

ORIGINAL ARTICLE

Granulocyte–Macrophage Progenitors as Candidate Leukemic Stem Cells in Blast-Crisis CML

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ABSTRACT

BACKGROUND

The progression of chronic myelogenous leukemia (CML) to blast crisis is supported by self-renewing leukemic stem cells. In normal mouse hematopoietic stem cells, the process of self-renewal involves the β -catenin–signaling pathway. We investigated whether leukemic stem cells in CML also use the β -catenin pathway for self-renewal.

METHODS

We used fluorescence-activated cell sorting to isolate hematopoietic stem cells, common myeloid progenitors, granulocyte–macrophage progenitors, and megakaryocyte–erythroid progenitors from marrow during several phases of CML and from normal marrow. *BCR-ABL*, β -catenin, and *LEF-1* transcripts were compared by means of a quantitative reverse-transcriptase–polymerase-chain-reaction assay in normal and CML hematopoietic stem cells and granulocyte–macrophage progenitors. Confocal fluorescence microscopy and a lymphoid enhancer factor/T-cell factor reporter assay were used to detect nuclear β -catenin in these cells. In vitro replating assays were used to identify self-renewing cells as candidate leukemic stem cells, and the dependence of self-renewal on β -catenin activation was tested by lentiviral transduction of hematopoietic progenitors with axin, an inhibitor of the β -catenin pathway.

RESULTS

The granulocyte–macrophage progenitor pool from patients with CML in blast crisis and imatinib-resistant CML was expanded, expressed *BCR-ABL*, and had elevated levels of nuclear β -catenin as compared with the levels in progenitors from normal marrow. Unlike normal granulocyte–macrophage progenitors, CML granulocyte–macrophage progenitors formed self-renewing, replatable myeloid colonies, and in vitro self-renewal capacity was reduced by enforced expression of axin.

CONCLUSIONS

Activation of β -catenin in CML granulocyte–macrophage progenitors appears to enhance the self-renewal activity and leukemic potential of these cells.

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N Engl J Med 2004;351:657-67.

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THE PHILADELPHIA CHROMOSOME IN chronic myelogenous leukemia (CML) gives rise to the *BCR-ABL* proto-oncogene and its constitutively active protein tyrosine kinase product p210^{BCR-ABL}.¹⁻¹⁶ *BCR-ABL* is important because in patients with CML, there is clonal expansion of hematopoietic cells that express this fusion gene. Moreover, continued expression of *BCR-ABL* is required for sustained proliferation of leukemic cells in mouse models of CML.⁶⁻⁹

Imatinib, a potent inhibitor of p210^{BCR-ABL}, can induce remission in patients with chronic-phase CML, but despite this event, cells in the marrow may continue to produce *BCR-ABL* transcripts.^{17,18} In some patients, resistance to imatinib develops as a result of *BCR-ABL* amplification or mutations in the binding site of p210^{BCR-ABL} for imatinib.^{19,20} In another myeloid leukemia, t(8;21) acute myelogenous leukemia, marrow from patients in complete remission contains apparently normal hematopoietic stem cells that produce *AML1-ETO* transcripts. The presence of these stem cells during remission suggests that they are preleukemic rather than leukemic cells. (These transcripts participate in the development of acute myeloid leukemia; *AML1-ETO* is formed by the fusion of part of the *AML1* gene on chromosome 8 with part of the *ETO* gene on chromosome 21.²¹) Similarly, genomic *BCR-ABL* persists in the marrow of some patients with CML who are in a sustained complete cytogenetic remission,²² and it has been detected at very low levels in leukocytes from healthy persons,²³ which suggests that preleukemic hematopoietic stem cells or more differentiated progenitor cells need additional mutations for progression to overt leukemia to occur.^{15,16,24-26}

In mice, self-renewal of hematopoietic stem cells entails activation of the β -catenin pathway,^{27,28} which results in the translocation of β -catenin to the nucleus, where it interacts with lymphoid enhancer factor/T-cell factor (LEF/TCF) transcription factors and regulates the transcription of genes such as *c-myc* and cyclin D1.²⁹⁻³² Activating β -catenin mutations occur in many epithelial cancers.³³⁻³⁷ The ability to isolate purified populations of hematopoietic stem cells and myeloid progenitors³⁸⁻⁴¹ has made it possible to identify genes involved in the self-renewal of hematopoietic stem cells (the ability to make more daughter cells at the same stage of differentiation).^{27,28,42-45} Deregulation of self-renewal pathways, which are normally tightly regulated in hematopoietic stem cells,^{27,28,39-45} has recently been recognized as an important step in leukemic

progression.^{46,47} We conducted a study to identify candidate leukemic stem cells^{13,21,24-26} that are responsible for disease progression and resistance to imatinib in patients with CML and to determine whether these stem cells acquire the potential for self-renewal by activating β -catenin.²⁹⁻³²

METHODS

BONE MARROW AND PERIPHERAL-BLOOD SAMPLES

Samples of normal bone marrow (All Cells) or peripheral blood mobilized by granulocyte colony-stimulating factor were obtained from 11 healthy volunteers as previously described.⁴¹ Samples were obtained from 20 patients with CML in chronic phase, 26 patients with accelerated-phase CML, and 13 patients with CML in blast crisis. All subjects provided written informed consent, and the study was conducted according to the regulations of the institutional review boards of Stanford University and the University of California, Los Angeles.⁴¹ Cells were obtained from patients before they began treatment with imatinib, from patients who had received imatinib for 6 to 15 months (22 with chronic-phase CML, 11 with accelerated-phase CML, and 2 with CML in blast crisis), and from patients with imatinib-resistant CML (5 with accelerated-phase CML and 1 with CML in blast crisis). Patients with chronic-phase CML received interferon alfa, whereas patients with advanced disease were often treated with cytoreductive agents before receiving imatinib (described in Table 1 of the Supplementary Appendix, available with the full text of this article at www.nejm.org).

ISOLATION OF HEMATOPOIETIC STEM CELLS AND MYELOID PROGENITORS

Hematopoietic stem cells (CD34⁺CD38⁻CD90⁺[Thy1⁺]Lin⁻ cells) and myeloid progenitors, including common myeloid progenitors (CD34⁺CD38⁺interleukin-3 receptor α ⁺CD45RA⁻), granulocyte-macrophage progenitors (CD34⁺CD38⁺interleukin-3 receptor α ⁺CD45RA⁺), and megakaryocyte-erythroid progenitors (CD34⁺CD38⁺interleukin-3 receptor α ⁻CD45RA⁻), were isolated from normal and CML mononuclear cells by fluorescence-activated cell sorting (FACS), as described previously.⁴¹

COLONY-FORMING CELL ASSAYS

Colony-forming cell assays were performed as described previously.⁴¹ In replating experiments, indi-

vidual colonies were obtained on day 14, replated in 96-well plates, and analyzed 14 days later. In some experiments, lentiviral constructs containing an LEF/TCF–green fluorescent protein (GFP) reporter, a phosphoglycerate kinase promoter– β -catenin–internal ribosome entry site (IRES)–GFP cassette, or a phosphoglycerate kinase–axin–IRES–GFP cassette were added to colony-forming cell assays (described in detail in Method 1 of the Supplementary Appendix).²⁷

ASSAY FOR BCR-ABL

RNA was isolated from 40 to 300 hematopoietic stem cells, common myeloid progenitors, granulocyte–macrophage progenitors, or megakaryocyte–erythroid progenitors from five control subjects, four patients with chronic-phase CML, seven with accelerated-phase CML, three with CML in blast crisis, four after imatinib therapy, and five with imatinib-resistant CML. Quantitative reverse-transcriptase–polymerase-chain-reaction (RT-PCR) analysis of the expression of *BCR-ABL*, β -catenin, *LEF-1*, and *HPRT* was performed (described in Method 2 of the Supplementary Appendix).^{48,49}

β -CATENIN FACS ANALYSIS

Normal or CML mononuclear cells were stained with phycoerythrin-conjugated antibody against human CD90 or interleukin-3 receptor α , in addition to allophycocyanin-conjugated antibody against human CD34 and biotinylated antibody against human CD38 followed by staining with an alexa 594-conjugated antibody against human streptavidin. Cells were then fixed with 0.8 percent paraformaldehyde and made permeable by exposure to 0.3 percent saponin.⁴¹ Cells were stained overnight with a fluorescein isothiocyanate-conjugated antibody against β -catenin (Transduction Laboratories) or a control fluorescein isothiocyanate-conjugated antibody against IgG1 isotype, washed, and analyzed by means of FACS.

CONFOCAL FLUORESCENCE MICROSCOPY

Hematopoietic stem cells or granulocyte–macrophage progenitors from six controls and nine patients with CML were sorted onto glass slides by means of FACS, stained with a fluorescein isothiocyanate-conjugated antibody against human CD45, fixed in 4 percent paraformaldehyde, and stained with a mouse monoclonal antibody against activated β -catenin (clone 8E4, Upstate Biotechnology) at a dilution of 1:200 (2.5 μ g per milliliter), as de-

scribed previously.⁵⁰ Slides were then stained with an alexa 594-conjugated goat antimouse antibody and a nuclear stain (Hoechst 33342, Molecular Probes). Confocal images were obtained with the use of a dual-photon confocal fluorescence microscope (model LSM510, Zeiss) at a magnification of 100 \times , and three-dimensional images were rendered with the aid of Volocity software (described in Method 3 of the Supplementary Appendix).

LEF/TCF REPORTER ASSAY

A lentiviral LEF/TCF reporter (Fig. 1 of the Supplementary Appendix) was used to assess the capacity of β -catenin to activate transcription by means of LEF/TCF in sorted populations of normal and CML hematopoietic stem cells and myeloid progenitors, essentially as previously described, with the substitution of human cytokines interleukin-6 (10 ng per milliliter), Flt3 ligand (50 ng per milliliter), steel factor (50 ng per milliliter), and thrombopoietin (10 ng per milliliter).^{27,51}

RESULTS

HEMATOPOIETIC STEM CELLS AND PROGENITOR CELLS IN CML

FACS analysis revealed higher levels of the progenitor pool (CD34⁺Lin⁻ cells) in bone marrow from patients with CML in the accelerated or blast phase than in normal bone marrow (Fig. 1A in the Supplementary Appendix). Within the progenitor pool, the population of hematopoietic stem cells (CD34⁺CD38⁻CD90⁺Lin⁻) did not expand significantly with disease progression (Fig. 1A). However, an evaluation of individual populations of myeloid progenitors (CD34⁺CD38⁺Lin⁻) revealed that in comparison with normal bone marrow, increased numbers of megakaryocyte–erythroid progenitors were present in marrow from patients with chronic-phase CML ($P < 0.001$), levels of common myeloid progenitors were increased in patients with accelerated-phase CML ($P = 0.004$), and levels of granulocyte–macrophage progenitors were increased in marrow from patients with CML in blast crisis ($P = 0.02$) (Fig. 1B). Among cells from patients with a response to imatinib, there was a significant decrease in the number of CD34⁺Lin⁻ cells, as compared with their normal bone marrow counterparts ($P = 0.03$), and the proportion of individual myeloid progenitors reverted to normal, whereas samples from patients with imatinib-resistant CML had increased numbers of granulocyte–macrophage pro-

Figure 1. Mean (+SE) Proportions of CD90+ Hematopoietic Stem Cells (Panel A) and Myeloid Progenitor Populations (Panel B) and Levels of BCR-ABL Transcripts (Panel C).

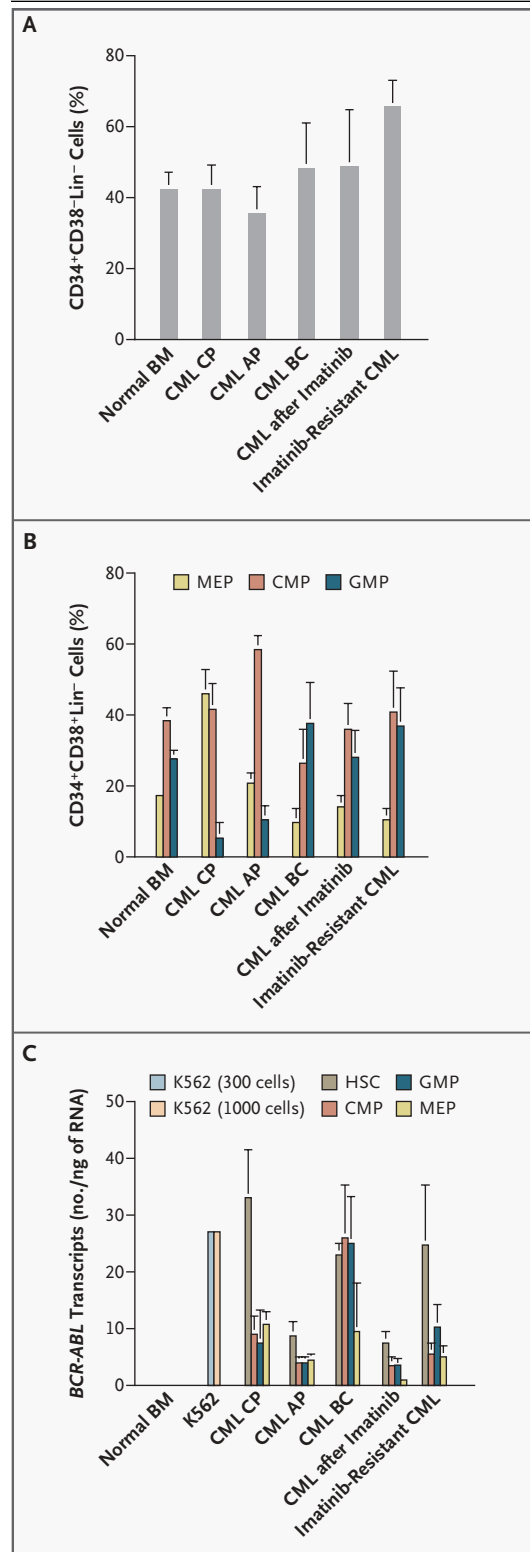
Panel A shows the proportion of hematopoietic stem cells (HSC) within the CD34⁺CD38⁻Lin⁻ population of cells in bone marrow (BM) from 11 control subjects, 5 patients with CML in chronic phase (CP), 6 patients with CML in accelerated phase (AP), 4 patients with CML in blast crisis (BC), 6 patients after treatment with imatinib, and 4 patients with imatinib-resistant CML. Panel B shows the percentage of individual populations of myeloid progenitors, including common myeloid progenitors (CMP), granulocyte–macrophage progenitors (GMP), and megakaryocyte–erythroid progenitors (MEP), expressed as the percentage of the CD34⁺CD38⁻Lin⁻ fraction of the same samples. Statistical analyses were performed with the use of Excel software and Student’s two-tailed unpaired t-test. Panel C shows the average number of BCR-ABL transcripts per nanogram of RNA derived from K562 (a Philadelphia chromosome–positive cell line) or bone marrow from 5 controls, 14 patients with CML (in chronic phase, accelerated phase, or blast crisis) before the initiation of imatinib therapy, 4 patients after treatment with imatinib, and 6 patients with imatinib-resistant CML, as well as from hematopoietic stem cells, common myeloid progenitors, granulocyte–macrophage progenitors, and megakaryocyte–erythroid progenitors.

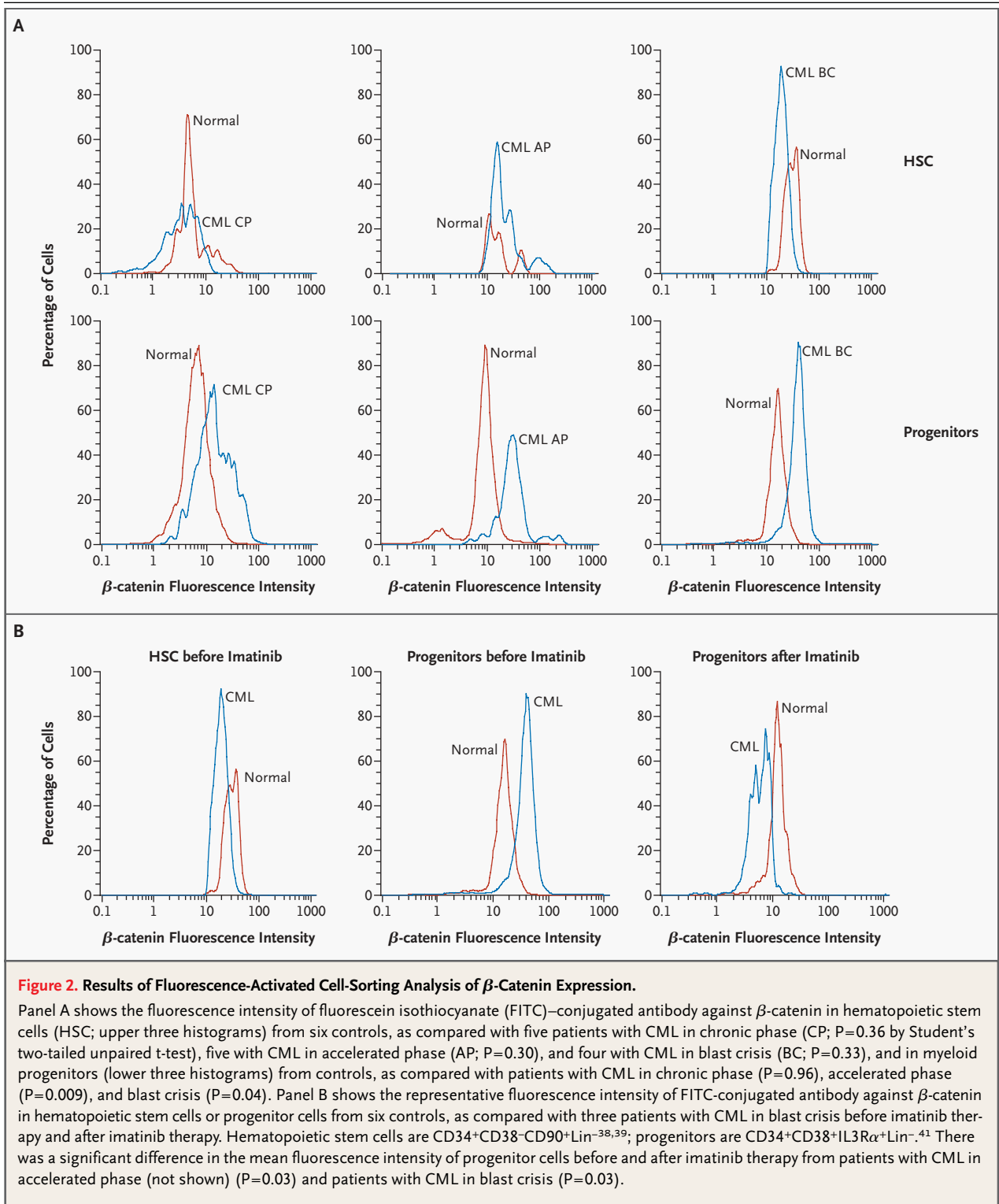
genitors (Fig. 1A and 1C in the Supplementary Appendix).

Quantitative RT-PCR analysis demonstrated that in samples from patients with chronic-phase CML, BCR-ABL transcripts were more abundant in hematopoietic stem cells than in myeloid progenitors. Conversely, blast crisis was associated with increased numbers of BCR-ABL transcripts in myeloid progenitors, particularly common myeloid progenitors and granulocyte–macrophage progenitors (Fig. 1C). Because of the small numbers of progenitors we were able to obtain from banked samples, we performed RT-PCR analysis for BCR-ABL rather than fluorescence in situ hybridization. For this reason, we cannot exclude the possibility of a mixture of Philadelphia chromosome–positive and Philadelphia chromosome–negative cells within the individual progenitor subgroups.

β-CATENIN ACTIVATION

FACS analysis revealed that total intracellular β-catenin levels in hematopoietic stem cells did not





differ significantly between controls and patients with CML at any stage of the disease. In contrast, myeloid progenitors from patients with CML in an accelerated phase or blast crisis had increased β -catenin levels, as compared with levels in controls (Fig. 2A). These levels normalized in patients who had received imatinib (Fig. 2B). In the absence of phosphorylation, activated β -catenin translocates to the nucleus (Fig. 2 in the Supplementary Appendix). Confocal fluorescence microscopy with monoclonal antibodies against unphosphorylated β -catenin showed that the staining intensity of nuclear β -catenin was similar in hematopoietic stem cells from controls, patients with accelerated-phase CML, and patients with CML in blast crisis. However, there was a striking increase in activated β -catenin in granulocyte–macrophage progenitors from patients in blast crisis (Fig. 3B) or those who had imatinib-resistant CML, as compared with such progenitors from normal marrow (Fig. 3C). Concordantly, an LEF/TCF–GFP reporter assay of β -catenin–mediated transcriptional activation revealed similar levels of GFP in hematopoietic stem cells from controls, patients with chronic-phase CML (not shown), and patients with CML in blast crisis, but an increase in GFP — and thus in nuclear β -catenin — in granulocyte–macrophage progenitors from patients in blast crisis (Fig. 3D). Moreover, colonies derived from blast crisis CD34+Lin– cells that were transduced with the LEF/TCF–GFP reporter had higher levels of GFP than did their normal counterparts (Fig. 3 in the Supplementary Appendix). Whereas normal granulocyte–macrophage progenitors had reduced expression of β -catenin or its transcriptional coactivator, LEF-1, as compared with normal hematopoietic stem cells, CML granulocyte–macrophage progenitors from patients in blast crisis expressed increased levels of both transcripts (Fig. 4 in the Supplementary Appendix), which most likely contributed to the nuclear accumulation of β -catenin.

SELF-RENEWAL OF CML GRANULOCYTE–MACROPHAGE PROGENITORS

We assessed whether granulocyte–macrophage progenitors in CML gained the high proliferative potential and self-renewal capacity of hematopoietic stem cells as a result of β -catenin activation.^{27–32} CD34+Lin– cells from patients with CML in the accelerated phase that were transduced with lentiviral β -catenin formed colonies that were larger than normal, whereas transduction of the cells with axin

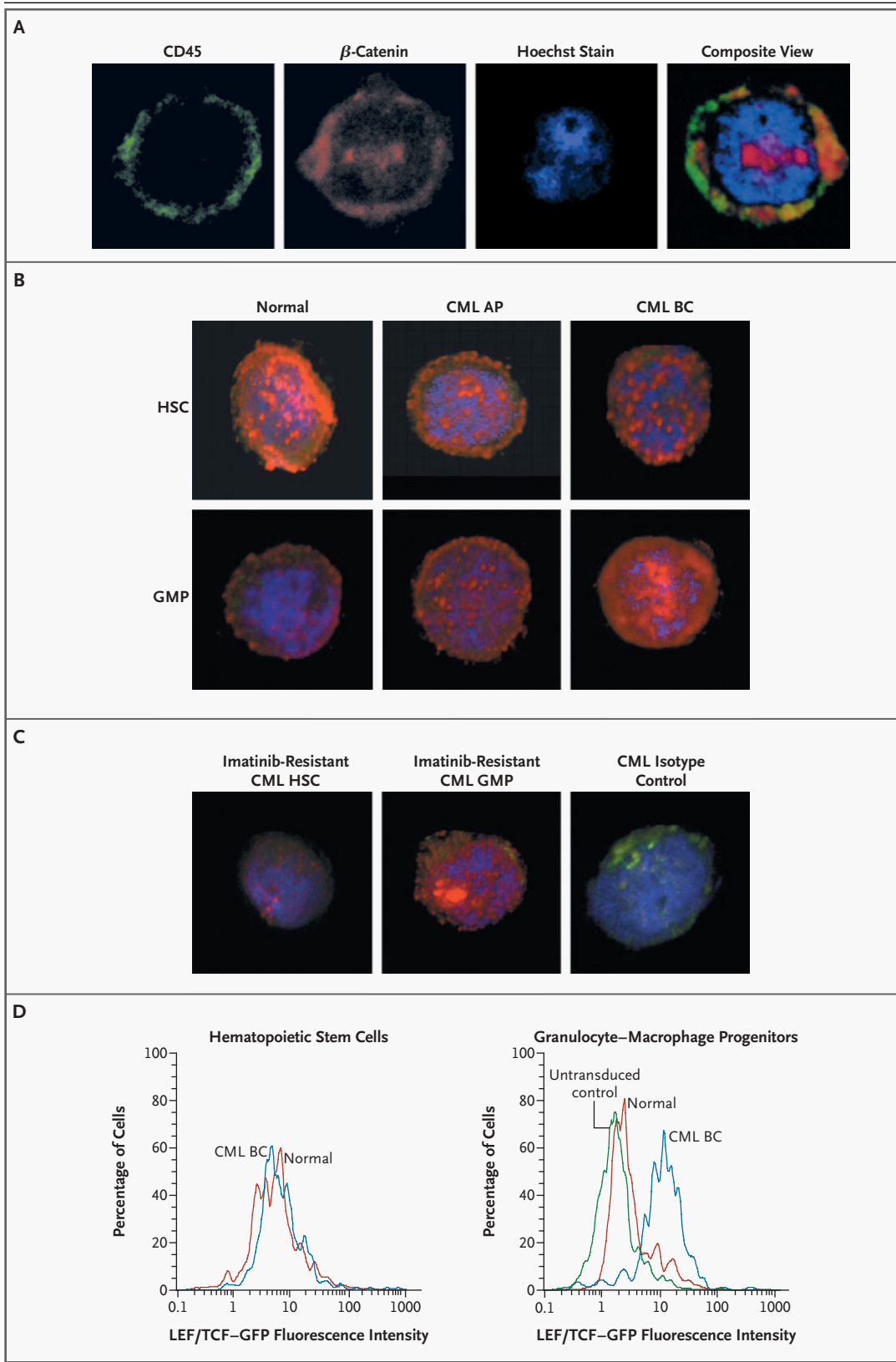
Figure 3 (facing page). Confocal Fluorescence Microscopical Images of β -Catenin Nuclear Localization (Panels A, B, and C) and the Results of Fluorescence-Activated Cell-Sorting Analysis of LEF/TCF Reporter Activity.

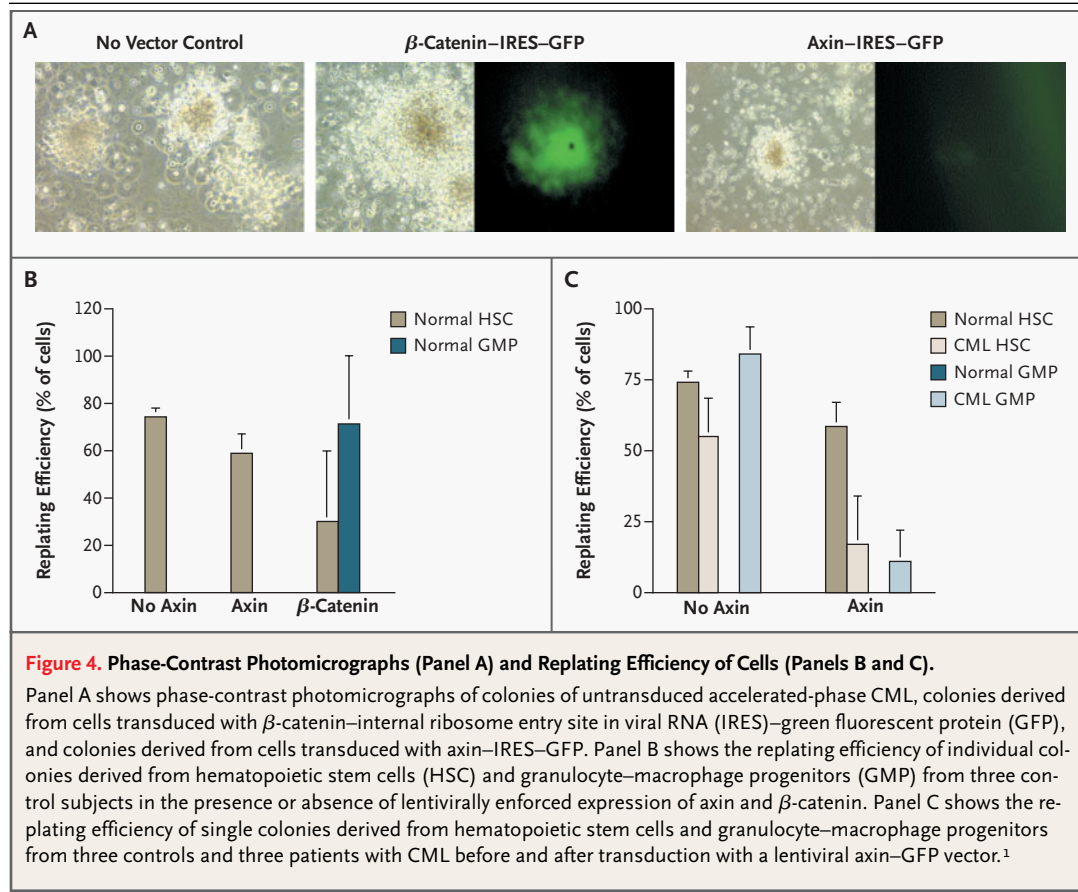
Panel A shows confocal fluorescence microscopical images of CD34+Lin– cells from a patient with accelerated-phase CML stained with fluorescein isothiocyanate–conjugated antibody against CD45 (green); an antibody specific for activated β -catenin (red); and Hoechst, a blue nuclear stain. Panel B shows the localization of β -catenin in hematopoietic stem cells (HSC; top three images) and granulocyte–macrophage progenitors (GMP; bottom three images) representative of five controls, three patients with CML in the accelerated phase (AP), and four patients with CML in blast crisis (BC). Panel C shows the localization of β -catenin in hematopoietic stem cells representative of imatinib-resistant CML, granulocyte–macrophage progenitors representative of imatinib-resistant CML, and an isotype control. Histograms in Panel D show the relative percentage of cells with the expression of LEF/TCF–green fluorescent protein (GFP) reporter in hematopoietic stem cells and granulocyte–macrophage progenitors from controls and patients with CML in blast crisis. In the histogram on the right, untransduced granulocyte–macrophage progenitors from a patient with CML in blast crisis was used as a control (green).

decreased the size of the colonies (Fig. 4A; and Fig. 5 in the Supplementary Appendix). In addition, enforced expression of β -catenin provided normal granulocyte–macrophage progenitors with self-renewal capacity in a replating assay (Fig. 4B). CML granulocyte–macrophage progenitors, but not normal granulocyte–macrophage progenitors, had a high replating capacity and retained the capacity to form myeloid colonies in colony-forming cell assays (Fig. 4C). Finally, transduction of CML granulocyte–macrophage progenitors with axin, an inhibitor of β -catenin signaling, reduced the replating capacity of leukemic cells (Fig. 4C).

DISCUSSION

CML is believed to arise as a consequence of the clonal expansion of hematopoietic stem cells that express the *BCR-ABL* fusion gene.^{13–15,18–24} However, recent work with transgenic mouse models of CML showed that although *BCR-ABL* is necessary for the development of a myeloproliferative syndrome resembling CML, hematopoietic stem cells need not be involved.⁸ Moreover, additional genetic or epigenetic events are required for progression



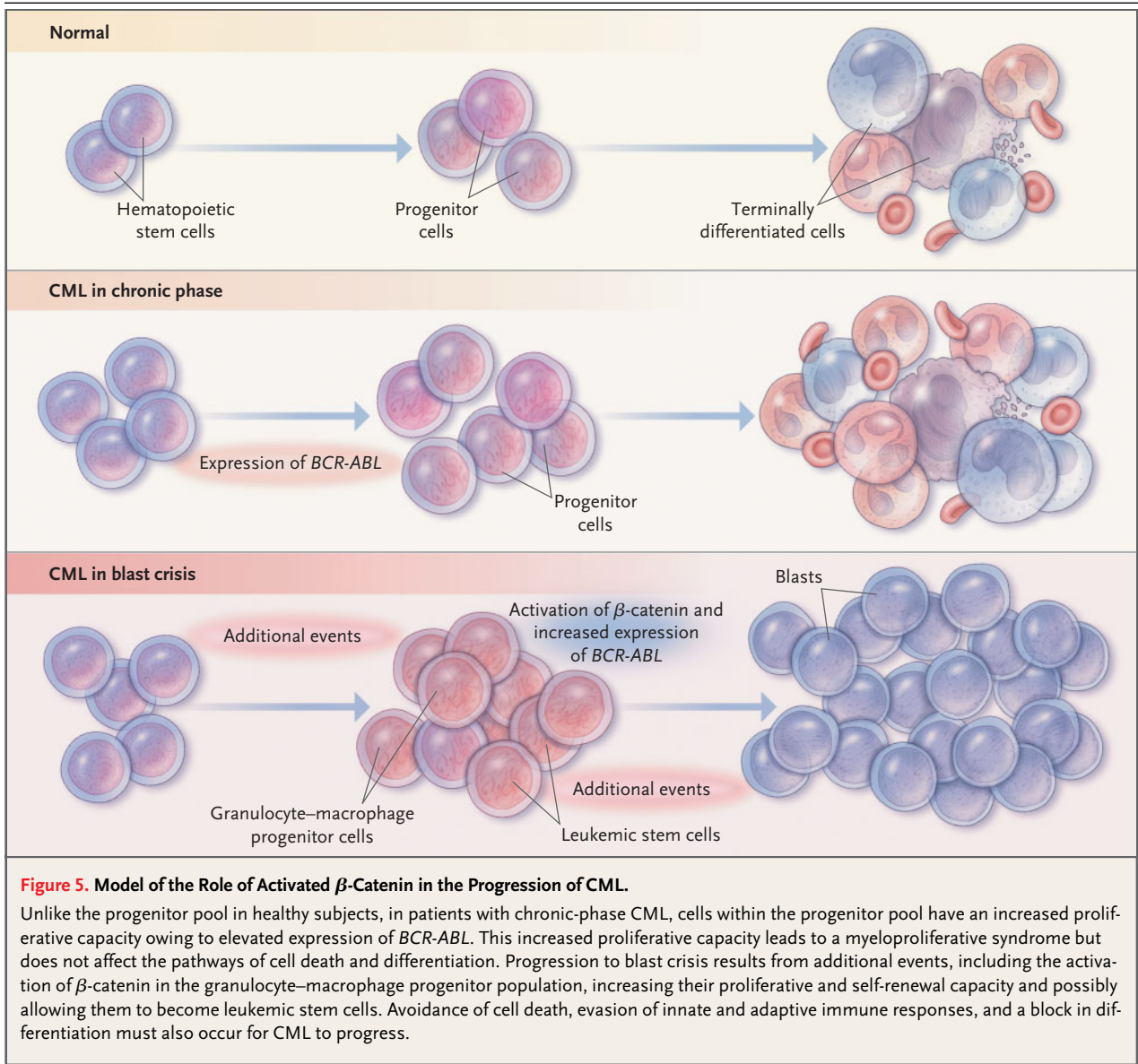


to blast crisis.^{8-10,15,16} In humans and mice, hematopoietic stem cells are the only normal progenitors that renew themselves,³⁸⁻⁴⁵ and therefore, they are widely considered to be the only cells in the marrow in which preleukemic changes can accumulate, whether by genetic or epigenetic means. However, it is also possible that a downstream progenitor can acquire self-renewal capacity.^{24-27,41} It is therefore important to identify the population that contains leukemic stem cells in CML and other myeloid leukemias and to identify events leading to the progression of leukemia, the outcomes of these events, and the order of their appearance in leukemic stem cells and their precursors.²⁴⁻²⁶

Several of our findings in CML cells were unanticipated. First, progression to blast crisis was associated with expansion of the myeloid progenitor fraction, which consists mainly of granulocyte–macrophage progenitors, rather than expansion of the pool of hematopoietic stem cells. Second, *BCR-ABL* amplification occurred in granulocyte–macrophage progenitors, whereas the *BCR-ABL* transcript

levels in hematopoietic stem cells remained relatively constant during progression of the disease. Third, the β -catenin pathway was activated in granulocyte–macrophage progenitors from patients with CML in accelerated phase and from those with CML in blast crisis, as well as in patients with imatinib-resistant CML. Fourth, granulocyte–macrophage progenitors in CML have self-renewal capacity, at least in vitro, although our data do not exclude the possibility that this capacity may be more limited than that of normal hematopoietic stem cells in vivo. Fifth, β -catenin–mediated renewal of granulocyte–macrophage progenitors in CML may be inhibited by enforced expression of axin — a potent and highly specific β -catenin antagonist.

We propose that in chronic-phase CML, there is an expansion of the progenitor pool and the downstream progeny of these progenitors that is due in part to the expression of the *BCR-ABL* fusion gene. This expansion causes the myeloproliferative syndrome (chronic-phase CML), but apoptosis and differentiation pathways remain intact. Progression of



CML to blast crisis probably involves several events in primitive progenitors, including *BCR-ABL* amplification, acquisition of resistance to apoptosis, genomic instability, escape from innate and adaptive immune responses, and activation of β -catenin in granulocyte-macrophage progenitors, resulting in the acquisition of self-renewal capacity (Fig. 5).^{15,16,24-26,52} Our *in vitro* replating data indicate that the activation of the self-renewal process by means of the β -catenin pathway in granulocyte-macrophage progenitors, which normally have no capacity for self-renewal, may not only lead to expansion of the granulocyte-macrophage progen-

itor pool but also play a role in the subsequent production of blasts that occurs in advanced phases of CML, although such blasts may be nonmalignant progeny of leukemic stem cells, rather than leukemic stem cells themselves.

The cause of activation of the β -catenin pathway in CML is unknown, and whether β -catenin or other components of the signaling pathway and p210^{BCR-ABL} interact directly has yet to be determined. Transcriptional targets of β -catenin/LEF-1 signaling, including the cyclin D1 and *c-myc* genes, also play a critical role in transformation mediated by Abl, a member of the Src kinase family of proto-

oncogenes, and by BCR-ABL; thus, these genes may provide a final common pathway between BCR-ABL and β -catenin leading to the progression of CML.^{53,54} Additional members of the Src family of kinases have also been shown to augment the activation of β -catenin.^{55,56} Other proto-oncogenes and tumor suppressors, such as *bmi-1*, *HOXB4*, and *notch*, also play a role in the self-renewal of hematopoietic stem cells and may interact with β -catenin during leukemogenesis.^{27,46,47,57,58} Detection of activated β -catenin in highly purified CML progenitors might be used to predict progression, relapse, or the development of imatinib resistance. Moreover, components of the β -catenin–signaling pathway, especially ones that are mutated, may provide new targets for the development of molecular and immune therapies for CML.

Supported by grants (CA55209 and CA86017, to Dr. Weissman; 2PO1CA49605, to Ms. Jones and Dr. Zehnder; and K23 HL04409, to Dr. Gotlib) from the National Institutes of Health, a de Villiers grant

from the Leukemia Society (to Dr. Weissman), a Stanford Center for Clinical Immunology Yu–Bechmann fellowship for Genomics and Oncology (to Dr. Jamieson), the Walter and Beth Weissman Fund, the Smith Family Fund, a Leukemia/Lymphoma Society Special Fellowship (to Dr. Ailles), and an American Cancer Society Edward Albert Bielfelt Postdoctoral Fellowship (to Dr. Dylla). Dr. Dylla is the recipient of a Stanford Immunology Fellowship (5T32AI07290) funded by the National Institutes of Health. Dr. Sawyers is an Investigator of the Howard Hughes Medical Institute and a Doris Duke Distinguished Clinical Scientist.

Drs. Jamieson, Ailles, and Weissman have applied for a U.S. patent entitled “Use of Beta-Catenin in the Diagnosis and Treatment of Leukemia and Lymphomas” through the Stanford University Office of Technology and Licensing. Dr. Weissman receives consulting fees from and has equity ownership or stock options in Cellera.

We are indebted to Drs. S. Schrier, L. Leung, L. Boxer, R. Negrin, J. Shizuru, G. Beilhack, R. Nusse, F. Staal, and W.J. Nelson for indispensable advice; to R. Falkow and Dr. P. Lee at Stanford and Dr. N. Shah at UCLA for providing samples from patients with CML; to L. Jerabek for excellent laboratory management; to the Stanford Cell Sciences Imaging Facility and the Stanford FACS facility for expert assistance; to members of the Center for Clinical Immunology at Stanford as well as the Division of Bone Marrow Transplantation at Stanford for their support; and to the patients who made this research possible.

REFERENCES

- Nowell PC, Hungerford DA. A minute chromosome in human chronic granulocytic leukemia. *Science* 1960;132:1497.
- Rowley JD. A new consistent chromosomal abnormality in chronic myelogenous leukaemia identified by quinacrine fluorescence and Giemsa staining. *Nature* 1973; 243:290-3.
- Shtivelman E, Lifshitz B, Gale RP, Canaani E. Fused transcript of *abl* and *bcr* genes in chronic myelogenous leukaemia. *Nature* 1985;315:550-4.
- Ben-Neriah Y, Daley GQ, Mes-Masson AM, Witte ON, Baltimore D. The chronic myelogenous leukemia-specific P210 protein is the product of the *bcr/abl* hybrid gene. *Science* 1986;233:212-4.
- Lugo TG, Pendergast AM, Muller AJ, Witte ON. Tyrosine kinase activity and transformation potency of *bcr-abl* oncogene products. *Science* 1990;247:1079-82.
- Daley GQ, Van Etten RA, Baltimore D. Induction of chronic myelogenous leukemia in mice by the P210**bcr/abl** gene of the Philadelphia chromosome. *Science* 1990; 247:824-30.
- Gishizky ML, Johnson-White J, Witte ON. Efficient transplantation of BCR-ABL-induced chronic myelogenous leukemia-like syndrome in mice. *Proc Natl Acad Sci U S A* 1993;90:3755-9.
- Jaiswal S, Traver D, Miyamoto T, Akashi K, Lagasse E, Weissman IL. Expression of BCR/ABL and BCL-2 in myeloid progenitors leads to myeloid leukemias. *Proc Natl Acad Sci U S A* 2003;100:10002-7.
- Huettner CS, Zhang P, Van Etten RA, Tenen DG. Reversibility of acute B-cell leukaemia induced by BCR-ABL1. *Nat Genet* 2000;24:57-60.
- Era T, Witte ON. Regulated expression of P210 Bcr-Abl during embryonic stem cell differentiation stimulates multipotential progenitor expansion and myeloid cell fate. *Proc Natl Acad Sci U S A* 2000;97:1737-42.
- Huettner CS, Koschmieder S, Iwasaki H, et al. Inducible expression of BCR/ABL using human CD34 regulatory elements results in megakaryocytic myeloproliferative syndrome. *Blood* 2003;102:3363-70.
- Udomsakdi C, Eaves CJ, Swolin B, Reid DS, Barnett MJ, Eaves AC. Rapid decline of chronic myeloid leukemic cells in long-term culture due to a defect at the leukemic stem cell level. *Proc Natl Acad Sci U S A* 1992;89: 6192-6.
- Sirard C, Lapidot T, Vormoor J, et al. Normal and leukemic SCID-repopulating cells (SRC) coexist in the bone marrow and peripheral blood from CML patients in chronic phase whereas leukemic SRC are detected in blast crisis. *Blood* 1996;87: 1539-48.
- Graham SJ, Jorgensen HG, Allan E, et al. Primitive, quiescent, Philadelphia-positive stem cells from patients with chronic myeloid leukemia are insensitive to STI571 in vitro. *Blood* 2002;99:319-25.
- Goldman JM, Melo JV. Chronic myeloid leukemia — advances in biology and new approaches to treatment. *N Engl J Med* 2003;349:1451-64.
- Sawyers CL. Chronic myeloid leukemia. *N Engl J Med* 1999;340:1330-40.
- O'Brien SG, Guilhot F, Larson RA, et al. Imatinib compared with interferon and low dose cytarabine for newly diagnosed chronic-phase chronic myeloid leukemia. *N Engl J Med* 2003;348:994-1004.
- Hughes TP, Kaeda J, Branford S, et al. Frequency of major molecular responses to imatinib or interferon alfa plus cytarabine in newly diagnosed chronic myeloid leukemia. *N Engl J Med* 2003;349:1423-32.
- Gorre ME, Mohammed M, Ellwood K, et al. Clinical resistance to STI-571 cancer therapy caused by BCR-ABL gene mutation or amplification. *Science* 2001;293:876-80.
- Azam M, Latek RR, Daley GQ. Mechanisms of autoinhibition and STI-571/imatinib resistance revealed by mutagenesis of BCR-ABL. *Cell* 2003;112:831-43.
- Miyamoto T, Weissman IL, Akashi K. AML1/ETO-expressing nonleukemic stem cells in acute myelogenous leukemia with 8;21 chromosomal translocation. *Proc Natl Acad Sci U S A* 2000;97:7521-6.
- Chomel JC, Brizard F, Veinstein A, et al. Persistence of BCR-ABL genomic rearrangement in chronic myeloid leukemia patients in complete and sustained cytogenetic remission after interferon-alpha therapy or allogeneic bone marrow transplantation. *Blood* 2000;95:404-8.
- Bose S, Deninger M, Gora-Tybor J, Goldman JM, Melo JV. The presence of typical and atypical BCR-ABL fusion genes in leukocytes of normal individuals: biologic significance and implications for the assessment of minimal residual disease. *Blood* 1998;92:3362-7.
- Jamieson CHM, Passegue E, Weissman IL. Leukemia and leukemic stem cells. In: Gage R, ed. *Stem cells in the nervous sys-*

- tem: functional and clinical implications. Berlin: Springer-Verlag, 2004:157-82.
25. Passegue E, Jamieson CHM, Ailles LE, Weissman IL. Normal and leukemic hematopoiesis: are leukemias a stem cell disorder or a reacquisition of stem cell characteristics? *Proc Natl Acad Sci U S A* 2003;100:11842-9.
 26. Reya T, Morrison SJ, Clarke MF, Weissman IL. Stem cells, cancer, and cancer stem cells. *Nature* 2001;414:105-11.
 27. Reya T, Duncan AW, Ailles L, et al. A role for Wnt signalling in self-renewal of hematopoietic stem cells. *Nature* 2003;423:409-14.
 28. Willert K, Brown JD, Danenberg E, et al. Wnt proteins are lipid-modified and can act as stem cell growth factors. *Nature* 2003;423:448-52.
 29. Nusse R, van Ooyen A, Cox D, Fung YK, Varmus H. Mode of proviral integration of a putative mammary oncogene (int-1) on mouse chromosome 15. *Nature* 1984;307:131-6.
 30. Nusse R. Wnts and Hedgehogs: lipid-modified proteins and similarities in signaling mechanisms at the cell surface. *Development* 2003;130:5297-305.
 31. van Noort M, Meeldijk J, van der Zee R, Destree O, Clevers H. Wnt signaling controls the phosphorylation status of β -catenin. *J Biol Chem* 2002;277:17901-5.
 32. Tian E, Zhan F, Walker R, et al. The role of the Wnt-signaling antagonist DKK1 in the development of osteolytic lesions in multiple myeloma. *N Engl J Med* 2003;349:2483-94.
 33. Korinek V, Barker N, Morin PJ, et al. Constitutive transcriptional activation by a β -catenin-Tcf complex in APC-/- colon carcinoma. *Science* 1997;275:1784-7.
 34. Morin PJ, Sparks AB, Korinek V, et al. Activation of β -catenin-Tcf signaling in colon cancer by mutations in β -catenin or APC. *Science* 1997;275:1787-90.
 35. Rubinfeld B, Robbins P, El-Gamil M, Albert I, Porfiri E, Polakis P. Stabilization of β -catenin by genetic defects in melanoma cell lines. *Science* 1997;275:1790-2.
 36. Rask K, Nilsson A, Brannstrom M, et al. Wnt-signalling pathway in ovarian epithelial tumours: increased expression of β -catenin and GSK3 β . *Br J Cancer* 2003;89:1298-304.
 37. Uematsu K, He B, You L, Xu Z, McCormick F, Jablons DM. Activation of the Wnt pathway in non small cell lung cancer: evidence of disheveled overexpression. *Oncogene* 2003;22:7218-21.
 38. Baum CM, Weissman IL, Tsukamoto AS, Buckle AM, Peault B. Isolation of a candidate human hematopoietic stem-cell population. *Proc Natl Acad Sci U S A* 1992;89:2804-8.
 39. Uchida N, Sutton RE, Frieri AM, et al. HIV, but not murine leukemia virus, vectors mediate high efficiency gene transfer into freshly isolated G0/G1 human hematopoietic stem cells. *Proc Natl Acad Sci U S A* 1998;95:11939-44.
 40. Akashi K, Traver D, Miyamoto T, Weissman IL. A clonogenic common myeloid progenitor that gives rise to all myeloid lineages. *Nature* 2000;404:193-7.
 41. Manz MG, Miyamoto T, Akashi K, Weissman IL. Prospective isolation of human clonogenic common myeloid progenitors. *Proc Natl Acad Sci U S A* 2002;99:11872-7.
 42. Kondo M, Wagers AJ, Manz MG, et al. Biology of hematopoietic stem cells and progenitors: implications for clinical application. *Annu Rev Immunol* 2003;21:759-806.
 43. Domen J, Weissman IL. Hematopoietic stem cells need two signals to prevent apoptosis; BCL-2 can provide one of these, Kit/c-Kit signaling the other. *J Exp Med* 2000;192:1707-18.
 44. Orkin SH, Zon LI. Hematopoiesis and stem cells: plasticity versus developmental heterogeneity. *Nat Immunol* 2002;3:323-8.
 45. Mikkola HK, Klintman J, Yang H, et al. Haematopoietic stem cells retain long-term repopulating activity and multipotency in the absence of stem-cell leukaemia SCL/tal-1 gene. *Nature* 2003;421:547-51.
 46. Park IK, Qian D, Kiel M, et al. Bmi-1 is required for maintenance of adult self-renewing haematopoietic stem cells. *Nature* 2003;423:302-5.
 47. Lessard J, Sauvageau G. Bmi-1 determines the proliferative capacity of normal and leukemic stem cells. *Nature* 2003;423:255-60.
 48. Raaijmakers MH, van Emst L, de Witte T, Mensink E, Raymakers RA. Quantitative assessment of gene expression in highly purified hematopoietic cells using real-time reverse transcriptase polymerase chain reaction. *Exp Hematol* 2002;30:481-7.
 49. Jones CD, Yeung C, Zehnder JL. Comprehensive validation of a real-time quantitative bcr-abl assay for clinical laboratory use. *Am J Clin Pathol* 2003;120:42-8.
 50. Schmelz EM, Roberts PC, Kustin EM, et al. Modulation of intracellular β -catenin localization and intestinal tumorigenesis in vivo and in vitro by sphingolipids. *Cancer Res* 2001;61:6723-9.
 51. Follenzi A, Ailles LE, Bakovic S, Geuna M, Naldini L. Gene transfer by lentiviral vectors is limited by nuclear translocation and rescued by HIV-1 pol sequences. *Nat Genet* 2000;25:217-22.
 52. Traver D, Akashi K, Weissman IL, Lagasse E. Mice defective in two apoptotic pathways in the myeloid lineage develop acute myeloblastic leukemia. *Immunity* 1998;9:47-57.
 53. Afar DE, McLaughlin J, Sherr CJ, Witte ON, Rousset MF. Signaling by ABL oncogenes through cyclin D1. *Proc Natl Acad Sci U S A* 1995;92:9540-4.
 54. Afar DE, Goga A, McLaughlin J, Witte ON, Sawyers CL. Differential complementation of Bcr-Abl point mutants with c-Myc. *Science* 1994;264:424-6.
 55. Schroeder JA, Adriance MC, Thompson MC, Camenisch TD, Gendler SJ. MUC1 alters β -catenin-dependent tumor formation and promotes cellular invasion. *Oncogene* 2003;22:1324-32.
 56. Haraguchi K, Nishida A, Ishidate T, Akiyama T. Activation of β -catenin-TCF-mediated transcription by non-receptor tyrosine kinase v-Src. *Biochem Biophys Res Commun* 2004;313:841-4.
 57. Antonchuk J, Sauvageau G, Humphries RK. HOXB4-induced expansion of adult hematopoietic stem cells ex vivo. *Cell* 2002;109:39-45.
 58. Varnum-Finney B, Xu L, Brashem-Stein C, et al. Pluripotent, cytokine-dependent, hematopoietic stem cells are immortalized by constitutive Notch 1 signaling. *Nat Med* 2000;6:1278-81.

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