Osteocyte Network; a Negative Regulatory System for Bone Mass Augmented by the Induction of Rankl in Osteoblasts and Sost in Osteocytes at Unloading

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Abstract

Reduced mechanical stress is a major cause of osteoporosis in the elderly, and the osteocyte network, which comprises a communication system through processes and canaliculi throughout bone, is thought to be a mechanosensor and mechanotransduction system; however, the functions of osteocytes are still controversial and remain to be clarified. Unexpectedly, we found that overexpression of BCL2 in osteoblasts eventually caused osteocyte apoptosis. Osteoblast and osteoclast differentiation were unaffected by BCL2 transgene in vitro. However, the cortical bone mass increased due to enhanced osteoblast function and suppressed osteoclastogenesis at 4 months of age, when the frequency of TUNEL-positive lacunae reached 75%. In the unloaded condition, the trabecular bone mass decreased in both wild-type and BCL2 transgenic mice at 6 weeks of age, while it decreased due to impaired osteoblast function and enhanced osteoclastogenesis in wild-type mice but not in BCL2 transgenic mice at 4 months of age. Rankl and Opg were highly expressed in osteocytes, but Rankl expression in osteoblasts but not in osteocytes was increased at unloading in wild-type mice but not in BCL2 transgenic mice at 4 months of age. Sost was locally induced at unloading in wild-type mice but not in BCL2 transgenic mice, and the dissemination of Sost was severely interrupted in BCL2 transgenic mice, showing the severely impaired osteocyte network. These findings indicate that the osteocyte network is required for the upregulation of Rankl in osteoblasts and Sost in osteocytes in the unloaded condition. These findings suggest that the osteocyte network negatively regulates bone mass by inhibiting osteoblast function and activating osteoclastogenesis, and these functions are augmented in the un loaded condition at least partly through the upregulation of Rankl expression in osteoblasts and that of Sost in osteocytes, although it cannot be excluded that low BCL2 transgene expression in osteoblasts contributed to the enhanced osteoblast function.

Introduction

Bone tissue is able to adapt its mass and three-dimensional structure to the prevailing mechanical usage to achieve higher load-bearing efficiency [1]. The lacunocanalicular network formed by osteocytes is thought to be an ideal mechanosensory system and suitable for mechanotransduction, by which mechanical energy is converted into electrical and/or biochemical signals [2], [3], [4], [5], [6], [7]; however, the function of the osteocyte network in the regulation of bone mass remains to be clarified.

The function of osteocytes in bone formation is controversial. Osteocytes have been considered to activate bone formation, because osteocytes induced anabolic factors, such as prostaglandin E2 (PGE2), prostaglandin I2 (PGI2), nitric oxide (NO), cyclooxygenase-2 (COX-2), and endothelial nitric oxide synthase (eNOS), after application of mechanical stimuli in vitro [5] and bone formation was severely inhibited after osteocyte ablation [8]. However, Marotti et al. theorized that osteocytes inhibit osteoblasts by means of inhibitory signals transmitted via gap junctions and recruit selected osteoblasts to the osteocyte lineage [9]. In accordance with this theory, osteocyte density and bone formation rate were inversely related [10], [11]. Further, Sclerostin, the SOST gene protein product, is specifically expressed in osteocytes and inhibits osteoblast function and bone formation by antagonizing canonical Wnt signaling through the binding to Wnt co-receptor low density lipoprotein receptor-related protein (LRP) 5 and LRP6, and Sost-deficient mice are resistant to bone loss at unloading [12], [13], [14], [15], [16], [17], [18], [19], [20].

Osteocytes have been considered to suppress bone resorption because osteocyte death is eventually followed by bone resorption [8], [21], [22]; however, apoptotic and necrotic death markers
Regulation of Bone Mass by the Osteocyte Network

Table 1. Bone histomorphometric analysis of trabecular bone at 10 weeks and 4 months of age.

<table>
<thead>
<tr>
<th>genotype (age)</th>
<th>BV/TV (mm)</th>
<th>O.Th (mm)</th>
<th>N.OB/B.Pm (mm)</th>
<th>N.OC/B.Pm (mm)</th>
<th>ES/BS (mm²/10 m²)</th>
<th>Osteocyte/Ar (mm²/10 m²)</th>
<th>MAR (mm²/10 m²)</th>
<th>MS/BS (mm²/10 m²)</th>
<th>BFR/BS (mm²/10 m²/year)</th>
</tr>
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<tbody>
<tr>
<td>wt (10w)</td>
<td>16.4 ± 7.2</td>
<td>2.56 ± 0.37</td>
<td>1715 ± 397.7</td>
<td>296 ± 64.4</td>
<td>9.7 ± 2.8</td>
<td>451.7 ± 67.7</td>
<td>1.77 ± 0.33</td>
<td>28.3 ± 4.8</td>
<td>0.18 ± 0.06</td>
</tr>
<tr>
<td>tg (10w)</td>
<td>14.5 ± 1.2</td>
<td>2.54 ± 0.69</td>
<td>1347 ± 120.5</td>
<td>262.8 ± 13.3</td>
<td>9.0 ± 3.2</td>
<td>1368 ± 120.5</td>
<td>1.52 ± 0.32</td>
<td>45.0 ± 11.2</td>
<td>0.20 ± 0.07</td>
</tr>
<tr>
<td>wt (4m)</td>
<td>18.3 ± 4.3</td>
<td>1.32 ± 0.20</td>
<td>599 ± 256.5</td>
<td>147.6 ± 56.7</td>
<td>4.9 ± 1.8</td>
<td>450.1 ± 62.5</td>
<td>1.33 ± 0.30</td>
<td>24.4 ± 4.0</td>
<td>0.06 ± 0.02</td>
</tr>
<tr>
<td>tg (4m)</td>
<td>24.8 ± 13.7</td>
<td>1.87 ± 0.83</td>
<td>448 ± 161.5</td>
<td>166.4 ± 19.9</td>
<td>5.6 ± 0.6</td>
<td>314.5 ± 67.5</td>
<td>1.71 ± 0.30</td>
<td>36.2 ± 16.4</td>
<td>0.24 ± 0.12</td>
</tr>
</tbody>
</table>

MS: mineralizing surface. *vs. wt (10w) P < 0.05, **P < 0.01. # vs. wt (4m) #P < 0.05, ##P < 0.01.

The data at 10 weeks of age are derived from ref. 31.

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can concomitantly be present in the same cell [23]; progression to secondary necrosis could ensue in apoptotic osteocytes that are protected in the bone from phagocytosis [24], [25]; molecules that can elicit necrosis-induced immune signaling or inflammation are released from the plasma membrane during necrosis to actively recruit a defensive or reparative response in regions that have sustained damage [26]; and osteoclasts are highly regulated to respond appropriately to inflammatory changes in their microenvironment [27]. Thus, it is necessary to reconsider whether bone resorption after osteocyte death is due to osteocyte necrosis or to the function of osteocytes itself; however, the anatomic sites of osteocytes, which are embedded in bone matrix, and lack an appropriate in vitro system or animal model, have made clarification of osteocyte functions difficult. Recently, the involvement of osteocytes in osteoclastogenesis and bone resorption was reported using conditional knockout mice of β-catenin by Dmp1-Cre, which resulted in enhanced bone resorption, and conditional knockout mice of receptor activator of NF-κB ligand (RANKL) by Dmp1-Cre, which resulted in osteopetrosis [28], [29], [30].

We generated osteoblast-specific BCL2 transgenic mice. Overexpression of BCL2 inhibited osteoblast maturation, and the osteocytes, in which the transgene was down-regulated, gradually died by apoptosis during bone development and terminal deoxynucleotidyl transferase-mediated dUTP nick end-labeling (TUNEL)-positive lacunae accumulated in the bone [31]. As the level of transgene expression in osteoblasts was low and TUNEL-positive lacunae were most accumulated at 4 months of age, we considered that BCL2 transgenic mice at 4 months of age might be an appropriate model for the evaluation of osteocyte functions. To pursue the functions of the osteocyte network at physiological and unloaded conditions, therefore, we investigated how destruction of the osteocyte network had influenced osteoblasts, osteoclasts, and bone mass under physiological and unloaded conditions using BCL2 transgenic mice at 4 months of age.

Materials and Methods

Ethics Statement

Prior to the study, all experiments were reviewed and approved by the Animal Care and Use Committee of Nagasaki University Graduate School of Biomedical Sciences. (Permit Number: 0906170767-4).

Animal Study

Two BCL2 transgenic mouse lines were established as previously described [31], and BCL2 transgenic mouse line with low expression was used in this paper. The serum level of osteocalcin was examined using BTI Mouse Osteocalcin ELA kit (Biomedical Technologies Inc., Stoughton, MA), and the serum level of tartrate-resistant acid phosphatase 5b (TRAP5b) was examined using the mouse TRAP Assay (Immunodiagnostic Systems, Boldon, UK). At 6 weeks or 4 months of age, wild-type mice and tg(L) were each divided into control and unloaded groups.

Unloading of the hind limbs was performed by tail suspension for 3–14 days in the unloaded group, while the mice in the control group were normally loaded, as previously described [32]. After tail suspension of the mice in the unloaded group, the mice in the control and unloaded groups were immediately anesthetized and sacrificed.

Cell Culture Experiments

Primary osteoblasts were isolated from newborn calvaria by sequential digestion with 0.1% collagenase A and 0.2% dispase. Osteoblastic cells from the third to fifth fraction were pooled and used for osteoblast differentiation and osteoclastogenesis. To examine osteoblast differentiation, staining for alkaline phosphatase (ALP) activity and mineralization was performed as previously described [31]. The co-culture of primary osteoblasts and bone marrow-derived monocyte/macrophage lineage cells (BMMs) was performed as previously described [33].

Micro-CT Analysis

Dissected femurs at 6 weeks, 10 weeks, 4 months, or 6 months of age were analyzed by a micro-CT system (μCT-20; Scanco Medical, Bruttisellen, Switzerland). Data from scanned slices were used for three-dimensional analysis to calculate femoral morphometric parameters. Trabecular bone parameters were measured using the distal femoral metaphysis. Approximately 2.4 mm (0.5 mm from the growth plate) was cranio-caudally scanned and 200 slices were taken at 12 μm intervals. Cortical thickness was measured at the mid-diaphyses of femurs. We used a threshold value of 275 to binarize the spongiosa and cortex in wild-type and BCL2 transgenic mice at all ages.

Histological Analysis

For histological analyses of the long bones, mice were sacrificed and fixed in 4% paraformaldehyde/0.01M phosphate-buffered saline (PBS), and the long bones were decalcified in 10% EDTA (pH 7.4) and embedded in paraffin. For Goland-Yoshiki method to detect osteoid, the long bones were refixed with Cyanuric Chloride before decalcification. Sections (3–7 μm thick) were stained with hematoxylin and eosin (H–E), stained for TRAP activity, or subjected to immunohistochemistry using monoclonal anti-human...
BCL2 antibody (Abcam, Cambridge, UK) or anti-Sost antibody (R&D, Minneapolis, MN). TUNEL staining was performed using the ApopTag Peroxidase In Situ Apoptosis Detection Kit S7100 (Chemicon, Billerica, MA) according to the manufacturer’s instructions. For assessment of dynamic histomorphometric indices, mice were injected with calcein at 10 d and 2 d before sacrifice at a dose of 0.16 mg/10 g body weight. Bone histomorphometric analyses were performed using femurs as previously described [34].
Figure 2. Transgene expression, osteocyte number, and the frequencies of TUNEL-positive lacunae. (A, B) Real-time RT-PCR analyses of the expression of transgene (A) and Col1a1 (B). The expression levels of the transgene and Col1a1 were examined using RNA that had been extracted from the whole femurs at 2 weeks of age [wt, 8 mice; tg, 7 mice] and osteoblast-enriched samples at 5–6 weeks [wt, 13 mice; tg, 11 mice], 10 weeks [wt, 8 mice; tg, 5 mice], and 4 [wt, 3 mice; tg, 9 mice] and 6 [wt, 5 mice; tg, 8 mice] months of age. The values of wild-type mice were defined as 1, and
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Real-time RT-PCR and Western Blot Analyses

Muscle, connective tissue, and periosseum were removed from femurs and tibiae, and the bones were cut at the metaphyses. After hematopoietic cells in the diaphyses of femurs and tibiae were flushed out with PBS, osteoblast-enriched cells were collected using a micro-intertooth brush (Kobayashi Pharmaceutical Co. Ltd., Osaka, Japan). The remaining bone was used as a source of osteocyte-enriched cells. At the beginning of each experiment, nearly complete removal of osteoblasts from the endosteum by the micro-intertooth brush was confirmed using a scanning electron microscope (Miniscope TM-1000; Hitachi) (Fig. S1). Total RNA was extracted using ISOGEN (Wako, Osaka, Japan), and real-time RT-PCR was performed using the following primers as previously described [35].

Mouse Bcl2 and human BCL2, 5′-GAGGATGTGGG-GCTTCTTTG-3′ and 5′-CTGATGGCCTCATGGAACAG-3′; human BCL2 5′-CCCGAGCTTCCGAGATGT-3′ and 5′-GTTTACGCTTCCACACAC-3′; Col1a1, 5′-CTCTGGAATCTGCAATGCT-3′ and 5′-CACGCTGCTTTCACAT-3′; and 5′-GAGGTACCAGATGGGACT-3′ and 5′-CAAGGTAGC-3′.

Statistical Analysis

Statistical analyses were performed by Student’s t-test using EKUSU-Toueki 2010 (Social Survey Research Information Co., Ltd., Tokyo, Japan). P<0.05 was considered significant.

Results

The Effects of BCL2 Transgene in Osteoblast Differentiation and Osteoclastogenesis

We established two lines of human BCL2 transgenic mice under the control of mouse 2.3 kb Colla1 promoter with different expression levels, and both lines showed osteocyte apoptosis probably due to the reduced osteocyte processes [31]. The transgenic line with low expression of BCL2 was used to analyze the effect of osteocyte death, because the functions of osteoblasts in these mice were less affected by the transgenic line with low expression [31] (Fig. 1B–E). Furthermore, we previously showed that the bone formation rate and osteoid thickness were reduced in the transgenic line with low expression but not the transgenic line with high expression between the co-culture of primary osteoblasts from the transgenic line with low expression and wild-type bone marrow cells [31]. However, the bone formation rate and osteoid thickness were increased in the transgenic line with high expression compared with those from wild-type mice (Fig. S2) [31]. Moreover, the bone formation rate and osteoid thickness were reduced with low BCL2 expression but not the transgenic line with low expression [31].

The transgenic expression was dependent on age; it was high in transgenic mice at 2 weeks of age, but it gradually fell during growth and was low in mice at 4–6 months of age (Fig. 2A). The change in the expression level of the transgenic line during aging was similar to that of Colla1 in wild-type mice (Fig. 2B). Further, we previously showed that retroviral introduction of BCL2 into wild-type mice had no effect on osteoclastogenesis in the co-culture with wild-type bone marrow cells [31].

Osteocyte Apoptosis in the Transgenic Line with Low BCL2 Expression

The transgenic expression was dependent on age; it was high in mice at 2 weeks of age, but it gradually fell during growth and was low in mice at 4–6 months of age (Fig. 2A). The change in the expression level of the transgenic line during aging was similar to that of Colla1 in wild-type mice (Fig. 2B). In immunohistochemical analysis using anti-human BCL2 antibody, which reacts on human BCL2 but not mouse Bcl2, the transgene expression
was strongly detected in osteoblasts and mildly in most of osteocytes at 2 weeks of age (Fig. 2F–G). At 6 weeks of age, the transgene expression was also strongly detected in osteoblasts, but its expression in osteocytes was restricted to immature osteocytes, which were located near the surface of cortical bone (Fig. 2G, H). At 4 months of age, the transgene expression was still clearly detected in osteoblasts but undetectable in osteocytes (Fig. 2I, J). The numbers of osteocytes were increased in BCL2 transgenic mice compared with wild-type mice in both cortical and trabecular bone until 10 weeks of age probably due to the increase of osteoblast density, whereas they were reduced in BCL2 transgenic mice compared with wild-type mice at 6 months of age (Fig. 2L and M). After the death of osteocytes, the lacunae contained only cellular debris but TUNEL reactivity was retained in the lacunae (Fig. 3), because the debris of dead osteocytes cannot be eliminated until the surrounding bone is resorbed [22], [36]. At 6–8 months of age, the cortical bone in BCL2 transgenic mice was partly remodeled and the remodeled bone contained osteocytes with a normal appearance, probably due to the reduction in transgene expression (Fig. 3K–P).

Bone canalicular staining showed that the severity in the disturbance of osteocyte network was different depending on the age in BCL2 transgenic mice. Osteocyte network was disturbed at the center but not at the periphery of cortical bone at 10 weeks of age, it was disturbed in the whole area of cortical bone at 4 months of age, and the disturbance was restricted to the inner half of cortical bone at 8 months of age (Figures S3, S4, S5). The reduction in the number of canaliculi was observed in trabecular bone as well as cortical bone of BCL2 transgenic mice until 4 months of age (Figures S3, S4, S5, S6) [31].

We also examined the frequency of TUNEL-positive lacunae in trabecular bone. About 1% of lacunae in the trabecular bone of femurs were TUNEL-positive in wild-type mice from 6 weeks to 8 months of age, whereas the corresponding percentage in BCL2 transgenic mice was about 20% at 5–6 weeks of age, about 50% at 10 weeks of age, about 75% at 4 months of age, and about 50% at 8 months of age (Figs. 2l and 3). After the death of osteocytes, the lacunae contained only cellular debris but TUNEL reactivity was retained in the lacunae (Fig. 3), because the debris of dead osteocytes cannot be eliminated until the surrounding bone is resorbed [22], [36]. At 6–8 months of age, the cortical bone in BCL2 transgenic mice was partly remodeled and the remodeled bone contained osteocytes with a normal appearance, probably due to the reduction in transgene expression (Fig. 3K–P).

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Next, we examined bone resorption in BCL2 transgenic mice by counting multinucleated TRAP-positive cells at 2, 5–6, and 10 weeks and 4 months of age, and by measuring the serum level of TRAP5b, which is a serum marker of bone resorption, at 4 months of age (Fig. 6). The number of osteoclasts in the periosteum was similar between wild-type mice and BCL2 transgenic mice at all ages examined. In the endosteum, the number of osteoclasts in BCL2 transgenic mice was increased compared with in wild-type mice at 2 weeks of age, whereas the number of osteoclasts in the endosteum in BCL2 transgenic mice was lower than in wild-type mice at 5–6 weeks, 10 weeks and 4 months of age (Fig. 6A–E). In accordance with these findings, bone marrow volume was reduced in BCL2 transgenic mice compared with wild-type mice at 10 weeks of age (Fig. 4B). Further, the serum level of TRAP5b was lower in BCL2 transgenic mice than in wild-type mice at 4 months of age (Fig. 6F). These findings suggest that cortical thickness increased in parallel with the reduction in the numbers of osteocytes and the accumulation of TUNEL-positive lacunae.
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A

10w
4m
6m

B

Cortical thickness

Total tissue volume

Bone marrow volume

C

D

E

MAR

F
dLS/BS

G

BFR/BS

H

osteocalcin

ng/ml

wt
tg
Trabecular Bone of BCL2 Transgenic Mice Was Increased Due to Enhanced Bone Formation through Augmented Osteoblast Function at 4 Months of Age

On micro-CT analysis, trabecular bone volume, trabecular number, and trabecular thickness were increased in BCL2 transgenic mice (control group) compared with wild-type mice (control group) at 4 months of age (Figs. 7A, B), although these parameters in BCL2 transgenic mice were similar to those in wild-type mice at 10 weeks of age [31]. Bone histomorphometric analysis of trabecular bone showed that the increase in bone volume was due to enhanced bone formation through augmented osteoblast function, because osteoblast number, osteoclast number, and eroded surface were similar between wild-type mice and BCL2 transgenic mice, but the parameters for bone formation, including osteoid thickness, mineral apposition rate, double-labeled surface, and bone formation rate, were increased in BCL2 transgenic mice compared with wild-type mice, indicating that the trabecular bone of BCL2 transgenic mice was increased due to enhanced bone formation through augmented osteoblast function at 4 months of age (Table 1). Osteoid was apparently increased in trabecular bone of BCL2 transgenic mice compared with wild-type mice at 4 months of age (Fig. 5E-I). However, osteoblast function was mildly impaired in BCL2 transgenic mice at 10 weeks of age as shown by the increased osteoblast density but normal level of bone formation (Table 1) [31].

No Reduction in Bone Mass at the Unloaded Condition in BCL2 Transgenic Mice at 4 Months of Age

To further investigate the effect of the accumulation of TUNEL-positive lacunae, we performed tail suspension to generate an unloaded condition in the hind limbs using BCL2 transgenic mice at 4 months of age and analyzed the femurs by micro-CT (Figs. 7A, B). Bone volume and trabecular thickness were reduced in the femurs of wild-type mice after unloading, whereas these parameters were unchanged in the femurs of BCL2 transgenic mice after unloading (Fig. 7B). Bone histomorphometric analysis showed that the reduction in bone volume after unloading in wild-type mice at 4 months of age was mainly due to enhanced osteoclastogenesis, as indicated by increases in the osteoclast number and eroded surface, and partly due to reduced osteoblast function, as indicated by the decrease in osteoid thickness (Fig. 7C). In contrast, the parameters of both bone formation and bone resorption were unchanged in BCL2 transgenic mice at 4 months of age after unloading. In accordance with the bone histomorphometric data, the expression of Ctsk was increased in the unloaded group compared with the control group in wild-type mice but not in BCL2 transgenic mice, indicating that osteoclastogenesis was enhanced at unloading in wild-type mice but not in BCL2 transgenic mice (Fig. 7D).

Upr egulation of Rankl Expression in Osteoblasts after Unloading in Wild-type Mice but not in BCL2 Transgenic Mice

We prepared osteoblast-enriched samples and osteocyte-enriched samples as described in the Materials and methods. We first compared the expression of Dmp1, Sost, Phex, Fig23, and Mepe, which are highly expressed in osteocytes [37], between the osteoblast-enriched samples and osteocyte-enriched samples prepared from wild-type mice at 4 months of age (Fig. 8A). Sost expression was specifically detected in the osteocyte fractions, Mepe expression was significantly high in the osteocyte fractions, and the levels of Dmp1 and Fig23 expression were marginally high in the osteocyte fractions compared with the osteoblast fractions, while Phex expression was similar in the osteoblast and osteocyte fractions. Although we previously reported that Dmp1 is expressed in osteocytes [38], Dmp1 expression was also detected in the osteoblast fractions, because Dmp1 was detected in osteoblasts, which are going to be embedded in the bone matrix, as well as osteocytes by immunohistochemistry (unpublished data). The expressions of these genes in individual osteocyte, which remained to be alive in BCL2 transgenic mice, were examined using the osteocyte fractions. These expressions in the osteocyte fractions of BCL2 transgenic mice were comparable to those in wild-type mice at 4 months of age (Fig. 8B). We also compared the expression of the genes, which were dominantly expressed in osteoblasts, between osteoblast-enriched samples and osteocyte-enriched samples to examine their purity. Keratin8 was specifically detected in osteoblast-enriched samples as previously reported [39]. The expressions of Runx2, Osterix, Colla1, and osteocalcin were also significantly higher in osteoblast-enriched samples than osteocyte enriched samples (Fig. 8C).

After unloading, Rankl expression in osteoblasts was upregulated in wild-type mice but not in BCL2 transgenic mice at 4 months of age (Fig. 8D). Further, the Rankl expression was significantly lower in BCL2 transgenic mice in the unloaded condition compared with that in wild-type mice in the control condition (Fig. 8D). The expression of Osteoprotegerin (Opg) in osteoblasts was not affected by unloading in either wild-type mice or BCL2 transgenic mice at 4 months of age (Fig. 8D). As Rankl is expressed in osteocytes as well as osteoblasts [40], we compared the expression levels of Rankl and Opg between osteoblast and osteocyte fractions from wild-type mice at 4 months of age (Fig. 8E). Both Rankl and Opg expressions were high in the osteocyte fractions compared with the osteoblast fractions. However, unloading had no significant effect on the expression of Rankl and Opg in the osteocyte fractions of both wild-type and BCL2 transgenic mice at 4 months of age (Fig. 8F).

Wnt antagonists play an important role in bone formation [19], [41], [42]. Thus, we also examined the expression of the genes whose proteins antagonize Wnt signaling in osteocyte fractions (Fig. 8G). Dkk1 and sFRP1 expression was high and sFRP5 expression was low in BCL2 transgenic mice compared with wild-type mice in the control groups. Dkk1 was down-

Figure 4. Micro-CT and bone histomorphometric analyses of cortical bone (A, B) Micro-CT analysis. Micro-CT images of mid-diaphyses of femurs (A) and cortical thickness, total tissue volume, and bone marrow volume (B) in male wild-type mice (wt) and BCL2 transgenic mice (tg) at 10 weeks [wt, 17 mice; tg, 7 mice], 4 months [wt, 14 mice; tg, 10 mice], and 6 months [wt, 8 mice; tg, 6 mice] of age. Data are presented as the mean ± S.D. (C–G) Dynamic histomorphometric analysis of cortical bone at 4 months of age. C and D, Cross-sections from the mid-diaphyses of femurs of male wild-type mice (C) and BCL2 transgenic mice (D), in which calcein had been injected twice. Scale bars = 0.5 mm. E-G, Mineral apposition rate (MAR) (E), double-labeled surface (dLS/Bs) (F), and bone formation rate (BFR/BS) (G) in the endosteum (En) and periosteum (Pe) at the mid-diaphyses of femurs of wild-type mice (w, blue) and BCL2 transgenic mice (t, red). Data are the mean ± S.D. of 10 mice. *, vs. wild-type mice. **, $P<0.05; $\$\$\$ P<0.01; $\$\$\$\$ P<0.001. (H) Comparison of the serum osteocalcin level in male four wild-type mice and five BCL2 transgenic mice at 4 months of age. Data are presented as the mean ± S.D. vs. wild-type mice. **P<0.01.

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regulated after unloading in wild-type mice but not in BCL2 transgenic mice, and sFRP5 was down-regulated after unloading in both wild-type and BCL2 transgenic mice. Unloading had no significant effect on the expression of Sost, sFRP1, sFRP2, and sFRP4 in both wild-type and BCL2 transgenic mice at 4 months of age.

Increase of Sost-positive Osteocytes in the Restricted Region of Tibiae after Unloading in Wild-type Mice but not in BCL2 Transgenic Mice

The reduction in bone formation in response to unloading is abrogated in Sost−/− mice, and Sost mRNA but not Sost-positive osteocytes is increased after unloading [20], [43]. Further, the down-regulation of Sost after loading is dependent on the site in tibiae [44]. Therefore, we examined the expression of Sost on the anterior and posterior sides of cortical bone at the metaphysis and mid-diaphysis of tibiae by immunohistochemistry at 4 months of age (Fig. 9A–D). As the lacunae, which were TUNEL-positive and contained cellular debris of dead osteocytes, were non-specifically reacted with anti-Sost antibody in BCL2 transgenic mice, we counted only the lacunae containing the cells with a nucleus in both wild-type and BCL2 transgenic mice at 4 months of age. Sost protein was distributed through the canaliculi throughout bone in wild-type mice.

Figure 5. Increase of osteoid in BCL2 transgenic mice at 4 months of age. Cortical bone (A–D) and trabecular bone (E–H) of femurs in wild-type (A, C, E, G) and BCL2 transgenic (B, D, F, H) mice at 4 months of age. The boxed regions in A, B, E, and F are magnified in C, D, G, and H, respectively. Osteoid was visualized by Gomori-Yoshiki method. Scale bars = 50 μm (A, B, E, F); 10 μm (C, D, G, H). (I) Osteoid thickness. Data are presented as the mean ± S.D. *vs. wild-type mice. *P<0.05, **P<0.01. wt, 4 mice; tg, 5 mice.

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Figure 6. Bone resorption in BCL2 transgenic mice. (A–E) Number of osteoclasts in cortical bone. A–D, Sections of femurs stained with TRAP in male wild-type mice (A, B) and BCL2 transgenic mice (C, D) at 4 months of age. Boxed regions in A and C are magnified in B and D, respectively. Arrows show TRAP-positive cells. Sections were counterstained with hematoxylin. Scale bars = 0.5 mm (A, C); 50 μm (B, D). E, Number of TRAP-positive cells in the endosteum (En) and periosteum (Pe) of femurs of male wild-type mice (blue) and BCL2 transgenic mice (red) at 2 weeks [wt, 4 mice; tg, 5 mice], 5–6 weeks [wt, 3 mice; tg, 4 mice], 10 weeks [wt, 6 mice; tg, 5 mice], and 4 months [wt, 5 mice; tg, 5 mice] of age. Data are presented as the mean ± S.D. (F) Comparison of the serum TRAP5b level in male three wild-type mice and five BCL2 transgenic mice at 4 months of age. Data are presented as the mean ± S.D. *vs. wild-type mice. *P<0.05.

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Figure 7. Micro-CT, bone histomorphometry, and real-time RT-PCR analyses after unloading at 4 months of age. (A, B) Micro-CT analysis. Tail suspension was performed for 2 weeks using male wild-type mice [control group, 13 mice; unloaded group, 9 mice] and BCL2 transgenic mice [control group, 8 mice; unloaded group, 8 mice] at 4 months of age. A, Micro-CT images of femurs. Scale bars = 0.5 mm. B, Trabecular bone volume (BV/TV), trabecular number (Tb.N), and trabecular thickness (Tb.Th) were evaluated by micro-CT. C, Bone histomorphometrical analysis of trabecular bone. The trabecular bone volume (BV/TV), osteoid thickness (O.Th), number of osteoblasts (N.Ob/B.Pm), number of osteoclasts (N.Oc/B.Pm), eroded surface (ES/BS), mineral apposition rate (MAR), double-labeled surface (dLS/BS), and bone formation rate (BFR/BS) were measured on

(A, B) Micro-CT analysis. Tail suspension was performed for 2 weeks using male wild-type mice [control group, 13 mice; unloaded group, 9 mice] and BCL2 transgenic mice [control group, 8 mice; unloaded group, 8 mice] at 4 months of age. A, Micro-CT images of femurs. Scale bars = 0.5 mm. B, Trabecular bone volume (BV/TV), trabecular number (Tb.N), and trabecular thickness (Tb.Th) were evaluated by micro-CT. C, Bone histomorphometrical analysis of trabecular bone. The trabecular bone volume (BV/TV), osteoid thickness (O.Th), number of osteoblasts (N.Ob/B.Pm), number of osteoclasts (N.Oc/B.Pm), eroded surface (ES/BS), mineral apposition rate (MAR), double-labeled surface (dLS/BS), and bone formation rate (BFR/BS) were measured on
distal femoral metaphysis in wild-type mice [control group, 8 mice; unloaded group, 11 mice] and BCL2 transgenic mice [control group, 8 mice; unloaded group, 6 mice] at 4 months of age. (D) Ctsk expression. Tail suspension was performed for 3 days and Ctsk expression was examined by real-time RT-PCR analysis using osteoblast-enriched samples from wild-type mice [control group, 9 mice; unloaded group, 11 mice] and BCL2 transgenic mice [control group, 6 mice; unloaded group, 5 mice] at 4 months of age. The values of the control groups were defined as 1, and relative levels are shown. In B–D, data are presented as the mean ± S.D. *vs. control. *, P<0.05; **, P<0.01.

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mice but not in BCL2 transgenic mice probably due to the reduction in the number of osteocyte processes and the accumulation of dead osteocytes in BCL2 transgenic mice (Fig. 9G–J).

As the distribution of Sost protein was interrupted in BCL2 transgenic mice at 4 months of age, we compared the protein levels of β-catenin in the osteoblast fractions between wild-type and BCL2 transgenic mice at 4 months of age by Western blot analysis. β-catenin protein was increased in BCL2 transgenic mice compared with wild-type mice, suggesting that Wnt signaling was enhanced in osteoblasts of BCL2 transgenic mice at 4 months of age (Fig. 9O).

Reduction in Bone Mass in the Unloaded Condition in BCL2 Transgenic Mice at 6 Weeks of Age

We analyzed the characteristics of osteocytes and the responsiveness to unloading in BCL2 transgenic mice at 6 weeks of age, when the number of osteocytes was increased but TUNEL-positive lacunae were not accumulated (Figs. 2L, 2M, 3B, 3D). On real-time RT-PCR using RNA from osteocyte-enriched samples at 6 weeks of age, Dmp1 expression was increased, Fgfr3 expression was decreased, and Sost, Phex, and Mepe were similarly expressed in BCL2 transgenic mice compared with wild-type mice (Fig. 10A). Serum levels of calcium and phosphate were similar between wild-type mice and BCL2 transgenic mice at 6 weeks of age (calcium: wild-type mice 8.58 ± 0.43 mg/dl, BCL2 transgenic mice 8.66 ± 0.49 mg/dl; phosphate: wild-type mice 11.85 ± 0.79 mg/dl, BCL2 transgenic mice 11.24 ± 0.9 mg/dl, n = 5–8). In the unloaded condition, bone volume and trabecular thickness were reduced in the femurs of both wild-type mice and BCL2 transgenic mice at a similar degree (Fig. 10B, C). After unloading, Rankl expression in osteoblasts was marginally increased in both wild-type and BCL2 transgenic mice with less response in the latter at 6 weeks of age. Opg expression in osteoblasts was similar between wild-type mice and BCL2 transgenic mice, and was not affected by unloading (Fig. 10D). The Rankl expression in osteocytes was reduced after unloading for 3 days in both wild-type and BCL2 transgenic mice, while unloading had no effect on Opg expression in osteocytes (Fig. 10E). Sost expression in osteocytes was upregulated after unloading significantly in wild-type and marginally in BCL2 transgenic mice at 6 weeks of age (Fig. 10E).

Discussion

Unexpectedly, overexpression of BCL2 in osteoblasts led to the reduction in the number of osteocyte processes, which seemed to be one of the causes of osteocyte apoptosis in BCL2 transgenic mice [31]. Thus, we examined the effects of osteocyte apoptosis and the reductions in the numbers of osteocytes and their processes on bone formation and resorption using BCL2 transgenic mice at 4 months of age, when TUNEL-positive lacunae were most accumulated, the number of osteocytes was reduced, and osteocyte network was most severely disturbed, but the expression of transgene was reduced, to minimize the effects of the transgene on osteoblasts and osteocytes. We found that osteoblast function was enhanced and osteoclastogenesis was inhibited in BCL2 transgenic mice at 4 months of age. These findings suggest that disruption of the osteocyte network might be related to the enhancement of osteoblast function and the suppression of osteoclastogenesis. In the unloaded condition, osteoblast function was inhibited and osteoclastogenesis was enhanced, leading to bone loss in wild-type mice, whereas osteoblast function and osteoclastogenesis were unaffected, leading to the maintenance of bone mass in BCL2 transgenic mice at 4 months of age. Further, Sost expression in osteocytes and Rankl expression in osteoblasts were upregulated in wild-type mice but not in BCL2 transgenic mice in the unloaded condition. Thus, we propose that the osteocyte network inhibits osteoblast function and stimulates osteoclastogenesis in the physiological condition, and that osteocytes further augment the inhibitory effects on osteoblast function through the induction of Sost in osteocytes and the stimulatory effect on osteoclastogenesis through the induction of Rankl in osteoblasts in the unloaded condition (Fig. 11).

In contrast to the general consensus that osteocyte death triggers bone remodeling by enhancing bone resorption [8], [21], [22], osteoclastogenesis was enhanced in parallel with an increase in osteocyte density, and osteoclastogenesis was reduced in parallel with the accumulation of dead osteocytes; therefore, our findings suggest that osteocytes stimulate osteoclastogenesis in the physiological condition. The enhanced bone resorption after osteocyte death in previous observations may have been caused by the stimulation of osteoclastogenesis through an inflammatory reaction in the microenvironment, which would be elicited by the elimination of inflammation-inducible molecules from lacunae through canaliculi when necrotic aspects appear in the cell death of osteocytes that are not phagocytosed [26]. In BCL2 transgenic mice, however, the reduction in the number of canaliculi and the...
gradual accumulation of TUNEL-positive lacunae may have limited the release of the inflammation-inducible molecules from lacunae through canaliculi after secondary necrosis, as shown in the immunostaining of Sost (Fig. 9H, J).

We pursued the mechanism of the enhanced bone resorption in the unloaded condition. Rankl and Opg were highly expressed in osteocyte fractions. Although the upregulation of Rankl expression in osteocytes at unloaded condition was reported [29], both Rankl and Opg expressions in osteocytes were unaffected by unloading. In contrast, Rankl but not Opg expression was upregulated in osteoblast fractions by unloading in wild-type mice but not in BCL2 transgenic mice. These findings suggest that the osteocyte network senses unloading and transfers unknown signals to osteoblasts to induce Rankl expression in osteoblasts. We found that pyruvate dehydrogenase kinase 4 (Pdk4), which is a negative regulator of pyruvate dehydrogenase complex, is upregulated at unloading and is one of the molecules that induce Rankl expression in osteoblasts at the unloaded condition [33].

As soluble factors released from MLO-Y4 regulate osteoclastogenesis [45], [46], osteocytes may release soluble factors to upregulate the expression of Pdk4 and Rankl in osteoblasts. As our findings suggest that the osteocyte network stimulates osteoclastogenesis in the physiological condition, Opg, which was highly expressed in osteocytes, may be trapped by Rankl on the surface of osteocytes. The conditional deletion of Rankl using Dmp1 promoter-Cre transgenic mice has been shown to result in the reduction in bone resorption and increase in bone mass [30], [47]. It may indicate that Opg, which was highly expressed in osteocytes, is secreted to the bone surface through canaliculi in the absence of Rankl on the surface of osteocytes.

The function of osteocytes in bone formation in the physiological condition has been controversial. Acute death of osteocytes by diphtheria toxin severely reduces bone formation [8], while osteocyte density is negatively correlated with bone formation [10], [11]. As both empty lacunar density and peristomal bone apposition increase with age, a link between the two phenomena has been suggested [48], [49], [50], [51], [52]. Furthermore, mice carrying a targeted mutation of CoIα1, encoding a collagenase-resistant form of type I collagen, showed osteocyte apoptosis and increased bone formation [53], and it has been shown that osteocytes secrete Sost, which is a potent antagonist of Wnt, and inhibits bone formation [54], [55], [56], [57]; therefore, there were contrasting observations that osteocytes can enhance or inhibit bone formation. Bone formation in both trabecular and cortical bones was enhanced in BCL2 transgenic mice at 4 months of age when the transgene expression was low, TUNEL-positive lacunae were most accumulated, osteocyte number was reduced, and osteocyte network was disturbed in the whole area of cortical bone. Although we cannot exclude the possibility that the expression of the transgene at the low level promoted bone formation at 4 months of age, this seemed to be unlikely because overexpression of BCL2 impaired osteoblast differentiation in a manner dependent on the expression levels of the transgene in vivo and in vitro (Fig. 1A) [31], osteoblast density was similar between BCL2 transgenic mice and wild-type mice at 4 months of age, and cortical bone in BCL2 transgenic mice was not further increased at 6 months of age irrespective of the similar level of transgene expression at 4 and 6 months of age. The disturbed osteocyte network was gradually restored after 4 months of age, probably because the level of the transgene expression was not sufficient to reduce the number of osteocyte processes. These seemed to be the reasons why the enhanced bone formation was observed only at 4 months of age. Thus, our findings suggest that the reductions in the numbers of osteocytes and their processes and the accumulation of TUNEL-positive lacunae were followed by the activation of osteoblast function, leading to an increase in bone formation. As the distribution of Sost protein was interrupted in osteocytes and β-catenin protein was increased in osteoblasts in BCL2 transgenic mice at 4 months of age, the activation of Wnt signaling in osteoblasts by the reduction of disseminated Sost protein seems to be one of the causes for the increase in bone formation in BCL2 transgenic mice at 4 months of age. In mice with osteocyte ablation by diphtheria toxin, the suppression of bone formation seemed to be due to maturational inhibition of osteoblasts, which was shown by the reduction in osteocalcin expression [8], and maturational inhibition may have been caused by a necrosis-induced inflammatory reaction.

The frequencies of TUNEL-positive lacunae in the trabecular bone of BCL2 transgenic mice were less than those in the cortical bone, probably because trabecular bone is more extensively remodeled than cortical bone and the dead osteocytes in the trabecular bone are rapidly replaced with live osteocytes. Irrespective of the relatively low frequency of TUNEL-positive lacunae, however, the increase of bone formation and unresponsive to unloading were observed in the trabecular bone at 4 months of age. Therefore, the reduction in the number of osteocyte processes in addition to the reduction in the number of osteocytes may be sufficient for the disturbance of osteocyte network in trabecular bone. The number of osteoclasts was reduced in the cortical bone but not in the trabecular bone of BCL2 transgenic mice at 4 months of age. It may indicate that osteoclastogenesis in cortical bone is more dependent on the osteocyte network than that in trabecular bone, because the number of osteoclasts was already reduced in the cortical bone in BCL2 transgenic mice at 5–6
Regulation of Bone Mass by the Osteocyte Network

A

B

C

D

E
weeks of age, when the frequency of TUNEL-positive lacunae was about 20%, an equivalent value detected in the trabecular bone at 4 months of age. The augmented function of the osteocyte network by unloading may be required for the enhancement of osteoclastogenesis by the osteocyte network in trabecular bone.

Our model also explains why exercise increases bone mass, which has been indicated by many clinical studies [38], because osteocytes decrease the inhibitory effects on bone mass by reducing the inhibitory effect on osteoblast function and the stimulatory effect on osteoclastogenesis in the loaded condition (physiological condition) compared with the unloaded condition (Fig. 11). Our findings suggest that the osteocyte network is a mechanosensor and mechanotransduction system that reduces its negative effects on bone mass by responding to mechanical stress, explaining how bone mass increases with exercise and decreases with bed rest. Our BCL2 transgenic mice was also a useful tool to search the molecular targets of disuse osteoporosis, because we found that Pdk4 is responsible for bone loss at unloading by comparing the genes induced in wild-type mice and BCL2 transgenic mice at 4 months of age in the unloaded condition [33]. Our findings will provide a basis for understanding the osteocyte network, which plays an important role in the regulation of bone mass.

Supporting Information

Figure S1 SEM images of endosteum. SEM images of the endosteum before (A, C) and after (B, D) blushing with a microintertooth brush. The boxed regions in A and B are magnified in C and D, respectively. Scale bars = 0.5 mm (A, B); 100 μm (C, D).

Figure S2 Decrease of osteoid in BCL2 transgenic mice with high expression at 10 weeks of age. Cortical bone (A–D) and trabecular bone (E–H) of femurs in wild-type (A, C, E, G) and BCL2 transgenic (B, D, F, H) mice with high expression at 10 weeks of age. The boxed regions in A, B, E, and F are magnified in C, D, G, and H, respectively. Osteoid was visualized by Goland-Yoshilki method. Scale bars = 50 μm (A, B, E, F); 10 μm (C, D, G, H). (I) Osteoid thickness. Data are presented as the mean ± S.D. *vs. wild-type mice. **P<0.01, ***P<0.001. wt, 5 mice; tg, 4 mice.

Figure S3 Canalicular staining (1). Canalicular staining of femurs at 10 weeks (A, B) and 8 months (E, F) of age and tibiae at 4 months of age (C, D) from wild-type (A, C, E, G) and BCL2 transgenic (B, D, F, H) mice with high expression at 10 weeks of age. The boxed anteroproximal regions indicated by “a” in A–F in supplementary figure 3 were magnified in A–F, respectively, in this figure. Scale bars = 100 μm.

Figure S4 Canalicular staining (2). The boxed anteroproximal regions indicated by “a” in A–F in supplementary figure 3 were magnified in A–F, respectively, in this figure. Scale bars = 100 μm.

Figure S5 Canalicular staining (3). The boxed regions in posterior mid-shafts indicated by “b” in A–F in supplementary figure 3 were magnified in A–F, respectively, in this figure. Scale bars = 100 μm.

Figure S6 Canalicular staining of trabecular bone. Trabecular bones in wild-type and BCL2 transgenic mice at 4 months of age are shown. Scale bars = 20 μm.

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Figure 10. Real-time RT-PCR and micro-CT analyses at 6 weeks of age. (A) Real-time RT-PCR analysis of osteocyte marker genes. RNA was extracted from osteocyte-enriched samples of control groups of wild-type mice and BCL2 transgenic mice at 6 weeks of age. The values of wild-type mice were defined as 1, and relative levels are shown. Data are presented as the mean ± S.D. of 3 mice. *vs. control. *P<0.05, **P<0.01, ***P<0.001. (B, C) Micro-CT analysis of femurs. Tail suspension was performed for 1 week using male wild-type mice [control group, 10 mice; unloaded group, 8 mice] and BCL2 transgenic mice [control group, 9 mice; unloaded group, 6 mice] at 6 weeks of age. B. Micro-CT images. Scale bars = 0.5 mm. C. Trabecular bone volume (BV/TV), trabecular number (Tb.N), and trabecular thickness (Tb.Th) were evaluated by micro-CT. Data are presented as the mean ± S.D. *vs. control. *P<0.05, **P<0.01. (D, E) Real-time RT-PCR analysis after unloading. Tail suspension was performed for 3 days or 7 days using male wild-type mice [control group, 9 mice; unloaded group, 6 mice] at 6 weeks of age, and RNA was extracted from osteoblast-enriched samples (D) and osteocyte-enriched samples (E) of the tibiae and femurs. The values of the control group of wild-type mice were defined as 1, and relative levels are shown. Data are presented as the mean ± S.D. *vs. control. *P<0.05, **P<0.01.

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Figure 11. A model of osteocyte functions. (A) In the loaded (physiological condition), the osteocyte network inhibits osteoblast function, enhances osteoclastogenesis, and negatively regulates bone mass. (B) In the unloaded condition, the effect of osteocyte network on osteoblast function is augmented through the induction of Rankl in osteocytes and that on osteoclastogenesis is augmented through the induction of Sost in osteocytes, resulting in reduced bone mass. The thickness of the lines and arrows in A and B reflects the strength of the effects.

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Author Contributions
Conceived and designed the experiments: TK. Performed the experiments: T. Morishita T. Miyazaki. Analyzed the data: T. Morishita RF MI T. Miyazaki T. Maeno YK HK. Wrote the paper: TK.

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