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Connection Between B Lymphocyte and Osteoclast Differentiation Pathways

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Osteoclasts differentiate from the hematopoietic monocyte/macrophage cell lineage in bone marrow through cell-cell interactions between osteoclast progenitors and stromal/osteoblastic cells. Here we show another osteoclast differentiation pathway closely connected with B lymphocyte differentiation. Recently the TNF family molecule osteoclast differentiation factor/receptor activator of NF-κB ligand (ODF/RANKL) was identified as a key membrane-associated factor regulating osteoclast differentiation. We demonstrate that B-lymphoid lineage cells are a major source of endogenous ODF/RANKL in bone marrow and support osteoclast differentiation in vitro. In addition, B-lymphoid lineage cells in earlier developmental stages may hold a potential to differentiate into osteoclasts when stimulated with M-CSF and soluble ODF/RANKL in vitro. B-lymphoid lineage cells may participate in osteoclastogenesis in two ways: they 1) express ODF/RANKL to support osteoclast differentiation, and 2) serve themselves as osteoclast progenitors. Consistent with these observations in vitro, a decrease in osteoclasts is associated with a decrease in B-lymphoid cells in klotho mutant mice (KL−/−), a mouse model for human aging that exhibits reduced turnover during bone metabolism, rather than a decrease in the differentiation potential of osteoclast progenitors. Taken together, B-lymphoid lineage cells may affect the pathophysiology of bone disorders through regulating osteoclastogenesis.


A multipotent hemopoietic stem cell undergoes lineage commitment and subsequent sequential differentiation along each lineage pathway, giving rise to all types of blood cells. The stem cells committed to the myeloid lineage (common myeloid progenitors) differentiate into granulocytes, monocyte/macrophages, and dendritic cells. The common lymphoid progenitors differentiate into NK, B, and T lymphocytes.

Osteoclasts, multinucleated cells primarily responsible for bone resorption, have been shown to differentiate from the monocyte/macrophage lineage (1–4). Mature osteoclasts can be formed in vitro from bone marrow cells in the presence of two cytokines, M-CSF and osteoclast differentiation factor/receptor activator of NF-κB ligand (ODF/RANKL)3 (5–9). Osteoblastic cells and stromal cell lines such as ST2 also support osteoclast formation from bone marrow cells in vitro. In addition to the in vitro studies, recent experiments using knockout mice demonstrated that disruption of either m-csf or odf/rankl gene causes increased bone mass (osteopetrosis) due to a complete lack of osteoclasts (10, 11). Thus, M-CSF and ODF/RANKL are regarded as key regulators of osteoclastogenesis. However, the osteoclast defect in m-csf mutant mice can be restored by overexpression of anti-apoptotic protein Bcl-2 in monocyte lineage cells (12), suggesting that M-CSF is essential for the survival but not the differentiation of osteoclast progenitors.

The monocyte/macrophage lineage cells that give rise to osteoclasts and lymphoid lineage cells are thought to be distantly related. However, evidence is accumulating in support of a close relationship between macrophage and B-lymphoid cell differentiation pathways. There are numerous reports on B cell lymphomas that acquired macrophage-like phenotypes, including characteristic morphological changes and expression of mature macrophage surface markers (see Ref. 13 for review). In addition, a subset of normal B cells (CD5− B cells) is known to have properties of both B cells and macrophages (13, 14). CD5+ B cells are adherent and highly phagocytic, and they coexpress surface markers characteristic of macrophages (F4/80 and Mac-1) and B cells (B220, IgM, and IgD). Recently, it was reported that Pax5-deficient pro-B cells have the ability to take various differentiation pathways, including the monocyte/macrophage lineage, and can give rise to osteoclasts in vitro (15). These findings are challenging current ideas of lineage commitment in B-lymphoid lineage cells.

Abbreviations used in this paper: ODF/RANKL, osteoclast differentiation factor/receptor activator of NF-κB ligand; KL, klotho; TRAP, tartrate-resistant acid phosphatase; PBS−, Ca2+−, and Mg2+−free PBS.
We recently established a mouse model for human aging termed klotho (16). The klotho mouse was serendipitously generated by insertional mutation of a transgene in a transgenic mouse, which disrupted the klotho gene encoding a novel single-pass membrane protein. A defect in klotho gene expression leads to a syndrome closely resembling human aging including a shortened lifespan, decreased spontaneous activity, infertility, skin atrophy, arteriosclerosis, premature thymic involution, pulmonary emphysema, and osteopenia, among others. Osteopenia observed in klotho mutant mice (KL+/− mice) is accompanied by low turnover during bone metabolism, in which the decrease in bone formation exceeds the decrease in bone resorption, resulting in a net bone loss (17). The number of osteoclasts was significantly decreased in KL+/− mice. In addition, osteoclast formation from bone marrow cells of KL+/− mice in vitro was significantly reduced (17). The pathophysiology of the bone in KL+/− mice recapitulates senile osteoporosis in humans rather than postmenopausal osteoporosis, which is primarily caused by increased bone resorption accompanied by an increase in the number of osteoclasts.

In an effort to find out the cellular mechanism by which KL+/− mice develop osteopenia resembling senile osteoporosis, we found two novel roles that B-lymphoid lineage cells appear to play in osteoclastogenesis. In the present study, we report that B-lymphoid lineage cells express abundant ODF/RANKL and have the ability to support osteoclast differentiation. In addition, we show that a subset of normal bone marrow cells that express markers of B-lymphoid lineage cells in early developmental stages can serve as osteoclast progenitors and are able to give rise to osteoclasts in vitro. We also show that KL+/− mice have significantly reduced numbers of B-lymphoid lineage cells in the bone marrow, which could cause a decrease in osteoclasts in KL+/− mice due to the simultaneous reduction in cells expressing ODF/RANKL and in cells serving as osteoclast progenitors. These findings provide new insights into current concepts of osteoclast differentiation and molecular mechanisms of bone disorders such as osteoporosis.

Materials and Methods

Animals

Wild-type (KL+/+) and KL+/− mice were generated by mating of heterozygous klotho mutant mice (KL+/−). The genetic background of the original klotho mouse was a mixture of C57BL/6J and C3H/J (16).

Histomorphometric analysis of the bone

All histological analyses were conducted using 8-μm-old KL+/+ and KL+/− littermates. Tibiae were excised, fixed with 100% ethanol, embedded in methyl methacrylate, and sectioned in 6-μm slices for Villanueva-Goldner staining and tartrate-resistant acid phosphatase (TRAP) staining. TRAP staining was conducted at pH 5.0 in the presence of L(+)-tartrate acid using naphthol AS-MX phosphate (Sigma, St. Louis, MO) in N,N-dimethylformamide as a substrate. The specimens were subjected to histomorphometric analyses under a light microscope with a micrometer using an image analyzer (System Supply, Nagano, Japan). Parameters for bone resorption were measured in a trabecular bone area (1.2 mm in length from 0.1 mm below the growth plate) at the proximal metaphysis of the tibiae. The number and function of osteoclasts were determined by counting the number of TRAP-positive cells and by measuring the percentage of bone surface area eroded by osteoclasts with the image analyzer.

Cell preparation

Bone marrow cells were prepared from mouse tibiae by flushing out the bone marrow with Ca2+- and Mg2+-free PBS (PBS−). The bone marrow cells were resuspended in 2 ml of ammonium chloride-Tris buffer to lyse red blood cells. The cell suspension was washed with PBS− three times and resuspended in 1 ml of PBS− containing 1% BSA. Spleen cell suspensions were prepared in the same way. PBMC were separated using Ficoll-Conray solution for mouse lymphocytes.

Flow cytometric analysis

Cells (1 × 10⁶) were incubated for 30 min on ice with various combinations of FITC-conjugated anti-B220/CD45R (RA3-6B2; BD PharMingen, San Diego, CA), Gr-1 (RB6-8C5; BD PharMingen), CD3 (17A2; BD PharMingen), or F4/80 (MCA497F; Serotec, Oxford, UK), and PE-conjugated TER-119 (TER-119; BD PharMingen) or IgM-μ-chain Abs (Tago Southern Life Science, Burlingame, CA) washed twice with PBS− and resuspended with PBS− containing 1% BSA. The cells labeled with fluorescent dyes were analyzed on a flow cytometer (FACSCalibur; BD Biosciences, Mountain View, CA). For two-color analysis of ODF/RANKL and B220, cells were incubated for 30 min on ice with FITC-conjugated anti-B220 and an affinity-purified goat polyclonal anti-ODF/RANKL Ab (C-20: sc-7627; Santa Cruz Biotechnology, Santa Cruz, CA) raised against a peptide map- ping to the carboxyl terminus of human ODF/RANKL and shown to react with mouse, rat, and human ODF/RANKL. After washing with PBS−, cells were incubated with biotin-conjugated rabbit anti-goat IgG (Jackson ImmunoResearch Laboratories, West Grove, PA) and washed twice with PBS−. The cells were then incubated for 10 min at room temperature with streptavidin-PE conjugate (BD PharMingen), and washed twice with PBS−. As negative controls, goat IgG (Jackson ImmunoResearch Laboratories) and FITC-conjugated rat IgG2a, κ (BD PharMingen) were used instead of anti-ODF/RANKL Ab and FITC-conjugated anti-B220 (isotype: rat IgG2a, κ, respectively). Two-color FACS analysis with PE-labeled anti-ODF Ab vs FITC-conjugated rat IgG2aκ and PE-labeled goat IgG vs FITC-conjugated anti-B220 Ab was used to set the appropriate levels of compensation.

Osteoclast formation in vitro

Bone marrow cells were collected from tibiae and femora of 6-wk-old KL+/+ or KL+/− mice. The bone marrow cells were cultured in αMEM containing 10% FBS. Osteoclast differentiation was induced for 8 days either with 1.25(OH)2 vitamin D3 (10−8 M) and PGE2 (10−8 M) or with ODF/RANKL (100 ng/ml; PeproTech, Rocky Hill, NJ) and M-CSF (recombinant human M-CSF, 20 ng/ml; Genzyme, Cambridge, MA). TRAP-positive multinucleated cells with three or more nuclei were counted as osteoclasts. Osteoclastic bone resorption was measured in a trabecular bone area (1.2 mm in length from 0.1 mm below the growth plate) at the proximal metaphysis of the tibiae. After osteoclastic bone resorption occurred, the plates were washed five times with PBS− to remove nonadherent cells that failed to differentiate into osteoclasts. Then, the plates were treated with 0.25% trypsin to dislodge the nonosteoclast adherent cells. Osteoclasts adhere to the culture plates so firmly that they are not dislodged by trypsin treatment. After three times trypsin treatment, every cell remaining on the culture plates was examined under the microscope to confirm that all were typical multinucleated osteoclasts. The osteoclasts on the plates were then treated with proteinase K (0.15 mg/ml) at 50°C for 3 h. The genomic DNA was precipitated by adding isopropanol to the cell lysate.

Magnetic cell sorting of B-lymphoid lineage cells

B-lymphoid lineage cells were isolated with a magnetic cell-sorting system (MACS; Miltenyi Biotec, Bergisch Gladbach, Germany). After washing suspended columns with PBS, the matrix of the column was incubated with magnetic steel-wool columns with PBS−. After washing with 2 column volumes of PBS−, the column was further washed with 4 column volumes of PBS− or 6M or with PBS− containing 1% BSA in PBS for 15 min to saturate nonspecific binding sites. After the column was flushed with ice-cold PBS/1% BSA, cells labeled with anti-B220, CD19, or CD43 Ab-conjugated magnetic beads were applied to the column. Unbound cells were then washed out with 2–4 column volumes of PBS/1% BSA or until no cells were collected at flow rates of 10 ml/h. The column was further washed with >3 volumes of PBS/1% BSA at an increased flow rate. After the steel-wool column was removed from the external magnetic field, bound cells were eluted and analyzed by flow cytometry. We repeated the sorting steps until >99% of eluted cells were positive for each marker.

Analysis of ODF/RANKL expression

Bone marrow cells were flushed out from femora and tibiae of 6-wk-old KL+/− mice with PBS− and fractionated into B220+ and B220− cells as described above. Poly(A)+ RNA and total protein were extracted from B220+ cells, B220− cells, whole bone marrow cells, and residual bones (bones without the bone marrow cells). Poly(A)+ RNA was extracted using oligodT columns (Pharmacia, Peapack, NJ). The poly(A)+ RNA (500 ng) was reverse-transcribed into single-strand cDNA with random hexamer and amplified with LA-Tag DNA polymerase with a commercially available kit (LA RT-PCR Kit; Takara, Kyoto, Japan), using primers specific for mouse ODF/RANKL (5′-CTCCGAGCTGTCGTAAGAAA-3′ and 5′-CAGGGGAATCAAAATGC-3′) or GAPDH (5′-CATGTAGGCCAT CAGGGGAATTACAAAGTGC-3′) and CAGGGGAATCAAAATGC-3′). Protein was extracted using TNE buffer (10 mM Tris-HCl, 150
mM NaCl, 1% Nonidet P-40, 1 mM EDTA, 10 mM NaF, 2 mM Na 3 VO 4, 10 mM NaCl, 1% Nonidet P-40, 1 mM EDTA, 10 mM NaF, 2 mM Na 3 VO 4, and 10 mM NaCl, 1% Nonidet P-40, 1 mM EDTA, 10 mM NaF, 2 mM Na 3 VO 4. Western blotting detection kit (Pierce, Rockford, IL). The blots were probed with anti-ODF/RANKL Ab and Abs against ODF/RANKL in the bone (Fig. 3). There was no difference in the frequency of granulocytes (Gr-1+ cells) or erythrocytes (TER119+ cells) between KL+/+ and KL−/− mice (Table I). The frequency of T lymphoid lineage cells (CD3+ cells) was slightly higher in KL−/− mice; however, the slight increase did not translate into an increase in the number of CD3+ cells because of the decrease in the number of total nucleated cells in KL−/− mice.

Expression of ODF/RANKL on B-lymphoid lineage cells
To test whether KL−/− mice have a defect in cells and/or molecules that support osteoclast differentiation, we examined expression of ODF/RANKL in the bone marrow. Dual-color flow cytometric analysis using anti-ODF/RANKL Ab and Abs against several lineage-specific markers revealed that ODF/RANKL is expressed primarily on the surface of B-lineage cells expressing B220 (Fig. 3a). The frequency of B220− cells in the bone marrow is significantly decreased in KL−/− mice, the percentage of cells expressing ODF/RANKL is also decreased from 13.3% in KL+/+ to 6.2% in KL−/− mice. Most of the ODF/RANKL-positive cells are also positive for B220 in KL+/+ mice (Fig. 3a). RT-PCR and immunoblot analysis confirmed that B220+ cells are a major source of endogenous ODF/RANKL in the bone (Fig. 3b). Expression of ODF/RANKL in various tissues and cell lines has been described; however, there had been no report on its expression in the bone marrow until quite recently. These data indicate that ODF/RANKL is principally expressed on B-lymphoid lineage cells in the bone. This finding is in agreement with a recent study reporting that B lymphocytes and the pre-B cell line 70Z/3 express ODF/RANKL more abundantly than bone marrow adherent cells, which contain stromal cells (19).

Taken together, these observations have raised the possibility that B lymphocytes and their progenitors may be involved in osteoclastogenesis. B-lymphoid lineage cells support osteoclast differentiation
We tested whether ODF/RANKL expressed on B220+ cells could support osteoclast formation in vitro. Bone marrow cells from KL−/− mice were separated into B220+ and B220− cell fractions using magnetic cell sorting. The sorted cells were cultured in medium containing 10−6 M 1,25(OH)2 vitamin D3 and 10−6 M PGE2 to induce osteoclast differentiation. According to the current consensus on osteoclast differentiation, osteoclast progenitors belong not to the lymphoid but to the monocyte/macrophage lineage and should be enriched in the non-B (B220−) cell fraction. Therefore, we expected that robust osteoclast formation from B220− cells
would be observed. Contrary to our expectation, very few osteoclasts were generated by B220− cells alone (Fig. 4a). However, when B220+ cells were added back to the fixed number of B220− cells, osteoclast formation was significantly augmented in proportion to the number of B220+ cells added (Fig. 4c). B220+ cells alone gave rise to very few osteoclasts under these conditions (Fig. 4a). These results clearly demonstrated that interactions between B220+ and B220− cells potentiated differentiation of osteoclasts. Osteoclast formation was completely abolished by the addition of anti-ODF/RANKL Ab or recombinant osteoprotegerin (100 ng/ml), a soluble decoy receptor of ODF/RANKL, indicating that endogenous ODF/RANKL is essential for osteoclastogenesis under these culture conditions.

To determine whether osteoclast progenitors in the bone marrow of KL−/− mice have an intrinsic defect in differentiation into mature osteoclasts, we prepared B220+ and B220− cells from KL−/− and KL+/+ mice and did coculture experiments. According to the origin of the cells, four different cell combinations were tested (Fig. 4, c–f). B220+ cells from KL−/− mice supported osteoclast formation to the same extent as those from KL+/+ mice. In addition, the B220− cells from KL−/− mice generated almost the same number of osteoclasts as those from KL+/+ mice. Thus, the bone marrow cells of KL−/− mice showed no difference in osteoclastogenesis in vitro from those of KL+/+ mice. Nevertheless, the number of osteoclasts generated from whole bone marrow cells of KL−/− mice was reduced to approximately one-third that of KL+/+ mice (Fig. 1c). It should be noted that, in KL−/− mice, the frequency of B220+ cells is also reduced to almost one-third (Table I). When the B220+/B220− ratio was reduced to that found in KL−/− mice (1 × 103 B220+ cells with 1 × 105 B220− cells), the number of osteoclasts generated was almost the same as that generated from the whole bone marrow mixture of KL−/− mice. The results were indistinguishable to the origin of the cells (Fig. 4, c–f). Therefore, it is unlikely that the reduction of osteoclast formation from whole bone marrow cells of KL−/− mice in vitro is caused by an inability of bone marrow cells to support osteoclast differentiation or by an intrinsic defect in osteoclast progenitors to differentiate. Rather, the reduction in osteoclastogenesis could simply be caused by the reduction in the number of B220+ cells.

The most likely explanation for the results of the coculture experiment is that ODF/RANKL expressed on the surface of B220+ cells supported differentiation of osteoclast progenitors in B220− cell fraction. In fact, the effect of B220+ cells could be replaced by soluble ODF/RANKL (Fig. 4b) and abolished with anti-ODF/RANKL Ab or osteoprotegerin. If B220+ cells serve exclusively as a source of ODF/RANKL, osteoclasts generated in the coculture experiment should have originated only from the B220− cell fraction that contains osteoclast progenitors. To test this possibility, we examined the origin of the osteoclasts. We generated osteoclasts by coculture of B220+ cells from KL−/− mice and B220− cells from KL+/+ mice (and vice versa) and determined klotho locus genotypes of the osteoclasts. Semi-quantitative PCR demonstrated that ~75% of osteoclasts originated from B220− cells and that 25% came from B220+ cells (Fig. 5). The majority of osteoclasts originated from the B220− cell fraction as expected, verifying the idea that B220− cells support differentiation of osteoclast progenitors in the B220− cell fraction. At the same time, however, these observations imply that a significant portion of osteoclasts (~25%) came from B220+ cells. This high percentage cannot be explained by contamination of B220− cells in the B220+ cell fraction, because the contamination was determined to

### Table I. Expression of lineage markers in bone marrow cells of KL+/+ or KL−/− mice

<table>
<thead>
<tr>
<th>Total Nucleated Cells (×10³)</th>
<th>B220 (%)</th>
<th>Gr-1 (%)</th>
<th>CD3 (%)</th>
<th>TER119 (%)</th>
<th>F4/80 (%)</th>
</tr>
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<tbody>
<tr>
<td>KL+/+</td>
<td>2.57 ± 0.27</td>
<td>29.6 ± 1.8</td>
<td>46.8 ± 2.1</td>
<td>4.2 ± 0.6</td>
<td>17.2 ± 1.5</td>
</tr>
<tr>
<td>KL−/−</td>
<td>1.44 ± 0.17*</td>
<td>8.9 ± 1.3**</td>
<td>52.8 ± 3.0</td>
<td>8.3 ± 1.0*</td>
<td>24.5 ± 1.9</td>
</tr>
</tbody>
</table>

*a The percentage of positive cells for each marker was indicated as means ± SEM of 15 animals. The total number of nucleated cells from bilateral tibiae and femora was counted in nine KL+/+ mice and eight KL−/− mice.

*p < 0.05 vs KL+/+; **p < 0.001 vs KL+/+.

![FIGURE 2](http://www.jimmunol.org/)

**FIGURE 2.** Two-color immunofluorescence analysis of B220 and IgM-μ-chain in bone marrow cells from KL+/+ and KL−/− mice. Respective typical patterns from five KL+/+ and KL−/− mice are shown.

![FIGURE 3](http://www.jimmunol.org/)

**FIGURE 3.** Expression of ODF/RANKL on the surface of B-lymphoid lineage cells. a, Two-color immunofluorescence analysis of B220 and ODF/RANKL expression on bone marrow cells from KL+/+ and KL−/− mice. Respective typical patterns from five KL+/+ and KL−/− mice are shown. b, Expression of ODF/RANKL at the protein and messenger RNA levels in bones without the bone marrow cells (Residual Bone), whole bone marrow cells (Whole BM), B220+ cells (B220+), and B220− cells (B220−) from KL+/+ mice were detected by immunoblotting and RT-PCR. Expression of p38 MAPK protein and G3PDH mRNA are shown as internal controls.
be <1% by FACS analysis. Rather, it suggests that B220<sup>+</sup> cells actually contributed to osteoclast formation. These observations raised the possibility that the B-lymphoid lineage cells functioned not only as a source of ODF/RANKL but also as osteoclast progenitors.

**Osteoclast formation from B220<sup>+</sup> cells**

To confirm that B220<sup>+</sup> cells are able to give rise to osteoclasts, we isolated cells from the bone marrow of KL<sup>+/−</sup> mice by cell sorting using several different B-lineage markers (CD43, B220, CD19) and induced osteoclast differentiation with soluble ODF/RANKL and M-CSF (Fig. 4). Under these conditions, CD43<sup>+</sup> B220<sup>+</sup> cells gave rise to the highest number of osteoclasts. B220<sup>+</sup> cells and CD19<sup>+</sup> cells gave rise to equivalent numbers of osteoclasts as did B220<sup>−</sup> and CD19<sup>−</sup> cells, respectively. However, B220<sup>+</sup> and CD19<sup>+</sup> cells from the spleen, most of which are positive for IgM-μ-chain, gave rise to very few osteoclasts. These splenic B-lineage cells are regarded as having already committed to the formation of mature B lymphocytes, and lost the capability of differentiating into other cell lineages.

Within the B220<sup>+</sup> population of bone marrow cells, CD43 (leukosialin) is a marker for B-lymphoid cells in early differentiation stages. It is expressed on the surface of pro-B, pre-BI, and early pre-BII cells and down-regulated thereafter (20). CD19 is another pan-B-lineage marker like B220, expression of which is dependent on expression of Pax5 (21), a transcription factor essential to the commitment of pre-B1 cells to the B-lymphoid lineage (15). Considering that CD43<sup>−</sup> cell fraction within the B220<sup>+</sup> population gave rise to more osteoclasts than did any other fractions, osteoclast progenitors are enriched in the differentiation stages earlier than the pre-BII stage. In fact, the number of osteoclasts generated from CD43<sup>−</sup> B220<sup>+</sup> cells (pre-BII or later) was less than one-fourth that from the total B220<sup>+</sup> cell pool (Fig. 6). Therefore, we conclude that B-lymphoid lineage cells in earlier developmental stages, before the pre-BII stage, contain significant osteoclast progenitor activity.

**Discussion**

Numerous reports have verified that osteoclasts can arise from the monocyte/macrophage lineage cells under the support of osteoblastic and/or stromal cells that express ODF/RANKL and M-CSF. Our present study demonstrates the existence of another pathway of osteoclast differentiation. A subset of normal B-lymphoid lineage cells may hold a potential to give rise to osteoclasts. Moreover, B-lymphoid cells are the major source of ODF/RANKL in the bone marrow and support osteoclast differentiation. Among B-lymphoid lineage cells, those in late developmental stages (immature/mature B cells) express ODF/RANKL abundantly, but do not differentiate into osteoclasts. In contrast, B-lymphoid lineage cells in early developmental stages (before the pre-BII stage) express lower levels of ODF/RANKL than those in late stages, but have the potential to differentiate into osteoclasts. In addition to the current paradigm of osteoclast differentiation pathway, we propose a novel pathway that involves B-lymphoid cells at various differentiation stages.

Recent studies challenge the current concept of lineage commitment for B-lymphoid cells. Nutt et al. (15) showed that Pax5-deficient pro-B cells have multilineage potential. Bone marrow

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**FIGURE 4.** Osteoclast formation in coculture of B220<sup>+</sup> and B220<sup>−</sup> cells from the bone marrow. a, Number of osteoclast-like cells generated from B220<sup>−</sup> cells (left) or B220<sup>+</sup> cells (right) alone. b, Induction of osteoclast differentiation with soluble ODF/RANKL protein. Recombinant soluble ODF/RANKL protein was added to the B220<sup>−</sup> bone marrow cells from wild-type mice at the indicated concentration. c-f, Number of osteoclast-like cells generated by adding B220<sup>+</sup> cells (from 0 to 30 × 10<sup>4</sup>/well) to a fixed number of B220<sup>−</sup> cells (1 × 10<sup>4</sup>/well). The origins of B220<sup>+</sup> and B220<sup>−</sup> cells are indicated. Data are shown as means (bars) ± SEMs (error bars) for eight wells per group.

**FIGURE 5.** Contribution of B220<sup>+</sup> cells to osteoclasts. Genotypes of the osteoclasts generated by coculture of B220<sup>+</sup> cells from KL<sup>+/−</sup> mice and B220<sup>−</sup> cells from KL<sup>−/−</sup> mice (lane 9) or B220<sup>+</sup> cells from KL<sup>−/−</sup> mice and B220<sup>−</sup> cells from KL<sup>+/−</sup> mice (lane 10) were determined at the klotho locus by the 3-primer-PCR (see Materials and Methods). Genomic DNA of tails from KL<sup>−/−</sup> and KL<sup>+/−</sup> mice was mixed in various ratios to obtain a standard for semiquantification (lanes 2–8). Ratios of the genomic DNA of KL<sup>−/−</sup> mice to that of KL<sup>+/−</sup> mice were 100% (lane 2), 95% (lane 3), 75% (lane 4), 50% (lane 5), 25% (lane 6), 5% (lane 7), and 0% (lane 8), respectively. Lane 1: 100 bp ladder.

**FIGURE 6.** Generation of osteoclast-like cells from B-lymphoid lineage cells. Bone marrow and spleen cells from wild-type mice were sorted according to the presence (+) or absence (−) of the indicated B cell markers. B220<sup>−</sup> cells were further sorted with CD43 (the right two columns under Bone Marrow). The sorted cells (2 × 10<sup>5</sup>/well) were cultured with the medium containing soluble ODF/RANKL and M-CSF for 8 days. Data are shown as means (bars) ± SEMs (error bars) for eight wells per group.
progenitors from Pax5−/− mice are unable to differentiate beyond the pre-B1 stage of the B-lymphoid lineage. However, when induced with appropriate cytokines, these early pre-B cells can give rise to several different lineage cells including macrophages, osteoclasts, dendritic cells, granulocytes, and NK cells. The lineage switch of Pax5−/− pro-B cells to osteoclasts may not be an abnormal pathway due to the blockade in the normal B cell differentiation, because our present data indicate that normal B-lymphoid lineage cells may also have the potential to differentiate into osteoclasts when induced by soluble ODF/RANKL and M-CSF. We conclude that a subset of normal pro-B cells is uncommitted and may still hold a potential to give rise to osteoclasts.

The fact that the pro-B cell fraction contains osteoclast progenitors may have implications in pathophysiology of osteoporosis because it is known that the number of pro-B cells is positively correlated to the number of osteoclasts in vivo in various pathologic conditions. Estrogen withdrawal causes a marked increase in the number of both B220low cells (containing pro-B cells) and osteoclasts, which leads to bone loss in humans (postmenopausal osteoporosis), and mice (osteopenia caused by ovariectomy) (1, 22, 23). In addition, IL-7, a cytokine that primarily stimulates B cell differentiation, also causes an increase in osteoclasts and bone loss when injected into mice (24). In contrast, a decrease in B220low cells is accompanied by a decrease in osteoclast numbers as observed in IL-7 receptor knock-out mice (24) and in KL−/− mice. Interestingly, the number of both osteoclasts and B220low cells decreases with age in mice (25) and humans (26). The positive correlation between the number of B220low cells and osteoclasts in various pathological conditions and the natural aging process may be partly explained by the possibility that pro-B cells actually serve not only as B cell progenitors but also as osteoclast progenitors in vivo.

ODF/RANKL expressed on B220+ cells may be another factor that is involved in pathophysiology of osteoporosis. Although our present study showed that B220low cells express less ODF/RANKL than B220high cells (Fig. 3a), a significant increase in B220low cells could result in a substantial increase in total amount of ODF/RANKL in the bone marrow, which may contribute to acceleration of osteoclastogenesis. A recent report indicated that the number of B220low cells that express ODF/RANKL was higher in bone marrow from ovariectomized mice than in bone marrow from sham-operated mice (27). Because the expression level of ODF/RANKL in each B220low cell was not significantly different, the increase in the number of B220low cells means a net increase in the amount of ODF/RANKL expression. Conversely, the decrease in B220low cells in KL−/− mice results in a net decrease in ODF/RANKL expression. Based on these observations, the number of B220+ cells could affect osteoclastogenesis and bone resorption in two ways: a change in the amount of ODF/RANKL in the bone marrow and a change in the number of osteoclast progenitors.

The mechanism by which B lymphopoiesis is impaired in KL−/− mice remains to be elucidated. A recent study indicated that the number of IL-7-responsive clonogenic progenitors (B-lymphoid progenitors) in bone marrow cells was markedly decreased in KL−/− mice (18). However, the number of hemopoietic stem cells and their capacity for B lymphopoiesis were normal (18), suggesting that a defect in hemopoietic environment might be responsible for poor B lymphopoiesis or survival in KL−/− mice. It remains to be determined whether the decrease in B220+ cells is the only explanation for the poor osteoclastogenesis in KL−/− mice. In addition to the decrease in B-lineage cells, it is possible that local and/or systemic factors affect osteoclast differentiation in KL−/− mice. In fact, we previously demonstrated that KL−/− mice had significantly higher blood proteoglycan levels than KL+/+ mice (17), which could also inhibit osteoclast formation in KL−/− mice in vivo. However, there was no significant difference in M-CSF mRNA levels between KL+/+ and KL−/− mice (18).

To our knowledge, there are no reports of osteoclast abnormality in B cell-deficient mice. There are two major differences between KL−/− mice and other B cell-deficient mice. First, although many B cell-deficient mouse strains, such as Rag2−/− and A−/− mice (28, 29), lack IgM+ cells, they have normal numbers of pro-B cells, which contain the osteoclast progenitors. In contrast, KL−/− mice show losses in both the IgM+ and pro-B cells, which results in a simultaneous reduction in both ODF/RANKL expression levels and the number of osteoclast progenitors. Therefore, KL−/− mice would be expected to have a more severe defect in osteoclastogenesis than the other B cell-deficient strains. Second, B-lymphoid lineage cells in the other B cell-deficient strains have intrinsic defects in the ability to differentiate into mature B lymphocytes. In contrast, the impairment of B lymphopoiesis in KL−/− mice was attributed to a defect in the “microenvironment” in the bone marrow (18), which could also affect osteoclast differentiation.

Our present study has indicated that B220+ cell fraction contains both ODF/RANKL-expressing cells and osteoclast progenitors. However, B220+ cells alone, when stimulated with 1,25(OH)2 vitamin D3 and PGE2, gave rise to many fewer osteoclasts than those cocultured with B220+ cells (Fig. 4a). The poor osteoclast formation was not completely restored by adding M-CSF (data not shown), suggesting that endogenous ODF/RANKL was insufficient for the effective osteoclast formation from B220+ cells and that B220+ cells played an important role in the osteoclast differentiation. Cell-cell interaction between osteoclast progenitors and stromal cells is believed to be indispensable for efficient osteoclast differentiation. Stromal cells express several adhesion molecules including VCAM-1 that binds to very late Ag-4 expressed on B-lymphoid lineage cells. Previous studies showed that very late Ag-4/VCAM-1 interactions are important in the adhesion of B cells to the bone marrow microenvironment and B cell differentiation (30). It is possible that stromal cells, which reside in the B220+ cell fraction, act as scaffolding to tether B220+ cells that express ODF/RANKL to produce a microenvironment where ODF/RANKL is focally concentrated. Such scaffolding may no longer be necessary when excessive ODF/RANKL is present, as we observed robust osteoclast formation from B220+ cells stimulated with M-CSF and soluble ODF/RANKL (Fig. 6).

In conclusion, we propose two possible mechanisms by which B-lymphoid lineage cells regulate osteoclastogenesis: they act as the major source of ODF/RANKL and support differentiation of osteoclast progenitors into mature osteoclasts. In addition, normal pro-B cells may be able to serve as osteoclast progenitor cells. The close association between B-lymphoid cell and osteoclast differentiation pathways may also imply involvement of B-lymphoid cells in the pathophysiology of bone disorders such as osteoporosis.

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References


