Bone marrow microenvironmental changes underlie reduced RAG-mediated recombination and B cell generation in aged mice

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Bone Marrow Microenvironmental Changes Underlie Reduced RAG-mediated Recombination and B Cell Generation in Aged Mice

Joseph E. Labrie III, Alex P. Sah, David M. Allman, Michael P. Cancro, and Rachel M. Gerstein

Abstract

During aging, adaptive immunity is severely compromised, due in part to decreased production of B lymphocytes and loss of immunoglobulin (Ig) diversity. However, the molecular mechanisms that underlie age-associated diminished B cell production remain unclear. Using in vivo labeling, we find that this reduction in marrow pre-B cells reflects increased attrition during passage from the pro-B to pre-B cell pool. Analyses of reciprocal bone marrow chimeras reveal that the magnitude and production rates of pre-B cells are controlled primarily by microenvironmental factors, rather than intrinsic events. To understand changes in pro-B cells that could diminish production of pre-B cells, we evaluated rag2 expression and V(D)J recombinase activity in pro-B cells at the single cell level. The percentage of pro-B cells that express rag2 is reduced in aged mice and is correlated with both a loss of V(D)J recombinase activity in pro-B cells and reduced numbers of pre-B cells. Reciprocal bone marrow chimeras revealed that the aged microenvironment also determines rag2 expression and recombinase activity in pro-B cells. Together, these observations suggest that extrinsic factors in the bone marrow that decline with age are largely responsible for less efficient V(D)J recombination in pro-B cells and diminished progression to the pre-B cell stage.

Key words: hematopoietic system • antibody formation • B lymphocytes • aging • gene rearrangement

Introduction

Advancing age is accompanied by compromised immune responses (1–3) and decreased vaccine efficacy (4, 5). These changes, in part, reflect age-associated decreases in B lymphocyte production and repertoire diversity (6–14), but the underlying molecular mechanisms remain unclear. RAG1 and RAG2 produce site-specific DNA double strand breaks that initiate V(D)J recombination (15, 16) as B cell progenitors transit differentiative stages associated with Ig gene rearrangement and B cell receptor assembly. Thus, age-associated reductions of RAG activity could contribute to diminution of pre-B cells in aged mice, and, indeed, rag1 and rag2 mRNA levels decline when assessed in total bone marrow preparations from aged mice (6, 9, 11).

However, the age-associated reduction in pre-B cells alone might account for apparently reduced rag levels in total bone marrow, inasmuch as pre-B cells outnumber pro-B cells 3:1 in young mice, but are often equal to or less than the number of pro-B cells in aged mice (9, 17–19). It is similarly unclear whether the age-related reductions in marrow B lineage progenitors and rag expression levels reflect lineage-intrinsic versus microenvironmental defects. For example, pro-B cells from aged mice yield diminished proliferative capacity in IL-7-supplemented cultures (17, 20, 21), yet stromal cell cultures established from aged mice support less in vitro proliferation of pro-B cells than cultures established from young mice (18, 20, 22).

To explore these questions, we have examined the magnitude and kinetics of each major B cell differentiative stage...
in aged versus young adults, coupled with single cell flow cytometric analyses of transgenic and knockin (KI) mice that afford direct assessments of RAG expression and activity (23–25). Our findings indicate that diminished pre–B cell numbers is a general feature of aging because it is observed in multiple stains and F1 combinations. Moreover, these changes are accompanied by reduction in RAG expression and activity within pre–B cells, whereas proliferative activity is unaffected, forging a link between reduced RAG activity and increased failure to transit the late pro–B cell stage. Finally, we show that these age-associated changes in population dynamics and RAG activity largely reflect microenvironmental changes because all of these properties are dictated by host age in reciprocal marrow chimeras.

Materials and Methods

Mice. C57BL/6, CBA/J, FVB/Nj, and B6.SJL–Pepe/Pep3/J (CD45.1) were obtained from The Jackson Laboratory. Young and aged BALB/c, DBA/2, C57BL/6, C57BL/6 × DBA/2jF1, and (C57BL/6 × Balb/c)F1 mice were obtained from National Institute of Aging Repository. C57BL/6 (JAX) were also aged at the University of Massachusetts Medical School under specific pathogen-free conditions. NG transgenic mice (FVB/Nj background) were obtained from M. Nussenzweig (The Rockefeller University, New York, NY; reference 23). NG mice were crossed specific pathogen-free conditions. NG transgenic mice (FVB/Nj background) were obtained from M. Nussenzweig (The Rockefeller University, New York, NY; reference 23). NG mice were crossed to C57BL/6j mice for 6–9 generations and crossed to H2-SVEX University, New York, NY; reference 23). The incorporated BrdU was analyzed according to previously published procedures (26, 29). Cytometric analysis was performed by gating on all nucleated cells as described previously (26). For each mouse, the percentage of BrdU-labeled cells in each subset was measured by flow cytometry and multiplied by the total cells in the subset to give the number of labeled cells. The mean ± SD values for these percentages and numbers were plotted as a function of time, and least squares regression analyses were performed to obtain the turnover and production rates, respectively.

Continuous BrdU Labeling In Vivo and Analysis of BrdU-labeled Cells. The rate of continuous in vivo BrdU labeling was assessed as described previously (26–28). Young and aged C57BL/6 mice were injected i.p. with 0.6 mg BrdU (Sigma-Aldrich) in 0.2 ml PBS at 12-h intervals for the duration of each experiment. The cells obtained from BrdU-treated mice were stained for three surface markers (PE, allophycocyanin, and biotin-conjugated Abs followed by streptavidin-Red670) as mentioned before and washed with cold PBS. FITC-labeled anti-BrdU (B44) was purchased from Becton Dickinson. The incorporated BrdU was analyzed according to previously published procedures (26, 29). Cytometric analysis was performed by gating on all nucleated cells as described previously (26).

Flow Cytometric Analyses of Cell Surface Antigens and GFP. For Figs. 2–5 and Tables II–IV, primary antibodies specific for production rates, respectively.

Microenvironmental Changes Underlie Reduced V(D)J Recombinase in Aged Mice

Statistical Analyses (see Figs. 2–5 and Tables II–V).

Statistical analysis was performed using SPSS version 10.0 for Mac and Ver-

412 Microenvironmental Changes Underlie Reduced V(D)J Recombinase in Aged Mice
Feature of Aging and Reflect Increased Pro–B Cell Attrition.

... rounds of division after successful heavy chain rearrangement... 

...corresponding to a production rate of $10^6$ cells/day... 

...the immature bone marrow B cell compartment shows less pronounced changes in magnitude, despite the striking reduction in newly formed B cell numbers. Surprisingly, the immature bone marrow B cell... 

...Diminished Marrow Progenitor Compartments Are a Common Feature of Aging and Reflect Increased Pro–B Cell Attrition. First, we analyzed the magnitude and kinetics of B lineage progenitor pools in several strains and F1 combinations. In accord with previous findings, the pre–B cell pool of aged individuals is markedly diminished in all strains examined (Fig. 1 A and Table I). This approximately fourfold difference in pre–B cell numbers is sufficient to account for most of the age-associated reduction in newly formed B cell numbers. Surprisingly, the immature bone marrow B cell compartment shows less pronounced changes in magnitude, despite the striking reduction in their immediate precursor pool.

The kinetic changes underlying shifts in the size of B cell progenitor pools were determined by analyzing in vivo BrdU-labeling rates within the B cell developmental subsets of aged (18–24 mo old) versus young mice. Proportional and absolute labeling rates of C57BL/6 mice (Fig. 1 B and Table I) are representative of all strains and F1 combinations tested. Both the proportional and absolute labeling rates of pro–B cells are similar in young versus aged mice (Fig. 1 B). Both ages display a pro–B renewal rate of $\sim 35\%$ per day, corresponding to a production rate of $\sim 10^6$ cells/day (Table I). However, the number and production rate of pro–B cells is somewhat diminished in aged mice (Fig. 1 and Table I), in accord with previous papers (19, 30).

In contrast, labeling kinetics within the pre–B cell pools of aged versus young adult mice differ dramatically (Fig. 1 B, middle). Young adults generate 9–13 million pro–B cells daily, whereas aged individuals produce only 2–5 million pro–B cells per day (Table I). Nonetheless, the renewal rates of pre–B cells are very similar (32–42%/day), indicating that the residency time within the pool is unchanged in aged individuals (Table I). This fourfold reduction in the generation rate but unchanged renewal rate corresponds well with the fourfold diminution of the pre–B cell pool. Because immature marrow B cells are nondividing, labeling among these cells reflects transit from the pre–B cell pool. Surprisingly, the entry rate of immature marrow B cells in aged individuals is less severely affected than pre–B cell generation (Fig. 1 B and Table I). Thus, unlike young adults where $\sim 20–24\%$ of the pre–B cells formed survive to reside within the immature pool, nearly 50% appear to do so in aged individuals. Furthermore, the renewal rate of immature marrow B cells is slower, indicating a lengthened residency in the immature compartment, and resulting in a compartment of similar magnitude despite the halved production rate.

Fr. C’ pro–B cells and large pre–B cells undergo several rounds of division after successful heavy chain rearrange-

...Thus, the differences in pro–B cell production could either reflect failure to proliferate, or might instead indicate that fewer pro–B cells successfully pass the checkpoints imposed before this proliferative burst. Therefore, we performed cell cycle analysis in conjunction with staining combinations that delineate the marrow B cell fractions (31). We found that the proportion of cells in S and G2/M phases is similar for young and aged mice in each fraction of marrow development (unpublished data); statistical analyses indicate no significant differences between aged versus young marrow in the proportion of cycling cells within any fractions. Thus, because the C’ and D...
Table I. Production and Renewal Rates of Marrow B Cell Subsets in Bone Marrow Chimeras Determined from In Vivo BrdU Labeling

<table>
<thead>
<tr>
<th></th>
<th>Untreated mice</th>
<th>Bone marrow chimeras</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Young</td>
<td>Aged</td>
</tr>
<tr>
<td>No. of cells (× 10^6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pro</td>
<td>3.5 ± 1.3</td>
<td>2.1 ± 1.3^bc</td>
</tr>
<tr>
<td>Renewal rate (% of pool/day)^c</td>
<td>33.8</td>
<td>34.1</td>
</tr>
<tr>
<td>Production rate (cells/day × 10^6)^e</td>
<td>1.2</td>
<td>0.7^d</td>
</tr>
<tr>
<td>Pre</td>
<td>28.0 ± 9.7</td>
<td>6.8 ± 4.3^c</td>
</tr>
<tr>
<td>Renewal rate (% of pool/day)</td>
<td>37.3</td>
<td>32.0</td>
</tr>
<tr>
<td>Production rate (cells/day × 10^6)</td>
<td>9.3</td>
<td>2.3^c</td>
</tr>
<tr>
<td>Immature</td>
<td>9.3 ± 3.2</td>
<td>7.8 ± 4.1^d</td>
</tr>
<tr>
<td>Renewal rate (% of pool/day)</td>
<td>20</td>
<td>11^d</td>
</tr>
<tr>
<td>Production rate (cells/day × 10^6)</td>
<td>2.0</td>
<td>0.8^e</td>
</tr>
</tbody>
</table>

^a3 × 10^−6 T- and B-depleted bone marrow cells from young or aged C57BL/6 mice were injected i.v. into young or aged (C57BL × DBA2)F1 mice. Adoptive hosts were allowed to reconstitute for >40 d. Chimeric bone marrow was harvested as described in Materials and Methods. The proportional representation of pro-, pre-, and immature B subsets was assessed by flow cytometry and multiplied by the marrow cell estimate of Osmond et al. (47) to obtain total numbers. Data for untreated mice are from young or aged C57BL/6.

^bMeans were compared (young vs. aged or reciprocal chimeras vs. control chimeras) using Student’s t test.

^cP < 0.01.

^dP < 0.05.

^eBrdU labeling was performed in reciprocal young→aged chimeric mice as described in Materials and Methods. The proportion of BrdU-labeled cells was determined by flow cytometry, and the numbers of BrdU-labeled cells calculated by multiplying these proportions estimates of total marrow cells. The regression coefficients of absolute and proportional labeling versus time provide estimates of production and renewal rates, respectively.

fractions show similar proportions of cells in S and G2/M phases, the proliferative burst associated with fraction C’ occurs in aged mice and, therefore, decreased proliferation does not underlie reduced pre–B cell production.

Host Age Dictates the Magnitude and Kinetics of the Pre–B Cell Pool in Reciprocal Bone Marrow Chimeras. Both aged→young and young→aged bone marrow chimeras were generated using C57BL/6 donors and either (C57BL × BALB/c)F1

Table II. Statistical Analysis of Data Obtained from Young and Aged rag2 Reporter NG Transgenic Mice

<table>
<thead>
<tr>
<th>Significance of differences</th>
<th>Young^a</th>
<th>Aged^a</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of pro–B cells (millions)^b</td>
<td>1.0 ± 0.29</td>
<td>0.70 ± 0.12</td>
<td>0.035</td>
</tr>
<tr>
<td>No. of pre–B cells (millions)^b</td>
<td>4.1 ± 1.0</td>
<td>1.3 ± 0.79</td>
<td>0.001</td>
</tr>
<tr>
<td>Pre:pro ratio^c</td>
<td>4.0 ± 0.67</td>
<td>1.7 ± 0.94</td>
<td>0.001</td>
</tr>
<tr>
<td>% of pro–B cells that are CD24^high</td>
<td>61 ± 4.1</td>
<td>45 ± 10</td>
<td>0.005</td>
</tr>
<tr>
<td>% of pro–B cells that are GFP^+</td>
<td>74 ± 2.7</td>
<td>45 ± 19</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Correlations b/t characteristics

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>r</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of pro–B cells that are GFP^+ and no. of pro–B cells</td>
<td>11</td>
<td>0.80</td>
<td>0.003</td>
</tr>
<tr>
<td>% of pro–B cells that are GFP^+ and pre:pro ratio</td>
<td>11</td>
<td>0.88</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Bone marrow from young (2–3.5 mo) and aged (26–27 mo) NG mice, and wild-type controls (both [FVBN × CBA]F1 background) was harvested and analyzed by flow cytometry and statistical analyses as described in Materials and Methods. In the NG mice, GFP is a reporter of rag2 expression. ^aMeans ± SD are presented.

^bNumbers of pro–B (B220^+CD43^+AA4.1+) and pre–B cells (B220^+CD43^+AA4.1^−CD24^−) in bone marrow of young and aged NG mice were determined by multiplying the frequency by the leg bone marrow cell number determined by counting to obtain total numbers.

^cThe pre:pro ratio was calculated by dividing the number of pre–B cells by the number of pro–B cells.

n, no. of mice; r, correlation coefficient.
or (C57BL × DBA/2)F1 recipients. Donor marrow depleted of T cells and slg+ cells was transferred to irradiated recipients. Young→young chimeras, as well as untreated F1 mice of appropriate age were analyzed to serve as controls. After ~40 d of reconstitution, recipients were treated with BrdU and the magnitude, turnover, and renewal rates of each marrow B cell compartment were determined. The results are summarized in Table I.

When transferred to young recipients, both aged and young donor marrow produced newly formed B cell subpopulations of identical magnitude, turnover, and renewal rates (Table I). These results indicate that B lineage progenitors derived from aged marrow are fully capable of generation and survival rates associated with young marrow progenitors. In contrast, when transferred to aged recipients, young marrow yields a pre–B cell compartment different from that of young recipients, which mirrors the production and turnover rates observed in aged individuals (Table I). Together, these findings show that age-associated microenvironmental changes, rather than altered differentiation or survival capacity of B lineage progenitors themselves, underlie altered generation and attrition rates.

**Age-associated Reduction in Pre–B Cells Is Correlated with a Reduction in the Percentage of Pro–B Cells That Express rag2.** We compared rag2 expression in the bone marrow of young (2–3.5 mo) and aged (26–27 mo) mice. Flow cytometric analysis of young and aged NG transgenic mice was used to determine the percentage of pro–B cells that express GFP as a reporter of rag2 expression (Fig. 2, A and C). The percentage of pro–B cells that express GFP+ is shown for the same mice depicted in B. (D) The percent of pro–B cells that express GFP+ and the pre:pro ratio are displayed for each NG mouse shown in B and C. Closed diamonds represent young mice, and open diamonds represent aged mice.
This suggests that the levels of rag2 per cell are similar within these pro–B cells, even though fewer pro–B cells express rag2 in aged mice.

The loss of rag2 expression in pro–B cells was correlated with reduced numbers of pre–B cells; the percentage of pro–B cells that are GFP+ is correlated with both the number of pro–B cells and the pre:pro ratio (Fig. 2 D and Table II). This relationship is also evident in Fig. 2 A, as the aged mouse with the lowest percent of GFP+ pro–B cells is the same mouse that has the lowest number of pre–B cells and pre:pro ratio. The finding that the reduction in pre–B cell numbers in aged mice is correlated with a reduction in the percent of pro–B cells that express rag2 supports the hypothesis that reduced numbers of pre–B cells in aged mice are due to alterations that affect expression of rag2.

Reduced Numbers of Pre–B Cells in Aged Mice Are Correlated with Reduced RAG2 Protein Levels in Pro–B Cells. Next, we analyzed B cell development in RAG2-GFP KI mice (24). These KI mice have two important advantages compared with NG mice: (a) the GFP reporter is located within the endogenous rag2 locus, and (b) GFP is expressed as a fusion protein with RAG2 and, thus, serves as a direct reporter of cellular RAG2 protein levels. The RAG2-GFP fusion protein maintains normal RAG enzymatic activity, and B cell development in these mice is not altered. GFP levels per cell and the percentage of pro–B cells that express GFP are lower in these mice compared with NG transgenic mice. This difference could be due to the single insertion of GFP in the KI compared with the multicopy NG transgene as well as differences in protein half-life for the RAG2-GFP fusion in the KI compared with GFP in the transgenic. We analyzed RAG2-GFP expression in pro–B cells harvested from young (4–7 mo) and aged (23–28 mo) RAG2-GFP KI mice. Results from flow cytometric analyses of pro–B cells and pre–B cells are shown in Fig. 3.

As with the NG mice, the percent of pro–B cells that express rag2 was significantly lower in aged mice as compared with young KI mice (mean: 14 vs. 33%; Fig. 3 C and Table III). Both the NG and KI models demonstrate that rag2 expression in pro–B cells is lower in aged mice.
Table III. Statistical Analysis of Data Obtained from Young and Aged RAG2-GFP KI Mice

<table>
<thead>
<tr>
<th>Significance of differences</th>
<th>Young&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Aged&lt;sup&gt;b&lt;/sup&gt;</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of pro–B cells (millions)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.28 ± 0.07</td>
<td>0.21 ± 0.12</td>
<td>NS</td>
</tr>
<tr>
<td>No. of pre–B cells (millions)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.0 ± 0.64</td>
<td>1.3 ± 0.75</td>
<td>0.001</td>
</tr>
<tr>
<td>Pre:pro ratio&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3.4 ± 1.2</td>
<td>1.3 ± 0.75</td>
<td>0.001</td>
</tr>
<tr>
<td>% of pro–B cells that are GFP&lt;sup&gt;d&lt;/sup&gt;</td>
<td>33 ± 3.6</td>
<td>14 ± 12</td>
<td>0.001</td>
</tr>
<tr>
<td>Correlations b/t characteristics</td>
<td>n</td>
<td>r</td>
<td>p-value</td>
</tr>
<tr>
<td>% of pro–B cells that are GFP&lt;sup&gt;d&lt;/sup&gt; and no. of pro–B cells</td>
<td>16</td>
<td>0.575</td>
<td>0.020</td>
</tr>
<tr>
<td>% of pro–B cells that are GFP&lt;sup&gt;d&lt;/sup&gt; and pre:pro ratio</td>
<td>16</td>
<td>0.709</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Bone marrow from young (4–7 mo) and aged (23–28 mo) RAG2-GFP KI mice was analyzed by flow cytometry and statistical analyses as described in Materials and Methods. In these mice, GFP is a reporter of RAG2 protein levels.

<sup>a</sup>Means ± SD are presented.

<sup>b</sup>Numbers of pro–B (Ly6C<sup>−</sup>DX5<sup>−</sup>IgM<sup>−</sup>B220<sup>−</sup>CD43<sup>+</sup>) and pre–B cells (Ly6C<sup>−</sup>DX5<sup>−</sup>IgM<sup>−</sup>B220<sup>−</sup>CD43<sup>+</sup>) in bone marrow of young and aged KI mice were determined by multiplying the frequency by the leg bone marrow cell number determined by counting to obtain total numbers.

<sup>c</sup>The pre:pro ratio was calculated by dividing the number of pre–B cells by the number of pro–B cells.

Bone marrow from young (4–7 mo) and aged (23–28 mo) RAG2-GFP KI mice was analyzed by flow cytometry and statistical analyses as described in Materials and Methods. In these mice, GFP is a reporter of RAG2 protein levels.

Also, because the KI reporter is a RAG2-GFP fusion protein, the data suggest that protein levels of RAG2 are lower in the pro–B cells of aged mice. The number of pre–B cells was significantly lower in aged (mean: 0.33 × 10<sup>6</sup> cells) as compared with young KI mice (1.0 × 10<sup>6</sup> cells; Table III). In addition, the pre:pro ratio was lower in the aged compared with young mice (mean: 1.3 vs. 3.4; Table III). Similar to our data with the NG mice, these results suggest that the reduction in the numbers of pre–B cells in aged mice is not solely due to a reduction in the size of the population of pro–B cells, and may also reflect reduced development of pro–B cells and generation of pre–B cells. Furthermore, we observed that the percent of pre–B cells that express GFP was correlated with both the number of pre–B cells and the pre:pro ratio (Table III). Together, our analyses of both the NG transgenic and RAG2-GFP KI mice indicate that the reduction in numbers of pre–B cells is correlated with reduced <i>rag2</i> expression in pro–B cells.

<i>rag2</i> Expression, V(D)J Recombinase Activity, and the Pre:Pro Ratio Are Reduced in Aged Mice. Next, we assessed whether reduced expression of <i>rag2</i> in aged mice yields a corresponding decrease in recombination activity using H2-SVEX transgenic mice (25). Cells that undergo V(D)J recombination of the transgenic recombination substrate express the GFP variant VEX (32, 33), are easily detected by flow cytometry, and are readily resolved from cells expressing conventional GFP (32, 33). In addition, the percent of VEX<sup>+</sup> cells within a population reflects the level of <i>rag2</i> expression (25, 34).

We crossed NG mice to H2-SVEX mice to generate double transgenic mice in which <i>rag2</i> expression could be measured in conjunction with V(D)J recombination activity at the single cell level. We used adoptive transfers to evaluate <i>rag2</i> expression and recombination activity in young versus aged recipient mice. This provided two advantages as follows: (a) we were able to isolate effects of the aged bone marrow microenvironment independent of cell-intrinsic defects, and (b) this was an expedient alternative to aging double transgenic mice. Whole bone marrow from young NG ×...
Table IV.  Statistical Analysis of Data Obtained from Adoptive Transfers of NG× H2-SVEX Transgenic Bone Marrow: Young→Aged and Young→Young

<table>
<thead>
<tr>
<th>Significance of differences</th>
<th>Young recipient†</th>
<th>Aged recipient†</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of donor pro–B cells that are GFP+</td>
<td>71 ± 5.1</td>
<td>37 ± 21</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>% of donor pro–B cells that are VEX+</td>
<td>33 ± 4.8</td>
<td>17 ± 6.4</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Pre:pro ratio‡</td>
<td>3.2 ± 0.56</td>
<td>0.66 ± 0.56</td>
<td></td>
</tr>
<tr>
<td>Log of pre:pro ratio‡</td>
<td>1.1 ± 0.18</td>
<td>-0.83 ± 1.0</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Correlations b/t characteristics,
all mice (n = 30)

<table>
<thead>
<tr>
<th>log pre:pro ratio</th>
<th>% of pro–B cells that are GFP+</th>
<th>% of donor pro–B cells that are VEX+</th>
</tr>
</thead>
<tbody>
<tr>
<td>r = 0.812, P &lt; 0.001</td>
<td>r = 0.860, P &lt; 0.001</td>
<td></td>
</tr>
</tbody>
</table>

Correlations b/t characteristics,
aged recipient mice (n = 17)

<table>
<thead>
<tr>
<th>log pre:pro ratio</th>
<th>% of pro–B cells that are GFP+</th>
<th>% of donor pro–B cells that are VEX+</th>
</tr>
</thead>
<tbody>
<tr>
<td>r = 0.550, P = 0.022</td>
<td>r = 0.670, P = 0.003</td>
<td></td>
</tr>
</tbody>
</table>

CD4.51 NG × H2-SVEX double transgenic mice (GFP serves as a reporter of rag2 expression, and VEX serves as a reporter of V(D)J recombinase activity) were used as donors for adoptive transfer. Bone marrow was harvested from wild-type young (3–4 mo at time of harvest) and aged (23–29 mo at time of harvest) CD45.2 recipient mice. 5–6 wk after adoptive transfer of bone marrow from young (1–3 mo) NG × H2-SVEX CD45.1 mice. Pro–B (IgM+ B220+CD43+) and pre–B cells (IgM+ B220+CD43+) of donor origin were identified based on expression of CD45.1, using flow cytometry as described in Materials and Methods.

†Means ± SD are presented.
‡The pre:pro ratio was calculated by dividing the number of pre–B cells by the number of pro–B cells. Numbers of pro–B and pre–B cells in bone marrow were determined by multiplying the frequency by the log bone marrow cell number determined by counting to obtain total numbers.

To determine if cell-intrinsic defects affect age-associated reduced recombinase activity and there was a lower pre:pro ratio after bone marrow transfer into aged as compared with young recipient mice (Fig. 4). This indicates that age-associated alterations specific to the bone marrow microenvironment are sufficient to produce these defects in B cell development. The presence of defects in B cell development due to changes in the bone marrow microenvironment does not preclude the existence of age-related, cell-intrinsic defects. To determine if cell-intrinsic defects affect rag2 expression...
in pro–B cells and the pre:pro ratio, we conducted adoptive transfer experiments in which bone marrow from aged and young donor mice was transferred into young recipient mice. The NG mice shown in Fig. 1 (four out of the six young and all of the aged) were used as sources of bone marrow for adoptive transfer into irradiated young wild-type recipient mice. Each recipient mouse received an adoptive transfer from either one young or one aged donor. Thus, progenitors from young and aged mice were evaluated after differentiation within the same microenvironment; the bone marrow of a young recipient.

Before adoptive transfer, all five of the aged donor mice displayed significantly lower pre:pro ratios (mean: 1.7) than those of the young donor mice (mean: 3.7; Fig. 5 A and Table V). The percentage of pro–B cells that express rag2 was also significantly lower in the five aged donor mice (mean: 45%) than in the young donor mice (mean: 75%; Fig. 5 A and Table V). 5 wk after adoptive transfer, B cell development and rag2 expression in young recipient mice was assessed by flow cytometry. In this experiment, a marker of donor cells was not available. However, efficient engraftment must have occurred for the following reasons: (a) recipients survived lethal irradiation; (b) in comparable experiments, engraftment in young mice routinely resulted in >90% pro–B cells of donor origin; and (c) the expression of GFP in pro–B cells (which clearly identifies cells of NG transgenic donor origin) was high (60–90% pro–B cells) in bone marrow harvested from recipient mice (Fig. 5 B). We found that rag2 expression in young recipient mice was not affected by the age of the bone marrow donors (Fig. 5 B and Table V). The mean percentage of GFP+ pro–B cells was 82% in mice that received bone marrow from young

Figure 5. Pro–B cells derived from young and aged sources display similar rag2 expression and pre:pro ratios in young hosts. Bone marrow from young (3 mo) and aged (26–27 mo) NG mice were transferred into lethally irradiated young (2 mo at time of transfer) recipient mice. (A) GFP expression in pro–B cells (left) and pre:pro ratio (right) in young and aged donor mice at time of transfer. These mice are four of the six young and all of the aged mice shown in Fig. 1. Black bars represent young donor mice, and diagonally striped bars represent aged donor mice. To aid comparisons, each young donor mouse is given a designation, Y1–Y4, and each aged donor mouse was given A1–A5, depicted below each panel. (B) Analyses of bone marrow harvested from young recipient mice 5 wk after transfer of cells from either young or aged donors. Pro–B cells were defined as IgM−B220−CD43−AA4.1+ and pre–B cells were defined as IgM−B220−CD43−AA4.1−CD24+. The percentage of pro–B cells that are GFP+ and the pre:pro ratios are shown. The pre:pro ratio of two young unmanipulated NG mice used as controls in this experiment were 1.2 and 1.3. Each bar represents values obtained from one recipient mouse. The designations Y1–Y4 and A1–A5 reflect the source of the transferred bone marrow as shown in A, and brackets show the groups of recipients according to the donor designation.

**Table V. Statistical Analysis of Data Obtained from Adoptive Transfer of NG Transgenic Bone Marrow: Aged→Young and Young→Young**

<table>
<thead>
<tr>
<th>Significance of differences: donor mice</th>
<th>Young donor a</th>
<th>Aged donor b</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre:pro ratio</td>
<td>3.7 ± 0.41</td>
<td>1.7 ± 0.94</td>
<td>0.006</td>
</tr>
<tr>
<td>% of pro–B cells that are GFP+</td>
<td>75 ± 2.5</td>
<td>45 ± 19</td>
<td>0.023</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Significance of differences: young recipient mice</th>
<th>Pre:pro ratio</th>
<th>% of pro–B cells that are GFP+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.7 ± 0.58</td>
<td>82 ± 9.8</td>
</tr>
<tr>
<td></td>
<td>1.7 ± 0.40</td>
<td>82 ± 9.3</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

Bone marrow from young (3 mo) and aged (26–27 mo) NG mice were transferred into lethally irradiated young (2 mo at time of transfer) recipient mice.

aGFP expression in pro–B cells and pre:pro ratio in young and aged donor mice at time of transfer. Pre–B cells (B220+/CD43−AA4.1−CD24+) and pro–B cells (B220+/CD43−AA4.1+) were evaluated by flow cytometry as described in Materials and Methods.

bMean ± SD are presented.

cAnalyses of bone marrow harvested from young recipient mice 5 wk after transfer of bone marrow cells from either young or aged donors. Pro–B cells were defined as IgM−B220−CD43−AA4.1+ and pre–B cells were defined as IgM−B220−CD43−AA4.1−CD24+. The pre:pro ratio of two young unmanipulated NG mice used as controls in this experiment were 1.2 and 1.3.
donors or from aged donors (Fig. 5 B and Table V). The degree of diminished \( \text{rag2} \) expression in pro–B cells of particular aged donors was not reflected in recipient mice. Of the donors, mouse A3 displayed the lowest percentage of pro–B cells with \( \text{rag2} \) expression (<15%; Fig. 5 A). In the two young mice that received bone marrow from A3, \( \text{rag2} \) was expressed in >70% of pro–B cells and was comparable to that of other recipient young mice (Fig. 5 B). These observations indicate that the reduction in \( \text{rag2} \) expression in pro–B cells of aged mice is not likely to be the result of defects that are intrinsic to the developing cells.

The pre:pro ratios were also compared in young reconstituted mice and were not significantly different due to the age of bone marrow donors (Table V). The mean pre:pro ratio was 1.7 in mice that received bone marrow from either aged or young donors (Fig. 5 B and Table V). In addition, the severity of the age-related defect in individual mice was not reflected after adoptive transfer into young hosts. Aged donor mice A1, A2, and A3 displayed the lowest pre:pro ratios (Fig. 5 A), yet the seven young recipients of bone marrow from these mice displayed pre:pro ratios that were as high as those observed in mice that received bone marrow from young donors (Fig. 5 B). This suggests that the age-related reduction in the pre:pro ratio is not the result of cell-intrinsic defects in hematopoietic precursors.

**Discussion**

These studies provide a direct assessment of turnover and production rates among B lineage progenitors in the marrow of aged mice. The results indicate that both the number and production rate of pro–B cells are reduced approximately fourfold compared with young adults. Because the proportion of cycling pro–B cells is similar in aged and young individuals, this difference reflects increased losses during passage from the pro–B to pre–B pool. Although pro–B cells from aged individuals clearly display impaired proliferative capacity in vitro (20), the similar proportions of cycling cells within fraction C suggest this impairment is unlikely the basis for reduced pro–B cell numbers in vivo. Furthermore, a shortened renewal pro–B cell rate was not observed (Table I), arguing against an increased attrition rate within the pro–B compartment. Thus, when considered together with the similar proportional labeling kinetics and reduced absolute production rates, our observations are most consistent with increased attrition as cells transit from the pre–B to pro–B compartment.

The transition into the pro–B compartment requires productive assembly of an \( \text{IgH} \) gene. Reduced expression of \( \text{rag1} \) and \( \text{rag2} \) could limit \( \text{IgH} \) assembly, although it was previously unclear whether the decline in \( \text{rag1} \) and \( \text{rag2} \) expression in total bone marrow reflects changes in gene expression or simply the loss of pro–B cells (6, 11, 13, 17, 18). Using a flow cytometric approach to evaluate \( \text{rag2} \) gene expression at the single cell level, we found the frequency of pro–B cells that express \( \text{rag2} \) is reduced, and that this is correlated with reduced numbers of pro–B cells, suggesting that the age-related reduction in pro–B cell numbers could be the direct result of diminished \( \text{rag2} \) expression. We used H2-SVEX mice to measure V(D)J recombinase activity at the single cell level. Using NG × H2-SVEX double transgenic mice as donors, we demonstrate that recombinase activity is reduced in pro–B cells that develop in aged mice. This supports the hypothesis that reduced \( \text{rag2} \) expression is of sufficient magnitude to reduce recombinase activity, potentially limiting heavy chain rearrangement, pre–BCR expression, and subsequent transit to the pre–B cell stage. Our findings of fewer pro–B cells and reduced \( \text{rag2} \) expression and recombinase activity in pro–B cells from aged mice supports a model in which reduced recombination of IgH might compromise both the pro–B cell compartment and the pro–B to pre–B cell transition. Specific attrition of later-stage pro–B cells was first noted by Van der Put et al. (19) and pro–B cell reduction was recently demonstrated by Miller et al. (30). We also observed altered distribution of cells within the pre–B cell stage, as indicated by the reduced percentage of CD24\(^{\text{high}}\) cells in aged mice (Table II), and decreases in the number of pro–B cells (Fig. 1 and Tables I and II). Failure to rearrange IgH is predicted to delete CD24\(^{\text{high}}\) pro–B cells and limit proliferation of pre–BCR\(^+\)Fr C’ cells.

Before our investigation, it was unclear if altered B cell development in aged mice was due to changes in the bone marrow hematopoietic microenvironment or to intrinsic changes in developing precursor cells. The reciprocal bone marrow chimera experiments herein show that the aged marrow microenvironment is sufficient to produce reduced \( \text{rag2} \) activity in pro–B cells, reduced pre:pro ratios, and reduced pre–B cell generation rates, whereas these parameters were similar when developing in young hosts regardless of donor age. These experiments indicate that the age-associated defects in \( \text{rag2} \) expression, recombinase activity in pro–B cells, and the generation of pre–B cells are the result of alterations in the bone marrow microenvironment and are unlikely to result from cell-intrinsic alterations. In these and additional studies (unpublished data), cells from old mice transferred to young hosts express normal levels of \( \text{rag2} \) and generate normal numbers of pre–B cells and mature peripheral B cell subsets. It will be of interest to determine whether this restoration also recapitulates complete B cell function and Ig repertoires. The bone marrow microenvironment includes factors derived from bone marrow stromal cells that are essential to the development of B cell precursors. Specific extrinsic factors that induce \( \text{rag} \) expression have yet to be identified; the age-related decrease in \( \text{rag2} \) expression in pro–B cells might reflect attenuation of yet unknown inductive signals. Reduced numbers of either stromal cells or specific cellular niches for B cell development (35) could also contribute to reduced pre–B cell generation rates. In aged mice, the percentage of pro–B cells that express \( \text{rag2} \) is reduced. However, in the pro–B cells that do express \( \text{rag2} \), the level of expression per individual cell is similar to that of young mice. This could indicate that fewer pro–B cells receive signals and factors...
from the stromal microenvironment, but those that do receive the required factors develop normally. We cannot exclude the possibility that additional host-derived factors contribute to the marrow environment. However, in contrast with a published paper (11), we find B cell development and recombination activity are normal in completely T cell–deficient mice (TCRβ−/−δ−/−H2-SVEX mice; unpublished data). Therefore, it seems unlikely that the decline in peripheral T cells with age limits bone marrow environmental support of B cell development.

Reduced numbers of pre–B cells in aged mice may also stem from a reduced expression of essential transcription factors during the pro–B cell stage. At this stage, pax5, E2A, and EBF govern commitment and development by controlling expression of B cell–specific genes that are important for the pro–B to pre–B transition. In particular, the E2A gene product E47 is essential for survival and proliferation of B lineage cells. E47 binds to the Eng enhancer required for expression of rag1 and rag2 in pro–B cells (36). E47 also regulates expression of A5 (37). Protein levels of E47 are reduced in pro–B cells of aged mice, and this reduction is correlated with a reduction in A5 expression (21, 38). It is possible that reduced E2A expression could attenuate B cell development due to reduced expression of both rag and A5 (39).

Our results indicate that fewer cells in the pro–B cell stage of development have an active V(D)J recombinase in aged mice. Consistent with this, Szabo et al. noted fewer cleaved DFL16.1 signal ends in pro–B cells from aged mice (40). Thus, reduced recombinase activity could contribute to reduced diversity of IgH chains and, thus, compromise the Ig repertoire in aged mice. Previous work has shown that receptor diversity is reduced in aged mice (3, 9, 14, 41–46). Interestingly, lower enzymatic activity of RAG in rag “core-only” KI mice resulted in reduced Vλ1 to Dλ1 joining and an altered repertoire (47–49). Alternatively, the reduced rag2 expression and V(D)J recombinase activity could support formation of a normal repertoire, but with decreased efficiency in the generation of pre–B cells. The immature B cell pool in aged mice is somewhat reduced, but not to the extent that might be predicted based on the diminution in the pro–B cell pool. This appears to reflect lengthened average residency time within this pool because the immature B cell renewal rate is twofold slower (Fig. 1 and Table I). Together, our data best support a model in which reduced V(D)J recombinase activity in the pro–B cell stage alters the formation and possibly the diversity of the IgH repertoire.

Our results demonstrate that the previously documented reduction in numbers of pre–B cells is linked to reduced generation of pre–B cells that occur concurrent with changes in pro–B cells that include reduced rag2 expression and V(D)J recombinase activity. Alterations in the aged bone marrow microenvironment are sufficient to produce these defects independent of cell-intrinsic alterations, although the nature of these changes remains to be determined.

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