrophages and partially reversed osteopetrosis in *op/op* mice (34), (c) the transgene

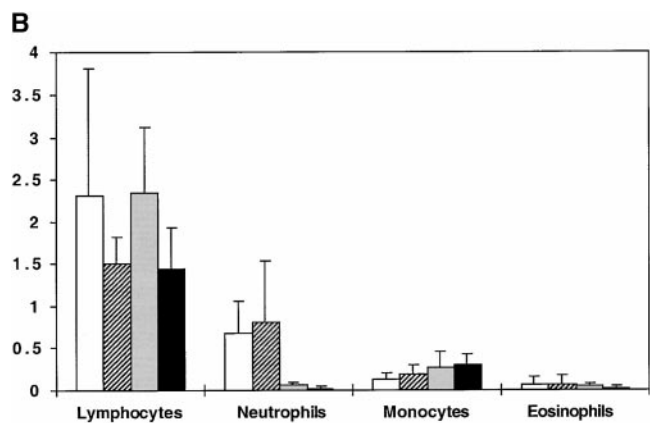
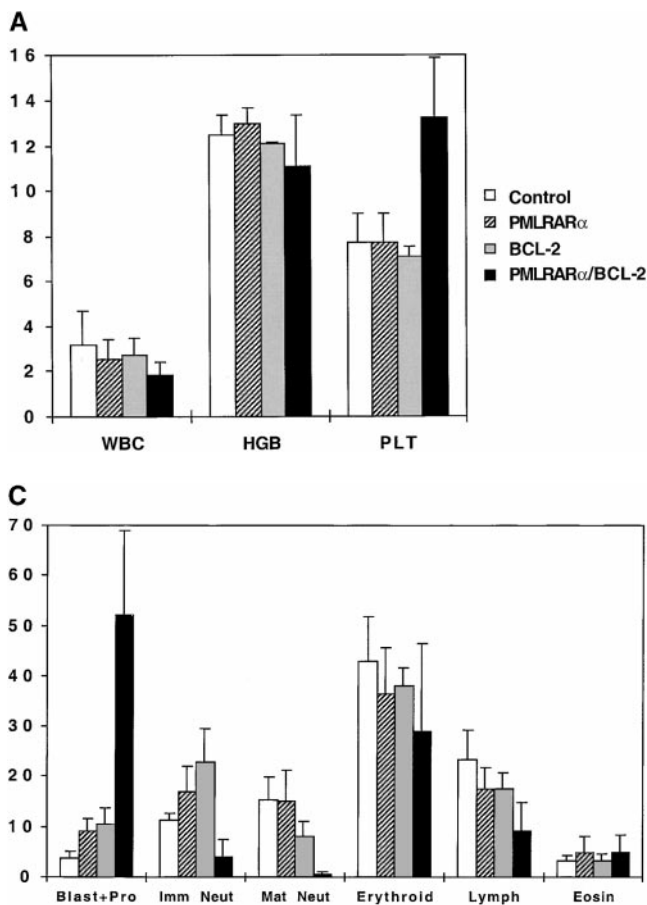


Figure 1. BCL-2 cooperates with PMLRAR α to impair neutrophil production in vivo. (A) Peripheral blood. White blood cell count (WBC, 1,000/ μL), hemoglobin (HGB, g/dL), and platelet count (PLT, 100,000/ μL) are shown. Littermate controls, *n* = 6; PMLRAR α , *n* = 5; BCL-2, *n* = 4; and PMLRAR α /BCL-2, *n* = 6. Platelet count was increased in PMLRAR α /BCL-2 mice (*P* = 0.002). (B) Peripheral blood. Absolute cell counts (1,000/ μL). Littermate controls, *n* = 6; PMLRAR α , *n* = 4; BCL-2, *n* = 4; and PMLRAR α /BCL-2, *n* = 6. Neutrophils were decreased in BCL-2 and PMLRAR α /BCL-2 mice (*P* = 0.01). Monocytes were increased in PMLRAR α /BCL-2 mice (*P* = 0.02). (C) Bone marrow. Percentages of nucleated cells were derived from 400 cell differential counts of Wright's Giemsa-stained bone marrow smears. Blast+Pro, blasts and promyelocytes; Imm Neut, neutrophilic myelocytes and metamyelocytes; Mat Neut, neutrophilic band, mature ring, and polymorphonuclear forms; Lymph, lymphocytes; Eosin, eosinophils. Littermate controls, *n* = 6; PMLRAR α , *n* = 4; BCL-2, *n* = 4; PMLRAR α /BCL-2, *n* = 6. In PMLRAR α mice, blasts plus promyelocytes were increased (*P* = 0.01). In BCL-2 mice, blasts plus promyelocytes were increased (*P* = 0.02), immature neutrophils were increased (*P* = 0.04), and mature neutrophils were decreased (*P* = 0.02). In PMLRAR α /BCL-2 mice, blasts plus promyelocytes were increased (*P* = 0.001), immature neutrophils were decreased (*P* = 0.003), mature neutrophils were decreased (*P* = 0.0004), and lymphocytes were decreased (*P* = 0.002). Graphs depict arithmetic means \pm SD.

inhibited Fas-induced apoptosis of myeloid progenitors (35), and (d) in the context of *FAS^{pr/lpr}* mice, the *BCL-2* transgene contributed to the development of a lethal proliferation of myeloid cells (35). These results showed that the *BCL-2* transgene was able to suppress apoptosis of myeloid cells and contribute to myeloid neoplasms.

MRP8-BCL-2 transgenic mice were mated with *MRP8-PMLRAR α* mice to examine the effects of the combination of transgenes on hematopoiesis. In the peripheral blood, total leukocyte counts and hemoglobin levels of 3–5-wk-old transgenic mice were normal (Fig. 1 A). Singly transgenic mice had normal platelet counts, whereas those of doubly transgenic mice were elevated. *PMLRAR α* transgenic mice had normal peripheral blood neutrophil counts, but mice expressing *BCL-2* alone or in combination with *PMLRAR α* were neutropenic (Fig. 1 B). Decreased neutrophil counts were previously observed in *MRP8-BCL-2* transgenic mice (34). In the bone marrow, both *PMLRAR α* and *BCL-2* singly transgenic mice exhibited a shift from mature neutrophilic cells to immature

neutrophilic cells with a small increase in promyelocytes. Doubly transgenic mice had very few neutrophilic cells beyond the promyelocyte stage (Fig. 1 C). Whereas the bone marrow of singly transgenic mice looked modestly different from control mice (Fig. 2, A–C), doubly transgenic bone marrow was filled with immature cells and morphologically resembled acute leukemia (Fig. 2 D). However, unlike leukemic animals, the organs of these doubly transgenic mice had a near normal appearance (Fig. 2, E–J).

We also assessed proliferation and apoptosis in the transgenic mice (Table I). *PMLRAR α* did not discernibly alter the number of proliferating or apoptotic cells detected in bone marrow. *BCL-2* increased the number of proliferating cells, and the combination of transgenes increased both proliferation and apoptotic cell numbers. Bone marrow histology provided additional evidence of increased cell turnover in doubly transgenic bone marrow; compared with control, increased numbers of tingible body macrophages were present (Fig. 2, K and L). The increased proliferation in doubly transgenic mice is consonant with the presence of

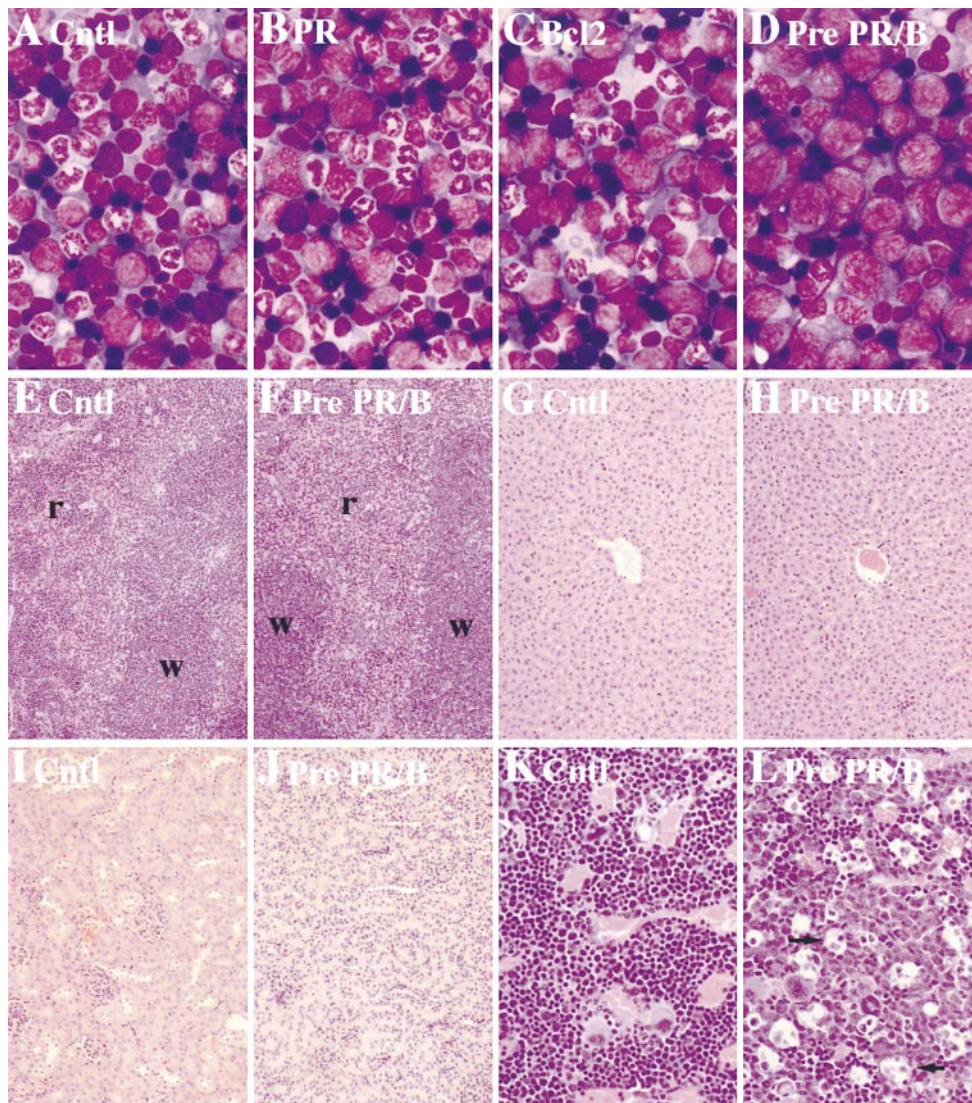


Figure 2. *PMLRAR α* and *BCL-2* transgenes cooperate to arrest neutrophil differentiation. (A–D) Bone marrow morphology: (A) Control (Cntl); (B) preleukemic *PMLRAR α* (PR); (C) *BCL-2*; (D) preleukemic *PMLRAR α /BCL2* (Pre PR/B). Wright's Giemsa stain; original magnifications: $\times 330$. Immature cells are not disseminated in preleukemic doubly transgenic mice. (E–F) Spleen. Red pulp (r); white pulp (w). (G–H) Liver. (I–J) Kidney. (E, G, and I) Control. (F, H, and J) Preleukemic *PMLRAR α /BCL-2*. Hematoxylin and eosin; original magnifications: $\times 66$. Tingible body macrophages are increased in preleukemic *PMLRAR α /BCL-2* mice. (K and L) Bone marrow histology. (K) Control. (L) Preleukemic *PMLRAR α /BCL-2*. Arrows indicate selected macrophages. Hematoxylin and eosin; original magnifications: $\times 165$.

Table I. Bone Marrow Proliferation and Apoptosis in Nonleukemic Animals

| Transgenic mice | Proliferation* | Apoptosis‡ |
|------------------------|-----------------------------|--------------------------------|
| Control | 24.6 ± 3.4 | 3.02 ± 1.08 |
| PMLRAR α | 23.7 ± 2.1 NS | 3.07 ± 1.31 NS |
| BCL-2 | 31.0 ± 3.1 <i>P</i> = 0.03 | 5.98 ± 2.87 NS |
| PMLRAR α /BCL-2 | 36.9 ± 1.3 <i>P</i> = 0.003 | 10.11 ± 1.27 <i>P</i> = 0.0002 |

Bone marrows of mice were harvested and analyzed without prior culture to assess the effects of the transgenes on proliferation and apoptosis in vivo. Data are shown as arithmetic means ± SD. For each group, *n* = 4. *P* values for comparisons with control are shown. NS, not significant.

*Percent S phase.

‡Percent live CD18⁺ (nonerythroid) cells stained by 7-AAD.

increased promyelocytes because promyelocytes, unlike mature neutrophils, are mitotically active. The increase in apoptotic cells likely reflects the fact that in some settings, such as growth factor deprivation, BCL-2 delays but does not prevent cell death (36). The combination of BCL-2 and PMLRAR α caused an accumulation of numerous immature myeloid cells in the bone marrow. These cells could proliferate, but very few differentiated into mature neutrophils. BCL-2 appeared unable to block indefinitely the death of the resulting expanded promyelocyte population.

Methylcellulose cultures were performed to examine the effects of the transgenes on myeloid colony formation in vitro (Table II). PMLRAR α did not alter the number of colonies formed in GM-CSF or G-CSF. In contrast, BCL-2 resulted in increased colonies, an effect that was statisti-

cally significant for doubly transgenic bone marrow. The effect of growth factor deprivation on CFU was also assessed for singly transgenic mice. Matched GM-CSF cultures of control, PMLRAR α , and BCL-2 bone marrow cells were plated with or without 24 h of growth factor deprivation. Both PMLRAR α and BCL-2 resulted in a trend towards enhanced survival (control 61 ± 7%, *n* = 6; PMLRAR α 77 ± 17%, *n* = 6, *P* = 0.07; BCL-2 95 ± 14%, *n* = 4, *P* = 0.01). With regard to differentiation, PMLRAR α , BCL-2, and PMLRAR α /BCL-2 transgenic bone marrows gave rise to a decreased percentage of neutrophils, accompanied by increased immature and monocytic cells. Of note, although the combination of BCL-2 and PMLRAR α caused profound neutropenia in vivo, neutrophil maturation was not completely blocked in bone marrow

Table II. Methylcellulose Cultures of Bone Marrow of Nonleukemic Animals

| | Colonies | Immature cells | Monocytes/macrophages | Neutrophilic cells | Total cells | Neutrophilic cells |
|------------------------|---------------------------------|----------------|---------------------------------|---------------------------------|-------------------------------|---------------------------------|
| | <i>n/ml</i> | % | % | % | 1,000/ml | 1,000/ml |
| GM-CSF | | | | | | |
| Control | 96 ± 25 | 9.7 ± 4.6 | 53.6 ± 2.9 | 33.8 ± 3.4 | 149 ± 39 | 51.1 ± 16.8 |
| PMLRAR α | 106 ± 16 | 9.3 ± 2.3 | 76.4 ± 7.1, <i>P</i> = 0.001 | 10.8 ± 6.5, <i>P</i> < 0.001 | 192 ± 72 | 17.4 ± 6.3, <i>P</i> = 0.008 |
| BCL-2 | 179 ± 78 | 13.0 ± 1.4 | 61.7 ± 10.6 | 19.3 ± 7.8, <i>P</i> = 0.03 | 323 ± 182 | 74.7 ± 61.1 |
| PMLRAR α /BCL-2 | 354 ± 147, <i>P</i> = 0.007 | 12.4 ± 4.8 | 77.6 ± 6.4, <i>P</i> < 0.001 | 7.7 ± 5.6, <i>P</i> < 0.001 | 732 ± 428, <i>P</i> = 0.02 | 45.7 ± 41.2 |
| G-CSF | | | | | | |
| Control | 40.0 ± 18 | 22.1 ± 9.4 | 37.3 ± 10.9 | 40.4 ± 17.5 | 16.5 ± 8.4 | 5.7 ± 2.2 |
| PMLRAR α | 36.0 ± 10 | 30.7 ± 12 | 50.5 ± 11.8 | 17 ± 5.5, <i>P</i> = 0.04 | 7.7 ± 7.5 | 1.1 ± 0.8, <i>P</i> = 0.007 |
| BCL-2 | 70.0 ± 20 | 32.6 ± 13.1 | 57.5 ± 21.3 | 9.3 ± 9.1, <i>P</i> = 0.01 | 21.8 ± 8.3 | 1.8 ± 1.3, <i>P</i> = 0.01 |
| PMLRAR α /BCL-2 | 114.0 ± 45, <i>P</i> = 0.009 | 40.0 ± 26 | 55.8 ± 25.4 | 3.5 ± 2.7, <i>P</i> = 0.009 | 51.7 ± 39.7 | 2.1 ± 3, <i>P</i> = 0.05 |

Bone marrows of mice were harvested and cultured in duplicate at 50,000 cells/ml culture in the presence of either GM-CSF or G-CSF. On day 7, colonies/plate were counted, cells were harvested, pooled from duplicate plates, and counted. Immature cells, monocytes/macrophages, and neutrophilic cells were identified among 200 cells counted on Wright's Giemsa-stained cytopins of pooled cells. Data are shown as arithmetic means ± SD. For each group, *n* = 4-6. *P* values (excluding values >0.05) for comparisons with control are shown.

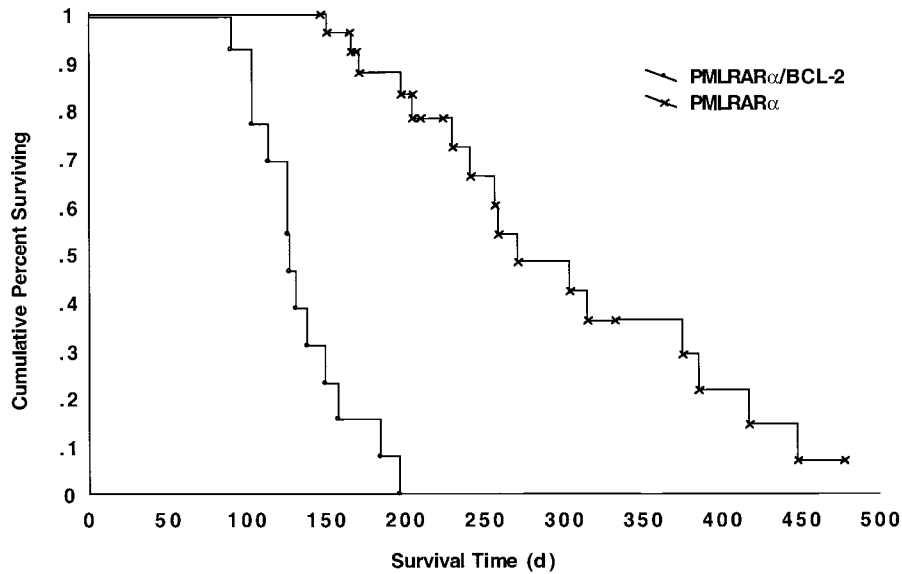


Figure 3. BCL-2 cooperates with PMLRAR α to initiate leukemia. Lethally irradiated nontransgenic FVB/N mice were reconstituted with bone marrow from PMLRAR α or PMLRAR α /BCL-2 transgenic mice. Kaplan-Meier curves are shown. All PMLRAR α /BCL-2 mice died of leukemia. Mortality among PMLRAR α mice from causes other than leukemia was censored at the date of death. PMLRAR α /BCL-2, $n = 13$; PMLRAR α , $n = 27$; $P < 0.00001$.

cultures. In GM-CSF, absolute numbers of neutrophils in BCL-2 and PMLRAR α /BCL-2 cultures were normal because increased colony numbers offset the relative decrease in neutrophil maturation. However, in G-CSF absolute numbers of neutrophils were decreased. These results suggest that PMLRAR α and BCL-2 impeded neutrophil differentiation of myeloid precursors. Altogether, our observations of doubly transgenic animals showed that BCL-2 expanded myeloid progenitors, allowed increased numbers of cells to proliferate, and enhanced the ability of PMLRAR α to inhibit neutrophil differentiation.

BCL-2 Cooperates with PMLRAR α to Initiate Leukemia. The experiments described above were performed on matched 3–5-wk-old littermates. We noted that mice that

inherited both transgenes were smaller than littermates at 3 wk of age, had the skin abnormalities we have seen in our PMLRAR α transgenics (4), and died between 4 and 6 wk of age. To assess the degree to which these deaths were due solely to a hematopoietic disorder or in part to nonhematopoietic effects of the transgenes, we harvested bone marrow from doubly transgenic mice and used this marrow to reconstitute lethally irradiated nontransgenic animals. Marrow harvested from PMLRAR α singly transgenic mice was similarly transplanted. Transplantation of either PMLRAR α transgenic or PMLRAR α /BCL-2 doubly transgenic bone marrow rescued recipient mice from lethal irradiation. Recipients remained healthy for 3 mo or more after transplantation, suggesting that the early deaths of un-

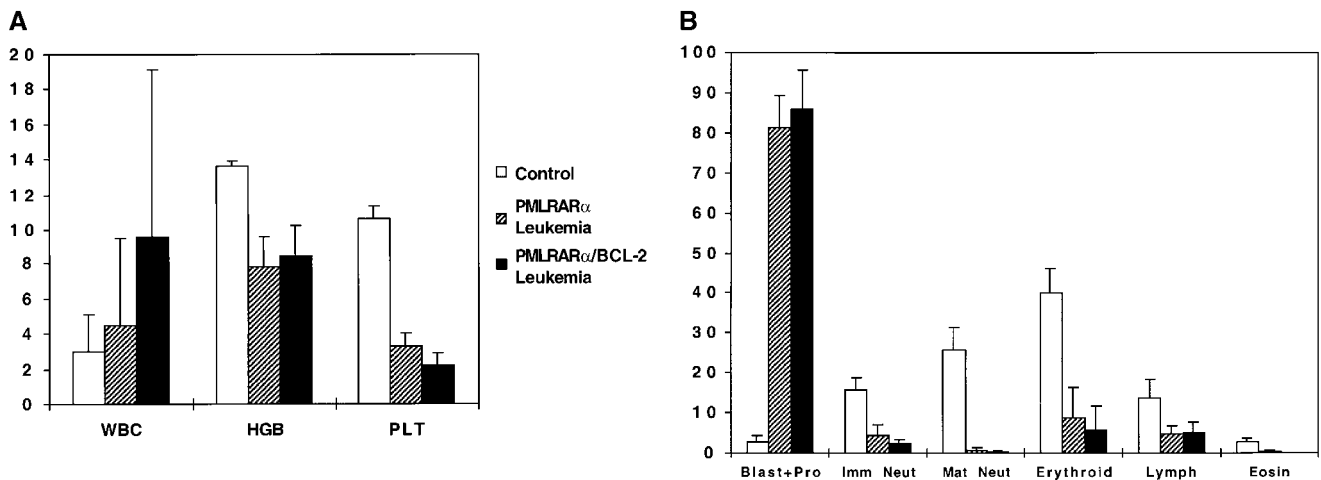


Figure 4. PMLRAR α and PMLRAR α /BCL-2 leukemic mice are anemic, thrombocytopenic, and have bone marrow that is filled with promyelocytes. (A) Peripheral blood. Results are displayed as in the legend to Fig. 1 A. Adult controls, $n = 7$; PMLRAR α leukemia, $n = 10$; PMLRAR α /BCL-2 leukemia, $n = 10$. White blood cell count (WBC) was not significantly different among the groups. Hemoglobin (HGB) and platelet count (PLT) were reduced in leukemic mice ($P < 0.00001$). (B) Bone marrow. Results are displayed as in the legend to Fig. 1 C. Adult controls, $n = 7$; PMLRAR α leukemia, $n = 6$; PMLRAR α /BCL-2 leukemia, $n = 6$. All values were significantly different in leukemic mice compared with controls ($P < 0.00001$ to $P = 0.002$), but were not significantly different between PMLRAR α and PMLRAR α /BCL-2 leukemias.

transplanted doubly transgenic mice were, at least in part, caused by nonhematopoietic effects of the transgenes.

Mice reconstituted with PMLRAR α or PMLRAR α /BCL-2 bone marrow were observed for the development of leukemia. Leukemias developed more rapidly in mice coexpressing PMLRAR α and BCL-2 than in mice expressing PMLRAR α alone (median time to leukemia 127 vs. 257 d; Fig. 3). All mice reconstituted with doubly transgenic bone marrow succumbed to leukemia by 196 d of age. Similar to the leukemias that arose from singly transgenic PMLRAR α mice, leukemias arising from PMLRAR α /BCL-2 doubly transgenic mice were characterized by anemia and thrombocytopenia, and by bone marrow that was effaced by cells at the blast-promyelocyte stage of differentiation (Figs. 4 and 5 A). Although there was a trend towards increased peripheral white blood cell counts in PMLRAR α /BCL-2 leukemias, this trend was not statistically significant ($P > 0.05$).

Dissemination Appears to Be a Central Characteristic of AML. PMLRAR α /BCL-2 transgenic mice had bone marrow that morphologically resembled acute leukemia (Figs. 2 D and 5 A), yet mice whose bone marrow expressed both transgenes did not become ill for a period of 3–7 mo. Therefore, we sought to identify differences between preleukemic and overtly leukemic, doubly transgenic animals. Bone marrow differential counts showed very low numbers of maturing neutrophils in preleukemic and leukemic animals (Fig. 1 C, PMLRAR α /BCL-2; Fig. 4 B). However, in the leukemias suppression of normal hematopoiesis was evident: there was a marked decrease of nucleated erythroid cells in the bone marrow, and in contrast to preleukemic animals, the leukemic mice were anemic and thrombocytopenic (Figs. 1 A and 4 A). Furthermore, in the leukemic mice, immature neutrophilic cells were disseminated. Small numbers of promyelocytes were present in the peripheral blood, and the spleens, livers, and kidneys in leukemic mice were enlarged and contained infiltrates of leukemic cells (Fig. 5, B–D). The existence of a prolonged preleukemic state in PMLRAR α /BCL-2 mice suggests that the suppression of normal hematopoiesis and dissemination of leukemic cells observed in AML are not a direct consequence of arrested differentiation.

Acquired Chromosomal Abnormalities Are Common in Murine APL. Preleukemic, doubly transgenic mice initially produced adequate red blood cells and platelets and did not become ill for 3–7 mo. These findings indicated that the combination of BCL-2 and PMLRAR α was sufficient to initiate but not complete leukemic transformation. Therefore, we sought to identify additional genetic changes in our leukemias. Comparative genomic hybridization was performed on 30 murine APLs, including 20 PMLRAR α leukemias and 10 PMLRAR α /BCL-2 leukemias. Chromosomal copy number abnormalities were observed in 17/20 PMLRAR α leukemias and 9/10 PMLRAR α /BCL-2 leukemias. Gain of chromosomes 7, 8, 10, and 15 and loss of chromosome 2 occurred in three or more samples including both PMLRAR α and PMLRAR α /BCL2 leukemias (Fig. 6). Losses of the X chromosome from female

samples and the Y chromosome from male samples were also observed. These results identify chromosomal regions whose loss or gain may complete the process of leukemic transformation initiated by PMLRAR α .

Murine APL Expressing BCL-2 Responds to Retinoic Acid and Arsenic Trioxide. We assessed whether the expression of BCL-2 influenced the ability of tRA therapy to cause differentiation and prolong survival of mice with APL. Nontransgenic mice received intravenous injections of 5×10^6 spleen cells from leukemia 2995A4, which expresses both PMLRAR α and BCL-2 transgenes. In one experiment, 32 d after the injection of leukemic cells, three mice were treated with placebo and three with tRA. The placebo-treated mice died on days 3 and 5, and five died after initiation of therapy, whereas tRA-treated mice died on days 17, 25, and 33. The difference in survival was significant ($P = 0.04$). In a second experiment, groups of six mice were treated 14 d after the injection of leukemic cells; again, tRA prolonged survival (Fig. 7 A). The prolongation in survival we observed (median 42 d, range 11–73) was comparable to the increase in survival seen in recipients of a PMLRAR α leukemia that was similarly treated (median 41 d, range 33–175; reference 32). tRA induced neutrophilic differentiation of leukemic blasts coexpressing PMLRAR α and BCL-2 (Fig. 7 B), but did not abrogate expression of the transgenes as assessed by Western blot analysis (data not shown).

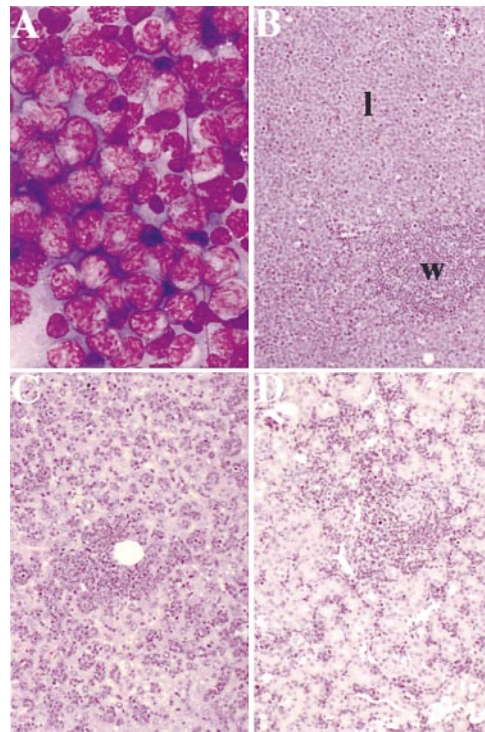


Figure 5. Leukemic transformation is characterized by dissemination of immature cells. Leukemic PMLRAR α /BCL-2. (A) Bone marrow morphology. Wright's Giemsa stain; original magnification: $\times 330$. (B) Spleen. I, leukemic infiltrate. (C) Liver. (D) Kidney. (B–D) Hematoxylin and eosin; original magnifications: $\times 66$.

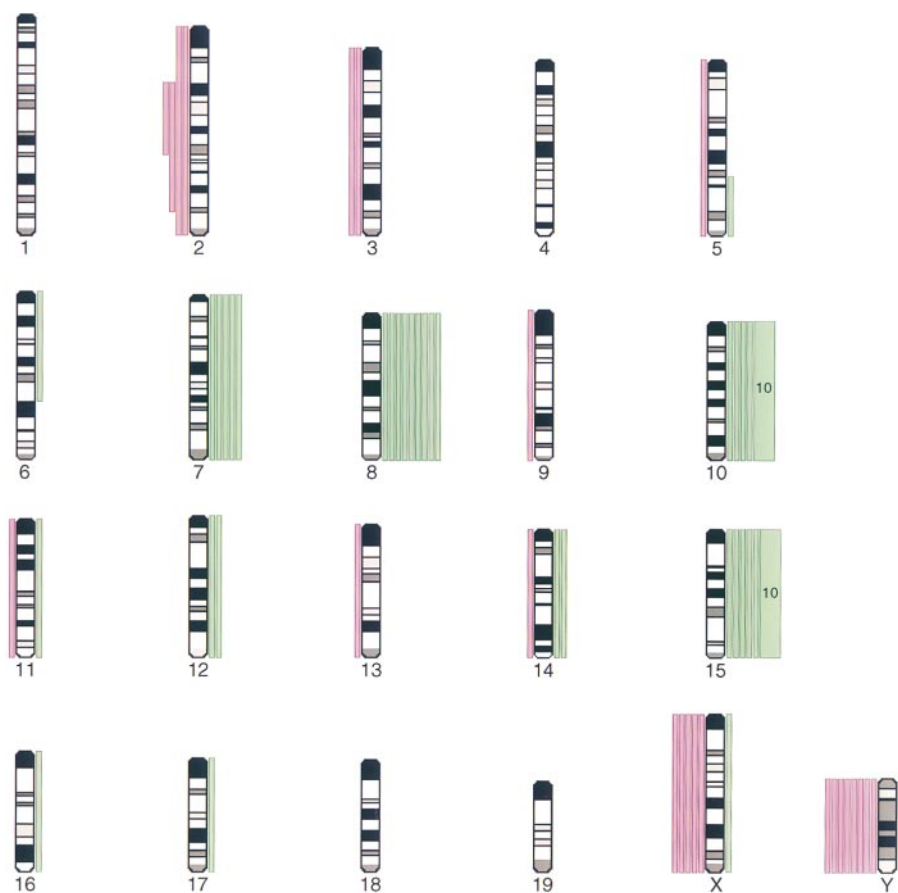


Figure 6. Murine APL is characterized by karyotypic abnormalities. Results of comparative genomic hybridization of 30 APLs (11 female, 19 male) are shown, including 20 PMLRAR α and 10 PMLRAR α /BCL-2 leukemias. Ideograms of mouse chromosomes are numbered. Each bar to the left of chromosomes indicates a region lost in one leukemic sample. Each bar to the right of chromosomes indicates a region gained in one sample. Each wide bar represents chromosomal gain in 10 samples. Losses of the X chromosome were seen in female samples.

We also examined whether arsenic and tRA were an effective combination therapy for APL expressing BCL-2. In three experiments, nontransgenic mice received intravenous injections of 10^7 leukemic 2995A4 cells. After 15 d, mice were treated with tRA and/or arsenic for 4 d, two mice per group, and then killed. Similar to what was previously observed for murine APL that does not express BCL-2 (32), arsenic-induced apoptosis and some differentiation, and the combination of arsenic and tRA, caused rapid regression of the leukemia. 4 d of therapy decreased spleen size (control, 0.57, 0.46 g; tRA, 0.21, 0.20 g; arsenic, 0.40, 0.30 g; tRA/arsenic: 0.10, 0.09 g; representative data from one of three experiments). In the liver, tRA caused regression but not the disappearance of disease, and the addition of arsenic eliminated the visible leukemic cell population (Fig. 7 C). These results suggest that APL cells expressing BCL-2 remain sensitive to arsenic plus tRA combination therapy.

Discussion

Expression of BCL-2 in mice that also express the APL-associated PMLRAR α fusion protein caused a marked accumulation of immature myeloid cells and accelerated the development of leukemia. Progression from preleukemia to acute leukemia was characterized by suppression of normal hematopoiesis and dissemination of leukemic cells. Addi-

tional genetic changes accompanied this transition from abnormal neutrophil maturation to lethal disease.

A Role for Suppression of Apoptosis in APL Pathogenesis. The possible role of apoptosis in APL pathogenesis has been unclear. Whereas PMLRAR α induces cell death in many cell lines, it also inhibits apoptosis of some myeloid cell lines and primary myeloid cells. We anticipated that BCL-2 might cooperate with PMLRAR α to initiate leukemia. On the other hand, given the ability of PMLRAR α itself to block apoptosis, it was possible that BCL-2 would have little impact on leukemogenesis. We observed that the antiapoptotic protein BCL-2 did cooperate with PMLRAR α to initiate leukemia, indicating that genetic changes that suppress apoptosis can cooperate with the PMLRAR α fusion in APL.

The *MRP8-BCL-2* transgene has been demonstrated to increase survival of myeloid cells (27, 34, 35, and our results). We observed increased CFU and young myeloid forms in bone marrows of *BCL-2* and doubly transgenic mice. It is likely that this increase is in part attributable to the ability of BCL-2 to enhance survival of immature myeloid cells. BCL-2 makes cells less dependent on external survival signals. BCL-2 did not, however, permit unlimited survival of immature cells. We speculate that the preleukemic, doubly transgenic cells remained responsive to extracellular signals that limited their expansion to hematopoietic microenvironments. Nevertheless, it appears that by

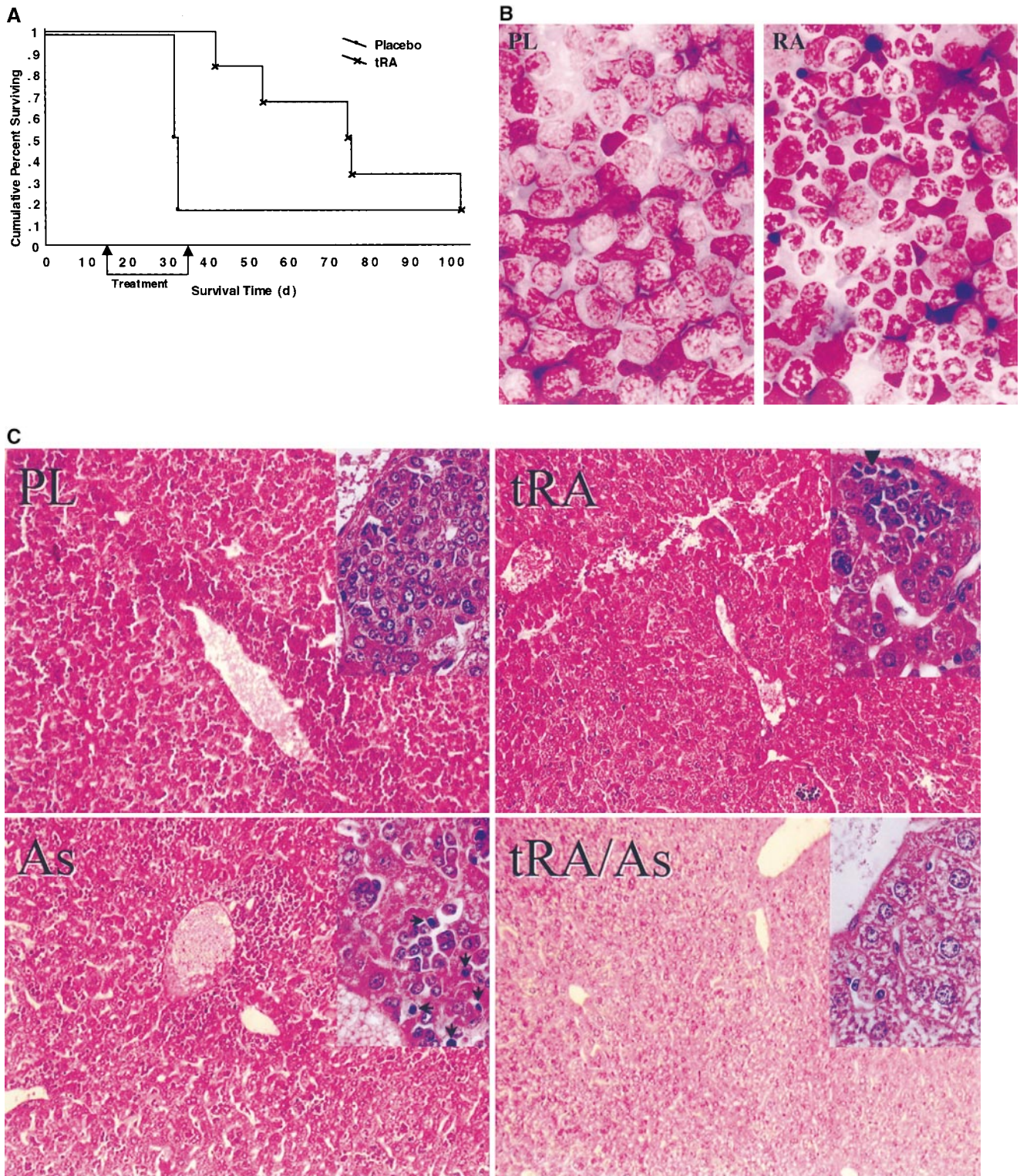


Figure 7. APL expressing PMLRAR α and BCL-2 is responsive to therapy. (A and B) Unirradiated nontransgenic FVB/N mice received 5×10^6 PMLRAR α /BCL-2 leukemic cells by intravenous injection. (A) 14 d after injection of leukemic cells, 5 mg placebo ($n = 6$) or tRA ($n = 6$) pellets (21-d release) were implanted into mice. Kaplan-Meier curves are shown. $P = 0.02$. (B) Bone marrow morphology. Recipients of PMLRAR α /BCL-2 leukemic cells were treated with placebo or tRA when ill. PL, placebo-treated; RA, tRA-treated, day 11. Wright's Giemsa stain; original magnification: $\times 455$. (C) FVB/N mice received 10^7 PMLRAR α /BCL-2 leukemic cells. 15 d after injection, mice were treated with tRA and/or arsenic for 4 d. Representative sections of livers are shown. PL, placebo: a leukemic infiltrate is present in the periportal and parenchymal regions of the liver; inset shows immature myeloid cells; tRA, retinoic acid: leukemic cells are much reduced; inset shows hepatocytes accompanied by smaller residual leukemic cells, arrowhead indicates a maturing neutrophil. As, arsenic; leukemic infiltrate present; arrows (inset) indicate condensed nuclei of apoptotic cells. tRA/As, retinoic acid/arsenic: leukemic cells are not seen. Hematoxylin and eosin; original magnifications: $\times 125$; inset $\times 625$.

expanding the population of immature myeloid cells in *PMLRAR α* transgenic mice, *BCL-2* made it inevitable that additional leukemogenic mutations would accumulate. Expression of *BCL-2* therefore promotes promyelocyte transformation but is not sufficient to complete this process. Interestingly, whereas *BCL-2* may facilitate the acquisition of genetic changes that induce acute leukemia in *PMLRAR α* transgenic mice, it does not appear to alter the type of chromosomal changes that occur.

Cytogenetic Changes in Murine APL. The t(15;17) translocation is present as an isolated karyotypic abnormality in the majority of APL patients at presentation. However, additional karyotypic abnormalities are observed in 24–39% of untreated APL patients (37–40). The fact that a substantial minority of new APL cases have additional cytogenetic changes provides evidence that human APL results from a combination of acquired mutations. The most common additional abnormality is trisomy 8, which is seen in ~17% of patients at presentation. Other recurrent aberrations include loss of chromosome 9q and isochromosome of the long arm of the derivative chromosome 17. The particular genes through which these additional cytogenetic changes may contribute to leukemia have not been identified.

Some of the changes seen in murine APL correspond to karyotypic abnormalities in human APL. Murine chromosomes 8 and 15 contain regions homologous to human chromosome 8. The area of loss we noted on mouse chromosome 2 contains genes that in humans are located on human chromosome 9q. In the broader context of attempts to understand leukemia pathogenesis in mice, the gain of chromosome 15 and the loss of chromosome 2 have been observed previously. Gibbons et al. (41) observed a common gain of chromosome 15 in B/myeloid leukemias that arose in irradiated *E μ -BCL-2* mice. The authors suggested that the presence of *BCL-2* permitted cells damaged by radiation to tolerate chromosomal damage, and the subsequently damaged cells gave rise to the observed leukemias. In our experiments, *BCL-2* could have similarly tolerized early myeloid cells to spontaneous genetic changes including a pathogenic gain of chromosome 15. Loss of murine chromosome 2 has been observed in radiation-induced myeloid leukemias in mice (for a review, see reference 42). The region of murine chromosome 2 identified in these leukemias was lost in all four APLs in which we observed copy number changes on chromosome 2. Of interest, another group studying the effects of *PMLRAR α* , under the control of a different promoter in a different strain of mice, has also identified recurrent gain of chromosome 15 and recurrent loss of chromosomes 2, X, and Y in their leukemias (43). The chromosome copy number abnormalities observed in murine APLs may facilitate identification of genetic changes that cooperate with *PMLRAR α* to cause acute leukemia.

BCL-2 Effects on Neutrophil Differentiation. Although *PMLRAR α* can inhibit differentiation, its effects on neutrophilic differentiation of primary bone marrow cells were modest and most apparent in vitro (Table II). In vivo, *BCL-2* cooperated with *PMLRAR α* to block maturation

at the promyelocyte stage. Given the central role of *BCL-2* family members in regulating cell death, the inhibition of neutrophil differentiation in *PMLRAR α* transgenic mice brought by coexpression of *BCL-2* is likely an indirect effect of *BCL-2*. Enhanced survival of neutrophil precursors may abrogate signals within the bone marrow that normally stimulate promyelocytes to differentiate into mature neutrophils. The finding that mature erythroid cells stimulate the death of erythroid progenitors (44) raises the possibility that interactions between mature and immature myeloid cells play a role in neutrophil maturation. Such interactions could be disrupted by enhanced survival of immature elements. On the other hand, our data are consistent with the speculative idea that *BCL-2* may directly influence neutrophil maturation. Our finding that *BCL-2* transgenic marrow gave rise to relatively decreased neutrophils in vitro might reflect enhanced production of monocytic cells, but, alternatively, this decrease could reflect a cell autonomous effect of *BCL-2* on neutrophil differentiation. In previous studies, *BCL-2* did not block tRA-induced differentiation of HL-60 cells (45), but *BCL-2* did delay neutrophilic maturation of 32DC13 cells in response to G-CSF (46). Another finding suggesting that, in some settings, *BCL-2* family members might directly influence neutrophil differentiation is the observation that tRA-mediated differentiation of APL cells is accompanied by caspase activation (13). *BCL-2* family members might influence differentiation through an activity that is distinct from their effects on cell survival. Such a possibility has precedent: *BCL-2* has an effect on proliferation separable from its effect on survival (47).

Multistep Pathogenesis for APL. The pathogenesis of human APL may parallel that of murine APL. The acquisition of the t(15;17)(q22,q11.2) with resulting expression of *PMLRAR α* could initiate leukemia. Increased expression of *BCL-2*, or other genetic changes that enhance survival and impair differentiation of the initiated cells, may occur in some patients and facilitate the acquisition of genetic changes that result in acute leukemia. Further study of human APLs could inform our understanding of the role of *BCL-2*-like proteins in the human disease. Although *BCL-2* expression was not seen in one study of APL cases (21), subsequent reports indicated that *BCL-2* is expressed in most APLs (22–25, 48). Elucidating whether this *BCL-2* expression is because of a genetic lesion in the *BCL-2* gene or a downstream result of other lesions should be of value, as should assessing the expression of other *BCL-2* family members in APL.

It is notable that the t(15;17) translocation is likely to have effects that are more pronounced than those caused by *PMLRAR α* alone. Similar to *BCL-2* expression, loss of *Pml*, a genetic event that suppresses apoptosis, facilitated the development of acute leukemia in *CathepsinG-PMLRAR α* transgenic mice (49). The reciprocal fusion protein, *RAR α PML*, also increased the penetrance of leukemia in mice expressing *PMLRAR α* (50). Given the fact that the incidence of t(15;17)-associated myeloid leukemia does not increase with age (51), we favor a model in which the

translocation initiates the disease and additional required genetic changes may accumulate in a relatively brief period of time.

BCL-2 Does Not Block the Response to APL Therapy. Downregulation of BCL-2 accompanies the differentiation of APL cells that is induced by tRA (52), and this downregulation may be important for some effects of tRA (13). We found that overexpression of BCL-2 did not block the differentiative effect of tRA. Similarly, BCL-2 might have blocked the therapeutic effect of arsenic because arsenic is thought to induce remissions primarily by stimulating apoptosis of the APL blasts (53–55). The fact that murine APL overexpressing BCL-2 still responded to arsenic suggests that arsenic can overcome a BCL-2-mediated delay in apoptosis. This result is also consistent with the hypothesis that differentiative effects of arsenic contribute to its therapeutic value. Although we studied the response of a single transplantable PMLRAR α /BCL-2 leukemia to tRA and arsenic and, therefore, have not addressed possible heterogeneity among such leukemias, our results nevertheless indicate that BCL-2 expression can be associated with an intact response. Thus, human APLs that overexpress BCL-2 or have acquired analogous changes may remain responsive to the novel APL therapies, tRA and arsenic.

Is Dissemination of Myeloid Leukemia Cells the Equivalent of Metastasis of Solid Tumors? Discussions of AML pathogenesis often focus on the inhibition of differentiation characteristic of the disease. The existence of a preleukemic state in PMLRAR α /BCL-2 transgenic mice characterized by maturation that is nearly arrested suggests that additional features of AML, including suppression of normal hematopoiesis and dissemination of leukemic cells, are not the direct result of inhibited differentiation. AML may result from two fundamental abnormalities: (a) a relative inhibition of differentiation that is accompanied by (b) a relative autonomy that allows the leukemic cells to survive and proliferate outside of their normal microenvironment. The idea that survival and proliferation outside of the normal microenvironment are central to AML parallels the concept that for solid tumors, invasion and metastasis define malignancy. In our APL model, although BCL-2 enhances cell survival, other genetic lesions are still required to fully overcome normal growth controls.

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