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Reduced Proliferative Capacity of Hematopoietic Stem Cells Deficient in Hoxb3 and Hoxb4

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Several homeobox transcription factors, such as HOXB3 and HOXB4, have been implicated in regulation of hematopoiesis. In support of this, studies show that overexpression of HOXB4 strongly enhances hematopoietic stem cell regeneration. Here we find that mice deficient in both Hoxb3 and Hoxb4 have defects in endogenous hematopoiesis with reduced cellularity in hematopoietic organs and diminished number of hematopoietic progenitors without perturbing lineage commitment. Analysis of embryonic day 14.5 fetal livers revealed a significant reduction in the hematopoietic stem cell pool, suggesting that the reduction in cellularity observed postnatally is due to insufficient expansion during fetal development. Primitive Lin−/Sca1+/c-kit+ hematopoietic progenitors lacking Hoxb3 and Hoxb4 displayed impaired proliferative capacity in vitro. Similarly, in vivo repopulating studies of Hoxb3/Hoxb4-deficient hematopoietic cells resulted in lower repopulating capability compared to normal littersmates. Since no defects in homing were observed, these results suggest a slower regeneration of mutant HSC. Furthermore, treatment with cytostatic drugs demonstrated slower cell cycle kinetics of hematopoietic stem cells deficient in Hoxb3 and Hoxb4, resulting in increased tolerance to antimitotic drugs. Collectively, these data suggest a direct physiological role of Hoxb4 and Hoxb3 in regulating stem cell regeneration and that these genes are required for maximal proliferative response.

Class I Homeobox (Hox) genes encode a family of 39 transcription factors sharing a highly conserved DNA-binding domain. In mammals they play a major role in specifying position and tissue fate in the embryo, as has been demonstrated by several lack-of-function Hox gene mutants that exhibit various developmental abnormalities (see, for example, references 6, 29, 30, 38, 41, 49, and 58). Hox genes are also expressed postnatally, and several of them are expressed in primitive hematopoietic cells and committed progenitors but downregulated upon differentiation to mature cells (44).

Murine models have been generated where enforced expression of Hox genes is used to determine the effect of overexpression on self-renewal, differentiation, and other cell fate decisions during hematopoiesis (for reviews, see references 10 and 55). Such models include overexpression of HOXA10, as well as HOXA9, which both affected myelo- and lymphopoiesis and ultimately lead to myeloid leukemia (5, 9, 23, 52, 53). Expression of HOXB3 and HOXB4 is found in the primitive CD34+ population that is highly enriched for human hematopoietic stem cells (HSCs) but is rapidly downregulated as the cells differentiate into committed progenitors (44). Despite very similar expression pattern of HOXB3 and HOXB4, suggesting a common role or collaboration between these factors, the consequences from overexpressing these genes are very different. Although enforced expression of HOXB3 blocks both T- and B-cell development and causes a myeloproliferative disorder (46), overexpression of HOXB4 greatly enhances the regenerative capacity of HSCs in serial transplantation models and results in selective expansion of HOXB4-transduced cells without causing altered lineage decisions or malignant transformations (1, 45, 54). It is noteworthy that this expansion continues until the stem cell pool is normal in size (without overriding it), differing significantly from transplantation of untreated bone marrow (BM) cells, which can only regenerate up to 10% of the number of HSCs found in normal mice. Furthermore, a recent report demonstrates that an ~40-fold net expansion of murine repopulating HSCs can be achieved by enforced expression of HOXB4 ex vivo for 10 to 14 days (2). This finding is in sharp contrast to ordinary cytokine induced cultures which can support maintenance of HSC numbers or at most expand by a factor of 2 to 4 (4, 12, 28). Less is known about the feasibility of using HOXB4 for human HSC expansion. Recent findings indicate that HOXB4 overexpression in human hematopoietic progenitors affects fate decisions in a concentration-dependent manner to determine whether self-renewal, differentiation, or a differentiation block ensues (7a, 8, 46a). These findings emphasize the importance of understanding the physiological effects of HOXB4 in HSCs in vivo. Interestingly, overexpression studies of HOXB4 also result in expansion of primitive human hematopoietic progenitors, suggesting a common role for paralog 4 genes on these progenitors (13).

Since HOXB3 and HOXB4 are expressed in the stem cell compartment and gain-of-function studies result in enhanced HSC regeneration, we wanted to further analyze the physiological role of these genes in controlling stem cell fate in a lack-of-function mouse model. Lack-of-function mouse models
have generated important insight into the role of various transcription factors in hematopoiesis. These include targeting of genes such as GATA-2, SCL/tal-1, Rbni2/Lmo2, AML1, PU.1/Sp1, Ilkrr, Hoxb6, and Hoxa9 (reviewed in references 34 and 51). Hoxa9-deficient mice exhibit prominent defects in erythroid, myeloid, and lymphoid development, including early T-cell development, as well as apparent defects in HSC function, although these have not been fully described (20, 27, 27a).

Hoxb6 deficiency mainly affects the erythroid development, increasing the numbers of erythroid progenitors (22). Here we describe a mouse model that is deficient in the contiguous Hoxb3 and Hoxb4 genes. All exons and intermediate sequences of these genes were excised by utilizing the Cre/LoxP technique (18, 43). Homozygous mouse deficient in Hoxb3 and Hoxb4 (Hoxb3/b4-/-) were born at normal Mendelian ratios, showed no major abnormalities in skeletal structure, and remained healthy. However, the hematopoietic organs of Hoxb3/b4-deficient mice exhibited a significant reduction in cellularity and reduced numbers of primitive hematopoietic progenitors, in particular of the HSC pool in fetal livers (FLs) from 14.5-day-old embryos. The proliferative capacity of primitive hematopoietic progenitors from mutant mice was diminished in vitro and the regenerative capacity of Hoxb3/b4-/- HSCs was reduced after primary and secondary transplantation. The defects in repopulating abilities were not caused by aberrations in homing but were more likely due to diminished proliferation of HSCs. This is supported by studies after hematopoietic stress, which demonstrated that repopulating Hoxb3/b4-/- HSCs exhibited slower cell cycle kinetics and a larger proportion of resting stem cells. In summary, these findings show that Hoxb3/b4-deficient HSCs harbor a functional defect, impairing the proliferation capacity when rapid regeneration is required.

**Materials and Methods**

Cloning of Hoxb3 and Hoxb4 and generation of targeting constructs. A 390-bp (SalI/FspI) cDNA fragment from exon 1 of Hoxb4 was used to screen a 129/SvJ mouse genomic BAC (bacteria artificial chromosome) library (Stratagene). A clone containing more than 100 kb of the Hox b locus was identified and isolated. For generating the Hoxb4 targeting construct, two overlapping subclones were used, a 9-kb EcoRI clone (pBS-ERI; Hoxb4 and 3' sequence) and a 6-kb EagI clone (pBS-Eagl; Hoxb4 and 5' sequence). For generating the Hoxb3 targeting construct, a 7.5-kb NheI fragment (pSL-NheI; Hoxb3 exons III and IV), as well as an overlapping 3' Apal fragment (pBS-Apal; 3' sequence) were used. Briefly, for the generation of the Hoxb4 targeting vector, the 6-kb Eagl fragment was ligated into a modified pBluescript (pBS-ΔHindIII) and then opened with HindIII and blunted. Into this site the loxP flanked (flanked) neomycin expression cassette, a 1.3-kb Xhol/SalI fragment isolated from pl2neo, was ligated. To the 3' end of this subclone a 1-kb Eagl/HindIII fragment (from pBS-ERI) was ligated, and this construct was then digested with PshAI/ClaI, resulting in a 7.2-kb targeting fragment (with a 1.6-kb homologous arm upstream and 4.4-kb arm downstream of the neomycin cassette). The targeting fragment was ligated into SmaI/Clal-cut pBS, resulting in pBS-B4ko. The herpes simplex virus thymidine kinase (tk) gene driven by the PGK promoter was isolated from pPNT by EcoRI and HindIII digestion. The fragment was blunt ligated into the Clal site in the 3' polylinker of pBS-B4ko, resulting in the final targeting construct, pBS-B4k0.

For generation of the Hoxb3 targeting construct, a 1.7-kb Xhel fragment, located 3' of exon IV, was isolated from pSL-NheI and ligated into pBS. This subclone was digested with MscI and BamHI and blunted, and into this site the flxed neomycin cassette was ligated, generating pBS-b3m3l3. pBS-b3m3l3 was then digested with SmaI, and a blunted 1.6-kb MscI fragment from pBS-Apal was ligated in that site, resulting in pBS-b3m3l3 with a 3' homologous short arm of 1.6 kb. pBS-b3m3l3 was opened in the 5' polylinker with Xhel and NotI, and into this a 4.5-kb Xhel/NotI (where the NotI has replaced the endogenous TthlllI site) fragment from pSL/NheI was ligated, resulting in pBS-B3ko with a 5'homologous long arm of 4.5 kb. The tk fragment was blunt ligated into the Clal site in the 3' polylinker of pBS-B3KO, resulting in the final targeting construct, pBS-B3KO.

**Gene targeting in ES cells**. The targeting constructs werelinearized with NotI and purified. A total of 25 to 30 μg of DNA was electroporated (Bio-Rad; 0.26 kV; 1500 μF; 0.1 cm gap) into ca. 107 RE embryos (ES) cells cultured in standard procedure (56). The cells were then cultured in selective medium (300 to 500 μg of G418/ml and 4 μM ganciclovir [when appropriate]) for 7 to 9 days. To verify homologous recombination (HR) the surviving colonies were screened by PCR with the external primers Bsl- (CTTGCGATAAGGACAGCCTCT), and the internal primers NotI (CCTTCTGGTCTTCTGGGAGGAT). Positive clones were further analyzed by Southern blot with external probes (data not shown). Southern blotting was also used to verify single integration of the targeting vectors. Genetic DNA was digested with either ApaLI or KpnI to screen Hoxb3 and Hoxb4 targeting, respectively, and then probed with a neomycin-specific probe (0.9-kb EcoRI fragment), resulting in a 8.5-kb band from the AplI digest and a 5.5-kb band from the KpnI digest (Fig. 1). Targeted clones were expanded and ca. 2 × 106 cells were electroporated with 15 μg of the plasmid pC-Cre for excision of the neomycin gene. Resulting neomycin sensitive (Neo+) clones were screened by PCR with the primers P2 (GAGGTGCAATGCTCCCTGCCT) and P6 (GGTGGCTGACGAGTTCTTCTGAGGGGAT). Positive clones were further analyzed by PCR-mediated total deletion of both the Hoxb3 and Hoxb4 genes, primers P1 and P2 were used (Fig. 1). Independently targeted clones of both the Hoxb3/b4-floxed and the Hoxb3/b4-deleted vectors were injected into 3.5-day-old C57BL/6 blastocysts and transferred into pseudopregnant (C57BL/6 × CBAF1) fostermothers by standard techniques (56). Chimeric males were mated to C57BL/6 females, resulting in offspring with a 298s/C57BL/6 genetic background. For screening of germ line offspring, DNA was isolated from tail biopsies and analyzed by PCR. Primers P3 (GGAGAGCAAGAAGAAAGAGGAGAAGGAAG) and P4 (CATAAGTTGGTACACAGGGAGGAAAG) were used to distinguish between homozygous and heterozygous offspring of Hoxb3/b4-deleted mice. Total RNA was isolated from the peripheral blood (PB) and BM (BNCasy, Qiacube) of Hoxb3/b4 mice and used for reverse transcription-PCR (RT-PCR) analysis to verify the presence or absence of the RNA transcripts.

**Cell harvest.** Hoxb3/b4 knockout and wild-type littermate mice were sacrificed at different ages (mainly 10 to 16 weeks), and cells were harvested from the PB, BM, spleen, thymus, and lymph nodes. Various other organs were also removed for pathological analysis. An aliquot of PB was used (Sysmex K1000; TOA Medical Electronics Co., Ltd.) to measure some of the hematological parameters described in Table 1. Femurs and tibias were crushed in a mortar in the presence of phosphate-buffered saline (Gibco-BRL) containing 2% fetal calf serum (Gibco-BRL) and then filtered through a 70-μm (pore-size) cell strainer. Cells were isolated from the spleen, thymus, and lymph nodes by means of the standard procedures. PB, BM, and FLs were harvested from embryos at 14.5 days postcoitus for further analysis.

**Cloning assays.** For myeloid clonal progenitor assays, BM cells were cultured in 35-mm petri dishes. For the cell CFU (CFU-C) assay, rich methylcellulose (M3534 containing stem cell factor [SCF]; 30 ng/ml), interleukin-3 (IL-3; 10 ng/ml), and IL-6 [10 ng/ml; Stem Cell Technologies], with the addition of 5 U of human erythropoietin (hEpo; Janssen-Cilag AB)/ml, was used. For the erythroid cell burst-forming unit (BFU-E) assay, serum-free methylcellulose (M3236; Stem Cell Technologies) supplemented with 50 ng of SCF (Amen)/ml, 50 ng of thrombopoietin (TPO; Kirin Brewery Co., Ltd.)/ml, and 5 U of hEpo/ml was used. Colonies were scored on days 7 to 12 of incubation. For the spleen cell CFU (CFU-S) assay, 30,000 to 75,000 fresh BM cells were injected into lethally irradiated recipient (950 cGy at 110 cGy/min, 17C gamma rays); 12 days later, the spleens were harvested and the macroscopic colonies were enumerated.

**Proliferation recruitment.** For single cell cultures, Lin- c-kit+ Sca1- (LSK) cells were used. Briefly, BM cells were treated with ammonium chloride (NH4Cl; Stem Cell Technologies) and then incubated in a lineage antibody cocktail (CD4, CD8, CD5, Gr-1, Mac, B220, and TER119; all antibodies were from BD Pharmingen unless indicated otherwise). After washing and resuspending steps, sheep anti-rat immunoglobulin G (Fc-)conjugated immunomagnetic beads (Dynal) were added, and lineage-positive cells were removed with a magnetic particle concentrator (MPC-6; Dynal). Lin- c-kit+ cells were stained with fluorescein isothiocyanate (FITC)-conjugated anti-Sca1 (anti-E13-161.7) and allophycocyanin (APC)-conjugated anti-c-kit (anti-2B8). The cells were washed and stained with fluorescein cyanine-5 (FACSAvant cell sorter (Becton Dickinson [BD]) and seeded into Terasaki plates (Nunc) at a concentration of one cell per well in 20 μl of serum free.
FIG. 1. Schematic overview of the Hoxb3/b4 locus and the targeting strategy. The gene targeting strategy successfully removes the Hoxb3 and Hoxb4 genes and generates mice without expression of Hoxb3 and Hoxb4 mRNA. (A) The Hoxb4 (exons shown as black boxes) and Hoxb3 (exons shown as gray boxes) loci. (B) The targeting strategy. The targeting constructs successfully remove the Hoxb3 and Hoxb4 genes and generate mice without expression of Hoxb3 and Hoxb4 mRNA.
medium (X-vivo 15; BioWhittaker) supplemented with 1% bovine serum albumin (Stem Cell Technologies), 100 IU of penicillin and 100 μg of streptomycin (Gibco-BRL) (1 ml/L-glutamine (Gibco-BRL), and 10−4 M 2-mercaptoethanol (Sigma)). The following cytokines were used in various combinations (see Results section): TPO (Kirin), FL-3 ligand (FL; Immunex), granulocyte–macrophage colony stimulating factor (G-CSF; Amgen), and granulocyte-macrophage colony stimulating factor (GM-CSF) and IL-3 (Novartis).

Cell cycle analysis. Lin− cells were isolated as described above. The cells were then stained with c-kit-APC and Scal-phycocerythrin (PeC) and thereafter pre-incubated in 0.4% formaldehyde (LabKemi) and 0.2% Triton-X (Sigma) overnight. The following day, the cells were labeled with KitF FITC and 7AAD (Sigma) and analyzed on a FACS Calibur (BD). When cyclophosphamide (Sendoxan; Asta Medica A.G.) treatment was included, the mice were injected intraperitoneally (200 mg/kg) at 96 h prior to BM harvest.

Transplantation experiments. For standard competitive transplantation experiments, 2 × 10^5 fresh BM cells from Hoxb3/b4−/− or control littermates (Ly5.2) were mixed together with 8 × 10^6 BM cells from B6.SJL recipient (Ly5.1) cells. The mixture was injected into the tail vein of lethally irradiated B6.SJL recipient mice. To measure reconstitution of Ly5.2-derived cells, PB samples were taken at weeks 6 and 12 and when the mice were sacri- cized. To measure reconstitution of Ly5.2-derived cells, PB samples were taken after 4 weeks and when the mice were sacrificed.

For evaluation of LSA (Lin−-gated anti-Ly5.1, FITC-conjugated anti-Ly5.2, and APC-conjugated anti-c-kit. Analysis was done on FACSCalibur (BD), and the results were analyzed with CellQuest software (BD). The mixture was injected into the tail vein of lethally irradiated B6.SJL recipient mice. To measure reconstitution of Ly5.2-derived cells, PB samples were taken after 4 weeks and when the mice were sacrificed. The mixture was injected into the tail vein of lethally irradiated B6.SJL recipient mice. To measure reconstitution of Ly5.2-derived cells, PB samples were taken after 4 weeks and when the mice were sacrificed.

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Table 1. Hoxb3/b4-deficient mice are born in normal Mendelian ratios

<table>
<thead>
<tr>
<th>Mouse genotype*</th>
<th>No. of pups (% frequency)</th>
<th>Avg wt (g) ± SD at 3 wk</th>
<th>Avg wt (g) ± SD at 12 wk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoxb3/b4−/−</td>
<td>45 (23.3)</td>
<td>16.5 ± 0.5*</td>
<td>21.9 ± 1.9†</td>
</tr>
<tr>
<td>Hoxb3/b4+/−</td>
<td>99 (51.3)</td>
<td>16.3 ± 0.5</td>
<td>21.6 ± 1.8</td>
</tr>
<tr>
<td>Hoxb3/b4+/+</td>
<td>49 (25.4)</td>
<td>15.2 ± 0.5*</td>
<td>20.9 ± 1.7</td>
</tr>
</tbody>
</table>

* Ten pups per genotype. b, P < 0.05; †, P = 0.2.

RESULTS

Generation of Hoxb3/b4-deficient mice. In order to study hematopoiesis in Hoxb3/b4-deficient animals, mice were generated that completely lacked expression of Hoxb3 and Hoxb4. The rationale was to generate conditional knockout mice for the contiguous Hoxb3 and Hoxb4 genes to avoid potential developmental abnormalities that could ensue and interfere with examination of postnatal hematopoiesis. LoxP sites were introduced upstream of the Hoxb4 gene and downstream of the Hoxb3 gene by using two different targeting constructs (Fig. 1). After we verified correct targeting in 129Sv ES cells by PCR and Southern blot analysis, the ES cells were used to produce chimeraic mice. Mice carrying the floxed (i.e., flanked by loxP sites) Hoxb3/b4 genes were generated in parallel to null mutant mouse lines lacking both genes along with inter- mediate regulatory elements (Fig. 1D). Both mouse lines (i.e., the “floxed” and the “deleted”) reproduce normally and are born at normal Mendelian ratios (Table 1). The homozygous Hoxb3/b4−/− siblings (Hoxb3/b4+/− mice) appear completely normal, and the presence of the loxP sites does not disturb the expression of the targeted genes (Fig. 1G). However, no Hoxb3 or Hoxb4 mRNA could be detected in the Hoxb3/b4−/− mice. These mice are slightly smaller (8% lower body weight, P < 0.05) than their healthy littermates at the time of weaning (3 weeks), but at 12 weeks of age this difference is usually negli-
viously published data on the blocking effect of overexpression of B220 were used in combination with CD43 and IgM for B-cell analysis. Antibodies to Hoxb3/b4 served, but the white blood cell count was normal. For comparison, the red blood cell count and hemoglobin values was also observed, but the white blood cell count was normal. For comparative studies involving the knockout mice, littermate controls were used in all of our experiments. The observed reduction in cellularity led us to ask whether the reduction was restricted to a specific lineage or compartment within the hematopoietic hierarchy. FACS was performed on cells derived from PB, BM, spleen, and thymus with antibodies to Gr1, Mac1, CD4, CD8, B220, CD3, and TER119. The results did not show any significant difference in the lineage distribution of the hematopoietic cells derived from Hoxb3/b4−/− mice compared to Hoxb3/b4+/- littermates (Fig. 2). In light of previously published data on the blocking effect of overexpression of Hoxb3 on B- and T-cell maturation (46), these populations were analyzed in more detail by FACS analysis. Antibodies to B220 were used in combination with CD43 and IgM for B-cell development, and CD4/CD8 were used in combination with α/βTCR or γ/δTCR for T-cell analysis; however, no difference was observed between Hoxb3/b4−/− cells and control cells (data not shown). Thus, the reduction observed in hematopoietic cell numbers suggested that the phenotype might arise from the primitive progenitor and stem cell compartment.

**The hematopoietic progenitor cell pool is reduced in Hoxb3/b4-deficient mice.** In order to analyze colony-forming abilities of Hoxb3/b4−/−-derived progenitor cells, fresh BM cells were plated out in methylcellulose optimized for either CFU-C or BFU-E assay. BFU-Es and CFU-Cs were enumerated on day 8 and on days 10 and 11, respectively. Hoxb3/b4−/− BM cells showed a nonsignificant reduction in the frequency of hematopoietic progenitor colonies compared to Hoxb3/b4+/- littermates, both for CFU-C (colonies/10,000 BM cells = 18 ± 4 versus 21 ± 3 [P = 0.2]) and for BFU-E (colonies/100,000 BM cells = 11 ± 3 versus 13 ± 3 [P = 0.3]). However, due to reduced BM cellularity of the Hoxb3/b4−/−, the absolute numbers of CFU-Cs were significantly reduced (Fig. 3A, P < 0.01) and the numbers of BFU-E were also reduced, although not significantly (Fig. 3A, P < 0.07). The frequency of day 12 CFU-S colonies in Hoxb3/b4−/− mice was also similar to that for control littermates (colonies/50,000 BM cells; 5.2 ± 0.9 for knockout mice versus 5.5 ± 1.4 for wild-type mice [P = 0.8; n = seven mice/group]), whereas the absolute number of CFU-S at day 12 was slightly reduced (Fig. 3A, P = 0.11).

**Normal cell cycle distribution but reduced absolute numbers of primitive hematopoietic progenitors in Hoxb3/b4−/− deficient mice.** Because enforced expression of HOXB4 has been shown to increase expansion and regeneration of HSCs, we analyzed whether there was a reduction in the proportion of cycling HSCs in the Hoxb3/b4−/− mice. The proportion of LSK...
Reduced proliferative capacity of primitive hematopoietic progenitors in vitro. Due to the reduction in hematopoietic cellularity and a mild reduction in the hematopoietic progenitor cell pool caused by the loss of Hoxb3/b4, we sought to determine whether proliferation recruitment of primitive hematopoietic progenitors was affected in Hoxb3/b4−/− mice. LSK cells were sorted out from the BM and plated in serum-free medium in a single cell assay to evaluate survival and proliferation. The cells were plated out in medium containing either TPO or SCF alone and, on day 6, a multicytokine mixture (SCF, FL, TPO, G-CSF, IL-3, and GM-CSF) was added to test the viability, which was found to be normal for the mutant cells. Recruitment into proliferation of single LSK cells was tested by supplementing the medium at day 1 with SCF alone, SCF-TPO, SCF-TPO-FL, or the multicytokine mixture described above. Low stimulatory growth conditions (few cytokines) did not give the mutant cells a proliferative disadvantage compared to control cells, but a significant difference in proliferation potential was detected between the Hoxb3/b4−/− and Hoxb3/b4+/+ littermates, when the multicytokine combination was used (Fig. 4 and data not shown). A significantly reduced number of LSK Hoxb3/b4−/− cell clones with high proliferative

CD34 cells in the BM of Hoxb3/b4−/− mice and healthy littermates was estimated by FACS analysis. The frequency of these cells was the same in Hoxb3/b4−/− mice as in controls, but the absolute numbers of this primitive hematopoietic population were reduced; this reduction, however, did not reach statistical significance (Fig. 3B; P = 0.27). The cell cycle distribution of freshly isolated LSK progenitors was analyzed by Ki67 and 7AAD staining. The findings demonstrate that in normal endogenous hematopoiesis, the ratio of Hoxb3/b4−/− cells in active cycle versus G0/G1 is not affected compared to controls (Fig. 3C), indicating that reduced cellularity and size of hematopoietic organs is not caused by a lower proportion of proliferating stem cells during endogenous hematopoiesis of adult mice. Rather, this result suggested that already at the fetal stage the expansion of hematopoietic cells is compromised due to the lack of Hoxb3 and Hoxb4. Therefore, we enumerated the FL cells at 14.5 days postcoitus. Although there was no difference in the total number of FL cells from Hoxb3/b4−/− and Hoxb3/b4+/+ littermate controls (19.7 ± 6.7 × 10⁴ [n = 24] and 19.2 ± 4.6 × 10⁴ [n = 12], respectively), the absolute number of Lin− Sca1+ AA4.1 cells per FL was significantly reduced in the Hoxb3/b4−/− mice compared to the Hoxb3/b4+/+ littermate controls (29 ± 12 × 10³ [n = 12] versus 49 ± 22 × 10³ [n = 24]; P = 0.04). These findings support the notion that there may be a reduction in primitive hematopoietic progenitors and stem cells of Hoxb3/b4−/− mice already at the FL stage.

FIG. 3. Normal cell cycle distribution during endogenous hematopoiesis but reduced numbers of primitive hematopoietic progenitors lacking Hoxb3/Hoxb4. (A) Hoxb3/b4−/− BM cells and BM cells from control littermates were plated out in methylcellulose for measurement of CFU-C and BFU-E ability or injected into lethally irradiated recipients for CFU-S day 12 assay. The findings show a reduction in the absolute numbers of hematopoietic progenitors. The numbers of CFU/femur are shown for BFU-E and CFU-S, but the number of CFU-C is per 1/10 femur. Data from four different experiments are shown (mean ± the standard deviation [SD]; seven Hoxb3/b4−/− and seven Hoxb3/b4+/+ littermates). (B) The absolute numbers of LSK CD34 cells in the BM of both femurs was estimated by FACS analysis. A mild reduction in absolute numbers of LSK CD34− cells was observed in mice deficient for Hoxb3 and Hoxb4. (C) The cell cycle distribution of LSK cells was analyzed by staining with Ki67 and 7AAD, enabling distinction and estimation of G0, G1, and S/G2/M contents. No difference in cell cycle distribution was detected. The results from two experiments are shown (six mice/group). Shaded bars, Hoxb3/b4−/−; solid bars, Hoxb3/b4+/+

FIG. 4. Reduced proliferation recruitment of single primitive hematopoietic progenitors in vitro. Single LSK cells were seeded directly into serum-free medium containing 25 ng of SCF, FL, TPO, and G-CSF/ml and 10 ng of GM-CSF and IL-3/ml to assay for in vitro expansion. After 10 days of culture, the cloning frequency (open bars) and clone size (shaded bars, representing the percentage of high proliferative clones covering >50% of the well) were evaluated. The results represent the mean ± the SD values of two experiments.
capacity (progeny cells cover ≥ 50% of the well) was observed compared to Hoxb3/b4−/− littermates (P < 0.001). Similarly, there was a reduction in the total number of responding clones from the mutant cells, although this was not statistically significant (Fig. 4, P < 0.07). These results indicate that primitive LSK Hoxb3/b4−/− derived cells proliferate less effectively than their normal counterparts in vitro and that the effects due to lack of Hoxb3 and Hoxb4 are most prominent in settings in which there is extensive pressure for proliferation on this primitive cell population.

Normal homing of Hoxb3/b4-deficient BM cells. Before evaluating the regeneration capacity of Hoxb3/b4-deficient repopulating HSCs, we sought to determine whether Hoxb3/b4−/− BM cells were defective in homing to hematopoietic sites. Fifteen million Hoxb3/b4−/− and control BM cells were transplanted into irradiated recipients, and homing into BM and spleen was evaluated by FACS. The homing capacity of total, Lin−, and Lin− c-kit+ Hoxb3/b4-deficient donor cells was not affected, and this included primitive, multipotent myeloid (CFU-S at day 12) progenitors (Fig. 5A). There was also no difference in the ability of normal donor cells to home into the BM stroma and spleens of Hoxb3/b4−/− mice compared to control mice, suggesting that the reduced cellularity of hematopoietic organs in Hoxb3/b4−/− mice was not simply due to an impaired ability to retain hematopoietic cells (Fig. 5B).

Repopulating HSCs from Hoxb3/b4-deficient mice have reduced regenerative capacity. In order to determine whether the lack of Hoxb3/b4 affected the function of repopulating HSCs after transplantation to lethally irradiated mice, a competitive transplantation experiment was performed. Fresh FL cells from Hoxb3/b4−/− mice or normal littermates (expressing the Ly5.2 marker) were transplanted together with B6.SJL competitor cells (expressing Ly5.1) into lethally irradiated B6.SJL recipient mice. PB samples were taken 3, 6, and 12 weeks posttransplant, and the level of reconstitution by the Ly5.2 cells was analyzed. Repopulation by Hoxb3/b4−/− cells lagged behind that of controls at 3 and 6 weeks (Fig. 6A), although by 12 weeks equivalent levels were reached. This finding prompted us to test the regenerative capacity of adult BM HSCs by the same approach. The Hoxb3/b4−/− derived BM cells showed significantly lower regenerative capacity than their Hoxb3/b4−/− counterparts 6 weeks posttransplantation (P = 0.01), but in long-term reconstituted mice at 17 weeks this difference was less prominent and not significant (P = 0.12; Fig. 6B). The animals were sacrificed at 17 weeks posttransplantation, and the lineage distribution of Ly5.2 cells in BM and PB was analyzed. All transplanted mice showed reconstitution of all hematopoietic lineages, and the lineage distribution was normal in mice transplanted with Hoxb3/b4−/− BM cells (data not shown). Since the Hoxb3/b4−/− cells exhibited
lower reconstitution ability in the primary recipients, we sought to determine whether these findings would be more prominent upon further proliferative stress after transplantation to secondary recipients. Reconstitution of Hoxb3/b4−/− cells in the secondary recipients was significantly lower compared to Hoxb3/b4+/+ cells, at 6 and 17 weeks posttransplant (Fig. 6C). These observations strongly suggest that deficiency of Hoxb3/b4 negatively affects the regenerative capacity of adult BM repopulating HSCs.

Hoxb3/b4−/− HSCs exhibit increased tolerance to 5-FU. To further investigate the effects of Hoxb3/b4 deficiency on the repopulating HSC compartment in adult mice, we sought to determine whether mutant HSCs exhibited abnormal proliferation kinetics. Therefore, the mice were treated with 5-FU twice (on day 1 and on day 5) to test the hypothesis that slower proliferation kinetics result from Hoxb3/b4 deficiency. The first treatment of 5-FU eliminated actively cycling cells, thereby forcing the primitive resting population into cycle. A second treatment of 5-FU then killed the primitive cells that had been recruited into proliferation as a response to the previous hit. Hoxb3/b4−/− and Hoxb3/b4−/− littermates were injected i.v. with 5-FU (150 mg/kg) on day 1 and on day 5 (96 h apart), BM was harvested the following day and transplanted together with fresh B6.SJL cells into lethally irradiated B6.SJL recipients. FACS analysis showed no difference in lineage distribution between the knockout donor cells and their normal counterparts (data not shown). However, there was a clear and significant difference in overall reconstitution of the recipient mice when the Hoxb3/b4−/− cells were compared to the Hoxb3/b4−/− cells. After two hits with 5-FU, the Hoxb3/b4−/− cells now had a clear advantage over the Hoxb3/b4−/− derived cells, showing two- to threefold-higher levels of reconstitution at 6 weeks posttransplantation (P < 0.001) and, on average, 40% higher reconstitution after 20 weeks (P = 0.001; Fig. 7A). These data indicate that the primitive compartment is less activated after the first 5-FU treatment in Hoxb3/b4−/− mice than in the normal littermates, resulting in a higher proportion of noncycling, protected stem and progenitor cells that are not affected by the second 5-FU hit. Activation of Hoxb3/b4−/− HSCs from G0 into cell division is delayed after hematopoietic stress. In order to support the hypothesis that primitive Hoxb3/b4−/− cells are less activated than control cells after treatment with cytotoxic drugs such as 5-FU, we performed cell cycle analysis after cyclophosphamide treatment. Cyclophosphamide acts similarly to 5-FU; however, it does not alter the expression of cellular markers such as c-kit and Mac1 posttreatment, as has been observed after 5-FU treatment (39, 50). Therefore, the primitive hematopoietic LSK cells have an unaltered immunophenotype after cyclophosphamide treatment. Hoxb3/b4−/− mice and normal littermates were treated with cyclophosphamide (200 mg/kg, given intraperitoneally); 96 h later, the BM cells were harvested and the LSK population was stained with Ki67 and 7AAD for an analysis of the cell cycle distribution. A significantly higher proportion of Hoxb3/b4−/− LSK cells were found in the noncycling G0 phase (P = 0.04), and a significantly lower proportion was in active (S/G2/M) cycle compared to control cells (P = 0.04; Fig. 7B). The frequencies of cells in G1 were the same in both groups. Collectively, these findings demonstrate that there is delayed activation and recruitment into proliferation of Hoxb3/b4−/−-deficient HSCs after hematopoietic stress that is induced by cytotoxic drugs.
DISCUSSION

Accumulating data show that Hox transcription factors play an important role in hematopoiesis. Here we report that deficiency of Hoxb4 and Hoxb3 decreases proliferation capacity of hematopoietic cells with repopulating ability and causes significantly reduced cellularity in hematopoietic organs. The reduction in cellularity is most pronounced in the spleen (30%) and in the BM (25%), with a more marginal reduction observed in the PB. The reduction is not caused by alterations in lineage commitment of hematopoietic cells, but rather the defect seems to be at a more primitive level, within the multipotent progenitor and stem cell compartment. The colony-forming ability of clonogenic progenitors seems not to be significantly affected by the deficiency of Hoxb3 and Hoxb4; however, their absolute numbers were reduced. Interestingly, the cell cycle distribution of endogenous LSK CD34 Hoxb3/b4−/− cells was normal; however, absolute numbers of this primitive population were mildly reduced. These findings suggest that the numbers of primitive hematopoietic progenitors may be reduced during embryogenesis. During fetal hematopoiesis a robust expansion of stem cells and progenitors occurs in the FL at days 11 to 15 (32). We therefore analyzed the FL of 14.5-day-old embryos and observed a significant reduction in the absolute number of the repopulating Lin− Sca1+ AA4.1+ cells (21) in Hoxb3/b4−/− embryos compared to controls and, moreover, a competitive transplantation assay demonstrated a slower regeneration capacity of FL HSCs. Furthermore, competitive repopulation assays with BM-derived cells demonstrated an impaired regeneration rate of Hoxb3/b4−/− HSCs in primary recipients, and this effect is amplified somewhat in secondary recipients, possibly in part due to a mild reduction of HSCs in the primary recipient. Collectively, these findings support the notion that deficiency of Hoxb3 and Hoxb4 negatively affects cycling of multipotent progenitors and stem cells undergoing rapid proliferation. However, other important parameters such as survival, differentiation, and homing of these primitive cells seem not to be affected. We have also generated mice with a deficiency in Hoxb4 alone (complete deletion), where the impact of the deficiency is qualitatively similar but is less pronounced quantitatively (5a). Therefore, the additional deletion of Hoxb3 seems only to enhance the effects seen without causing a new phenotype, a dose-dependent phenomenon that has been observed in other compound Hox knockout models (see discussion below).

It is of interest to compare the findings presented here with those of previous reports that have used gain-of-function models to define the role of Hoxb4 and Hoxb3 in hematopoiesis. The loss of Hoxb3 expression did not affect B- or T-cell maturation and had no aberrant effects on the myeloid lineages, as reported by Sauvageau et al. in a retrovirally engineered overexpression study (46). This would indicate that Hoxb3 expression is redundant but that downregulation of this gene is important for normal differentiation. The loss of Hoxb3 and Hoxb4 does not seem to affect the hematopoietic lineage commitment pathways but rather reduces the proliferation capacity of stem cells, although the effects of deficiency are clearly not as dramatic as enforced HOXB4 expression resulting in 50-fold expansion of long-term repopulating HSCs (1, 45, 54). In a recent, elegant overexpression study, a new additional function of HOXB4 is suggested in promoting primitive HSCs, derived from yolk sac as well as from ES cells, to become definitive (26, 40). However, this promotion cannot entirely depend on Hoxb4 since the lack of this gene does not block the onset of definitive hematopoiesis. These effects could also be dose dependent, where exceeding a certain threshold-level changes the functional effect of the transcription factor, as has been seen for GATA-1, where the lineage outcome is correlated with the level of GATA-1 expression (25).

Given the functional complexity of the Hox gene clusters with regard to redundancy, as well as shared internal regulation, the deletion of a single gene might not give an accurate
picture of its role since a neighboring or a paralog gene(s) might rescue the phenotype. Indeed, compound knockouts of paralog genes can display dose-dependent degrees of synergism in the homeotic transformations observed, based on the mutant combinations analyzed (19, 59). Surprisingly, in our double-knockout model, homozygous Hoxb3/b4−/− mice were born at a normal Mendelian ratios without signs of any life-threatening phenotype as reported for Hoxb4 mutants, which died at or around the time of birth due to a split sternum (38). The penetrance of this lethal phenotype was reported to be stronger (100%) in a pure 129SvEv genetic background but is still quite significant (50%) in the mixed C57BL/6J × 129SvEv background, which is the one that we have mainly used. The absence of this phenotype in our model is intriguing. A possible explanation could lie within the very different targeting strategies used since in the study by Ramirez-Solis et al., Hoxb4 mutants were generated either by disrupting the first exon by insertion of a double selection cassette and stop codons or by inserting a stop codon in the second exon. The split sternum phenotype was only observed in the first model (38). This might indicate that aberrant splice variants or the presence of a selection cassette driven by strong promoters within the complex regulated Hox cluster could affect the observed phenotype (i.e., see reference 6). In the present study, all exons and introns of Hoxb4 and Hoxb3 are completely removed, along with intermediate and flanking sequences containing specific and shared regulatory elements (i.e., see references 15, 16, 17, 31, and 47). This leaves no possibility for expression of abnormal splice variants or truncated proteins with aberrant function. However, the deletion brings Hoxb2 and Hoxb5 together, thereby possibly altering the sequential expression pattern of the Hox cluster during embryogenesis (as well as in hematopoiesis).

The mechanism by which Hox genes affect transcription remain largely unknown, as well as their target genes. In addition to classical transcriptional activities, including DNA binding or direct involvement in transcription complexes, recent studies suggest that these genes might also be involved in chromatin modulation by affecting the acetylation of histones, thereby either functioning as repressors or activators (14a, 42, 48). With regard to Hoxb4, cellular proliferation induced by Hoxb4 has been reported to cause increased activity of the AP-1 complex and higher levels of cyclin D1, both directly involved in cell cycle regulation (24). Hoxb4 has also been reported to bind to and participate in downregulation of c-myc, resulting in differentiation of a promyelocytic leukemic cell line (35, 36).

Regulating maintenance and expansion of the stem cell pool involves a very complex mixture of internal and external signals. In addition to Hoxb4, a number of other molecules have also been reported to have an important role in this scheme. Among these is the cyclin-dependent kinase inhibitor, p21cip1/waf1, which is necessary for maintaining stem cells in a quiescent state, and deficiency of this molecule leads to stem cell exhaustion (11). Interestingly, p21cip1/waf1 has been suggested to be a transcriptional target of another Hox transcription factor, namely, HOXA10 (7). Other factors important for maintenance of hematopoietic activity include molecules such as Pbx1 (14) and Rac2 (33), both with strong connections to Hox genes. A few candidate genes with the ability to expand stem cells have been reported. An example of this is HOXA9 (52); however, long-term overexpression of this gene leads to AML (23). Other examples include Hedgehog and Sonic hedgehog, which enhance proliferation of primitive human hematopoietic cells via BMP regulation (3), and Notch1 (57) and the homeobox gene Lhx2 (37), which have been successfully used to generate immortalized HSCs.

In summary, the data presented here suggest that proliferation, but not commitment of true stem cells, is negatively affected by Hoxb3/b4 deficiency. Furthermore, it appears that Hoxb3 and Hoxb4 are mainly important under conditions that call for a rapid proliferation response and are dispensable for normal, steady-state hematopoiesis. These findings are important for understanding the regulatory mechanisms that control fate, particularly self-renewal, of HSCs. Further studies are required to elucidate fully the mechanism of Hoxb4 action in HSCs in order to determine whether enforced expression of Hoxb4 can be used safely to generate or expand stem cells ex vivo for cell or gene therapy.

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