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Phosphatidylserine-Containing Liposomes Inhibit the Differentiation of Osteoclasts and Trabecular Bone Loss

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Liposomes containing phosphatidylserine (PS) are engulfed by phagocytes including macrophages, microglia, and dendritic cells. PS liposomes (PSLs) mimic the effects of apoptotic cells on these phagocytes to induce the secretion of anti-inflammatory molecules and to inhibit the maturation of dendritic cells. However, the effects of PSLs on osteoclasts, which are also differentiated from the common myeloid precursors, remain to be determined. This study investigated the effects of PSLs on the osteoclastogenesis. In the rat bone marrow culture system, osteoclast precursors phagocytosed PSLs to secrete TGF-β1 and PGE₂, which in turn inhibited osteoclastogenesis through the downregulation of receptor activator for NF-κB ligand, receptor activator of NF-κB, ICAM-1, and CD44. Consistent with these in vitro observations, i.m. injection of PSLs significantly increased the plasma level of TGF-β and PGE₂ and decreased the expression of receptor activator for NF-κB ligand, receptor activator of NF-κB, and ICAM-1 in the skeletal tissues of ankle joints of rats with adjuvant arthritis (AA). A quantitative analysis using microcomputed tomography revealed that PSLs as well as TGF-β1 together with PGE₂ significantly inhibited AA-induced trabecular bone loss. These observations strongly suggest that PSLs generate TGF-β1 and PGE₂ release, leading to inhibit osteoclastogenesis and AA-induced trabecular bone loss. Because PS is a component of the cell membrane, PSLs therefore can be a potentially effective pharmacological intervention against abnormal bone loss, such as osteoporosis without deleterious side effects. The Journal of Immunology, 2010, 184: 3191–3201.
Materials and Methods

Reagents

- α-MEM was from Life Technologies BRL (Grand Island, NY), 1α,25-dihydroxyvitamin D3, [1α,25(OH)2D3], and SQ22536 were from BIOUL (Plymouth Meeting, PA). PBS was from BioWhittaker (Walkersville, MD).
- Soluble RANKL was from Peprotec Science (London, U.K.). TGF-β1 was from AbD Serotec (Kidlington, U.K.). PGE2 was from Cayman Chemical (Ann Arbor, MI).
- PS, phosphorylcholine (PC), 4-nitrobenz-2-oxa-1,3-diazole (NBD)-labeled PS, and NBD-labeled PC were from Avanti Polar Lipids (Alabaster, AL). Rabbit polyclonal anti–TGF-β type II receptor (TGF-βRII), anti-RANKL, anti-RANK, anti-osteoprotegerin (OPG), mouse monoclonal anti-ICAM-1, anti-CD44, goat polyclonal anti-calcitonin receptor (CTR), and normal rabbit IgG were from Santa Cruz Biotechnology (Santa Cruz, CA).
- Human myeloma cell line 6G10 column (Amersham Biosciences, Uppsala, Sweden), and then remaining chemical components were added to the BM and OP cell cultures. At day 4 (96 h) of the cultures, cells were fixed by 4% paraformaldehyde in PBS for 90 min. In this culture condition, only mononuclear tartrate-resistant acid phosphatase (TRAP)-positive cells with 3 nuclei were counted as osteoclast-like MNCs (mature osteoclasts).

Liposome

PSLs consisted of PC and PS at a molar ratio of 7:3; PC only, PSLs, and PC liposomes (PC/PSLs) were prepared as described previously (16). In some experiments, NBD-labeled PS and PC were used for preparing NBD-labeled PSLs and PCLs, respectively.

Animals

Female Lewis rats (4 to 5 wk old) were from Kyudo (Fukuoka, Japan) and cared for according to the manual of Animal Care and Use Committee, Kyushu University, Fukuoka, Japan.

Systemic PSL treatment for AA rats and sample preparation

Female Lewis rats (5 wk old, n = 120) were used for in vivo experiments. The animals (n = 93) were injected intradermally with CFA (1.5 mg heat-killed *M. butyricum* well suspended in 0.15 ml mineral oil) at the base of the tail to induce AA as described previously (30, 31). Rats were injected with mineral oil only as sham rats (n = 27). We injected i.m. with PSLs (5 mg/kg/day; PSL-treated AA rats, n = 27) or PCLs (5 mg/kg/day; PCL-treated AA rats, n = 27) in the hind limbs from days 14–28 after CFA injection. At this time point, acute synovial inflammation of ankle joints was confirmed without bone destruction occurring (31, 32). The AA rats were injected i.m. with PBS (n = 27). Rats were anesthetized with sodium pentobarbital (30 mg/kg, i.p.) at days 2, 7, and 14 after PSL or PCL treatment. After obtaining the blood samples, animals were perfused intracardially with 2% paraformaldehyde fixative in PBS for 15 min. The ankle joints and the bones were removed and immersed in the same fixative for 12 h at 4°C. Some samples were for microcomputed tomographic (μCT) analyses (n = 6); other samples were decalcified in 10% EDTA for another 3 wk. After being immersed in 30% sucrose in PBS for 2 d, samples were embedded in an optimal cutting temperature compound (Sakura Finetech, Tokyo, Japan). Serial coronal frozen sections (10 μm) were prepared for histological and immunohistochemistry as described previously (31). For real-time PCR analyses, the rats (n = 3 for each time point) were perfused intracardially with PBS, and the ankle joints were removed and stored at −80°C. In other groups, we injected rats i.m. with TGF-β1 (25 μg/kg/day) and PGE2 (2.5 μg/kg/day) from days 14–28 after CFA injection at the same time course of PSL treatment on AA rats (n = 6). We also injected rats i.m. with anti–TGF-β1 Ab (100 μg/kg/day) and SQ22536 (125 μg/kg/day) from day 12, and then treatment with PSLs from days 14–28 after CFA injection (n = 6). Rats were anesthetized with sodium pentobarbital (30 mg/kg, i.p.) and perfused intracardially with 2% paraformaldehyde fixative in PBS after 14 d of the treatments. The ankle joints were removed and immersed in the same fixative for μCT analyses.

μCT analysis

The ankle joints of sham and the AA rats at day 14 after the treatments of each group (n = 6) were examined using ScanXnate-E909840 in vivo (Coms-echimetry, Kanazawa, Japan). After being immersed in 10% EDTA, ankle joints were immersed in 30% sucrose in PBS for another 24 h. The cells were fixed with 2% paraformaldehyde for 30 min and stained with a TRAP kit (Sigma-Aldrich, St. Louis, MO), the general marker of osteoclast. TRAP-positive cells with >3 nuclei were counted as osteoclast-like MNCs (mature osteoclasts).

Western blotting

PSL-treated or untreated BM and OP cell extracts were prepared with cell lysis buffer (16), and Western blots were performed with the following Abs: rabbit polyclonal anti-RANKL (1:500 dilution), anti-RANK (1:500 dilution), anti-OPG (1:500 dilution), or anti-actin (1:2000 dilution). Blots were final-detected by an ECL detection system (ECL kit, Amersham Bioscience, Uppsala, Sweden) and quantified with image analyzer FLA3000 (Fuji Photo Film, Tokyo, Japan). Values were normalized to actin.

Flow cytometry analysis

OP cells were treated with PSLs (100 μM), TGF-β1 (500 ng/ml), or PGE2 (500 ng/ml). After removal by cell dissociation buffer enzyme-free PBS-based GIBCO (Invitrogen, Carlsbad, CA) at each time point, the cells (5 × 107) were incubated with mouse monoclonal ICAM-1 (1:200) or anti-CD44 (1:200) Abs for 1 h on ice, with normal mouse IgG as negative control. After washing with PBS with 2% FBS, the cells were incubated for 30 min on ice with donkey anti-mouse FITC-labeled IgG. After washing by PBS with 2% FBS, immunofluorescence was analyzed using a FACScan analyzer (BD Biosciences, San Jose, CA).
experiments, the ankle joint sections were incubated with anti-goat CTR Ab mixed with anti-mouse CTR-1 overnight at 4°C. After being incubated with a mixture of FITC-conjugated donkey anti-mouse IgG and rhodamine-conjugated donkey anti-goat IgG for 1 h at 24°C, the slides were mounted in antifading medium Vectashield (Vector Laboratories) and examined by a confocal laser scanning microscope LSM510META (Carl Zeiss, Jena, Germany).

Real-time RT-PCR
Skeletal tissues of ankle joints of rats were obtained after removal of the soft tissues. RNA from the skeletal tissues was extracted with RNeasy Lipid Tissue Midi Kit (QIAGEN, Germany) according to the manufacturer’s instructions. RNA was reversely transcribed to cDNA using PrimeScript RT reagent Kit (Takara, Shiga, Japan). The real-time RT-PCR was performed using SYBR Premix Ex Taq (Takara). The thermal cycling was holding at 95°C for 10 min, followed by 30 cycles of 95°C for 15 s and 60°C for 30 s. After amplifying the PCR reaction, melting curve analysis was performed from 55°C to 95°C (0.5°C/s). GAPDH was used as an internal control. Primer sequences were as follows; RANKL: 5'-TCCGGTTTCCCATAAAGTCAG-3' and 5'-CTGAACGCAAATGTGGCCTA-3'; RANK: 5'-TCCGGTTTCCCATAAAGTCAG-3' and 5'-CTGAACGCAAATGTGGCCTA-3'; TGF-β: 5'-ACACCAAACCTGCCTACCA-3' and 5'-TGGCCACCAGAACACTCAG-3'; OPG: 5'-ATCCACGAACTTGAACAGG-3' and 5'-ATCCACAATGCCAGTGTACG-3'. The standard curve method was used for quantification of gene expression, and target genes/GAPDH were compared between the AA rats and sham rats and between the PSL- or PC liposome-treated AA rats and the untreated AA rats.

Statistical analysis
Data are expressed as means ± SD. The significant differences between groups were determined with the Student t test.

Results
Phagocytosed PSLs by OP inhibits rat osteoclastogenesis
The present study used two rat osteoclast-generating culture systems: BM and OP cell cultures. BM cell cultures contain the whole BM cells including stromal cells and osteoblasts, whereas OP cell cultures contain only mononuclear OP cells (29). To assess the effects of PSLs on osteoclastogenesis, it was necessary to determine whether PSLs could be phagocytosed by OP cells. To visualize the margin of the cells, OP cells were stained by Texas red-conjugated phallolidin, which binds to F-actin. At 24 h after treatment, large granular aggregates of NBD-labeled PSLs were localized in the cytoplasm of OP cells, for which cell marginal F-actin was visualized by Texas red-conjugated phallolidin (Fig. 1Aa). PSLs were also detected in the cytoplasm up to 96 h after treatment (Fig. 1Ad). The merged confocal laser scanning microscopic (CLSM) images show that NBD-labeled PSLs (green) corresponded well with the immunoreactivity for ED1 (red), a lysosomal membrane Ag of rat monocytes (33) (Fig. 1Ab, e), thus suggesting that PSLs were transported into the endosome/lysosome of OP cells after engulfment (16). To further elucidate a phagocytosis of PSLs by OP cells, CLSM was used to construct orthogonal cross sectional images of cultured OP cells that were immunohistochemically stained by an anti-CTR Ab, a marker for OP cells. CLSM images of a plane view with two orthogonal cross-sectional views of CTR-labeled cultured OP cells clearly demonstrated that PSLs were engulfed by OP cells (Fig. 1Ac, f). However, no granular aggregates of the NBD-labeled PCLs were found in OP cells posttreatment (Fig. 1Ag, h).

Next, the effects of PSLs on rat osteoclastogenesis were examined using both OP and BM cell cultures. TRAP-positive cells with >3 nuclei are counted as osteoclast-like MNCs. On the other hand, TRAP-positive mononuclear cells are considered OP cells. In the control condition of both BM and OP cell cultures, TRAP-positive MNCs were not detected until 48 h, and the number of TRAP-positive MNCs peaked at 96 h (Fig. 1B, indicated by red arrows), whereas some cells still remained as TRAP-positive mononuclear cells (Fig. 1B, blue arrows). Fig. 1B also showed TRAP-negative cells consisting mainly of osteoblasts and stromal cells in BM cell cultures. The effect of PSLs on rat osteoclastogenesis was thus examined in both BM and OP cell cultures at 96 h. PSLs significantly decreased the number of TRAP-positive MNCs in a dose-dependent manner in both cell cultures at 96 h (Fig. 1B, 1C). These results suggest that the primary target of PSLs is OP cells to inhibit osteoclastogenesis. As previously noted, the minimal concentration of PSLs for a significant inhibition of TRAP-positive MNC formation in OP cell cultures was lower than that in BM cell cultures. However, PCLs did not affect the mean number of TRAP-positive MNCs in either type of cultured cells at 96 h (Fig. 1C). Next, the stage when PSLs inhibited TRAP-positive MNC formation was determined. As shown in Fig. 1D, the number of TRAP-positive MNCs significantly decreased when application of PSLs (100 μM) was started at an early stage (from 0–48 h) but not at the later stage (from 72 h) in both types of cultured cells. However, PSLs did not inhibit the mean number of TRAP-positive mononuclear cells (OP cells) at 96 h (Fig. 1E). These observations strongly suggest that PSLs inhibit rat osteoclastogenesis from the precursors by acting on OP cells directly without affecting the precursor formation.

PSLs downregulated the expression of RANKL, RANK, ICAM-1, and CD44 in cultured cells
To elucidate the mechanism underlying the inhibitory effects of PSLs on rat osteoclastogenesis, the effects of PSLs on the expression levels of RANKL, RANK, and OPG, which play essential roles in osteoclastogenesis, were examined. The expression of RANKL and OPG was examined in both BM cell cultures, because the treatment of soluble RANKL (20 ng/ml) is required for TRAP-positive MNC formation in OP cell cultures. The protein amount of RANKL in BM cells increased from 48 h to 72 h during the 96-h culture period. PSLs significantly decreased the mean level of RANKL from 48 to 72 h (Fig. 2A, 2B), but not that of OPG (Fig. 2A, 2C). On the other hand, the protein amount of RANK in OP cell cultures increased from 48 h during the culture period. PSLs significantly decreased the mean level of RANK from 48 h in OP cell cultures (Fig. 2A, 2D). Furthermore, PGE2 significantly decreased the mean level of RANKL in BM cell cultures, but did not affect that of either OPG in BM cell cultures or RANK in OP cell cultures. In contrast, TGF-β1 significantly decreased the mean level of RANK in OP cells from 48 to 72 h, but did not affect that of either RANKL or OPG in BM cells (Fig. 2A–D). On the other hand, PCLs did not affect the mean level of RANKL and OPG in BM cell cultures or that of RANK in OP cell cultures (Fig. 2A–D). Next, the effects of PSLs, PCLs, TGF-β1, and PGE2 on the expression of both ICAM-1 and CD44 by cultured OP cells were further examined using flow cytometry, because ICAM-1 and CD44 are involved in the fusion of the precursors into mature osteoclasts (25–27). As shown in Fig. 3A, 3C, ICAM-1 was expressed in OP cells during the culture period. PSLs significantly decreased the number of ICAM-1–positive OP cell cultures to 53.4% and 75.8% of the control level at 48 and 72 h, respectively. In addition, both TGF-β1 and PGE2 also significantly decreased the number of ICAM-1–positive cells to 77.3% and 78.2% of the control level at 48 h, respectively. As shown in Fig. 3B, 3D, CD44 was also expressed in OP cell cultures during the culture times. PSLs significantly decreased the number of CD44–positive OP cell cultures to 79.5% of the control level at 48 h. Furthermore, TGF-β1 but not PGE2 significantly decreased the number of CD44–positive cells to 86.2% of the control level at 48 h. It was also noted that PSLs, TGF-β1, and PGE2 did not affect the expression level of either ICAM-1 or CD44 in OP cell cultures at 72 h posttreatment. On the other hand, PCLs did not affect the expression of both ICAM-1 and CD44 in OP cell cultures (Fig. 2C, 2D). These observations strongly suggest that
PSLs, TGF-β1, and PGE2 decreased the expression levels of RANKL, RANK, ICAM-1, and CD44 that are involved in the differentiation and fusion of OP cells.

**PSLs increase the release of TGF-β1 and PGE2 and thereby inhibit rat osteoclastogenesis**

Next, the effects of PSLs on secretion of TGF-β1 and PGE2 from both BM and OP cells were examined, because PSLs can induce the production of these molecules after they are phagocytosed by macrophages and microglia (11, 16). TGF-β1 release in both culture cells significantly increased from 24 h after PSL treatment in comparison with that in the untreated cells (Fig. 4A), and the increased level of TGF-β1 lasted up to 96 h (data not shown). The release of PGE2 reached the maximal level at 24 h posttreatment with PSLs, lasted up to 48 h, the early period of the culture, and then returned rapidly to the control level thereafter (Fig. 4B). However, no increase of TGF-β1 and PGE2 was found in either BM or OP cell culture posttreatment with PCLs (Fig. 4A, 4B). These observations indicate that OP cells induce the secretion of both TGF-β1 and PGE2 following phagocytosis of PSLs. The roles of TGF-β1 and PGE2 in osteoclastogenesis are still matters of controversy, depending on the cell types, species, and concentrations of these molecules. It has been reported that TGF-β1 enhances osteoclastogenesis even at low concentrations (<100 pg/ml), whereas it inhibits it at a higher dose (e.g., 2 ng/ml) (34, 35). Although PGE2 is generally believed to stimulate osteoclastogenesis in murine cultured cells at a relatively high concentration (36–38), PGE2 has also been shown to inhibit osteoclastogenesis in human and rat culture systems (39–42). Therefore, the effects of TGF-β1 and PGE2 on rat osteoclastogenesis were examined. As shown in Fig. 4C, TGF-β1 significantly decreased the mean number of TRAP-positive MNCs at the concentration of 500 pg/ml but not 50 pg/ml. The inhibitory effect of TGF-β1 (500 pg/ml) was completely reversed by rabbit anti–TGF-β1RII Ab (5 μg/ml), but not control rabbit IgG (Fig. 4C). Furthermore, PGE2 also significantly inhibited the formation of TRAP-positive MNCs at the concentration of 500 pg/ml but not 50 pg/ml. The inhibitory effect of PGE2 was completely antagonized by SQ22536 (10 μM), a specific inhibitor of adenylate cyclase. It is noted that combined treatment with TGF-β1 (50 pg/ml) and PGE2 (50 pg/ml) significantly inhibited the formation of TRAP-positive MNCs. Moreover, the inhibitory effect of PSLs (100 μM) on the formation of mature osteoclasts was reversed by either rabbit anti–TGF-β1 Ab (5 μg/ml) or SQ22536 (Fig. 4D). However, control rabbit IgG did not affect the inhibitory effects of PSLs on the formation of TRAP-positive MNCs (Fig. 4D). PSL-induced secretion of either TGF-β1 or PGE2 in the culture medium did not reach the concentration to inhibit osteoclastogenesis. Therefore, it is reasonable to consider that PSL-induced the inhibition of osteoclastogenesis was mediated by presumable synergistic effect of TGF-β1 and PGE2.
Systemic treatment with PSLs increases the plasma level of TGF-β1 and PGE₂ and markedly suppresses trabecular bone loss in the AA rats

To confirm the inhibitory effect of PSLs on osteoclast formation in vivo, the effects of PSLs on an osteoclast-induced trabecular bone loss model, the AA rats, was investigated. Systemic treatment with PSLs was initiated 14 d after CFA injection, when the peak of paw inflammation was established. However, the number of osteoclasts increases with bone destruction after the peak of inflammation in the ankle joints of the AA rats (30, 31). At 24 h after i.m. treatment, CLSM images of a plane view with two orthogonal cross-sectional views clearly demonstrated that PSLs were engulfed by CTR-labeled OP cells in the tibia marrow (Fig. 5Aa) of the AA rats. In the peripheral blood of the AA rats, CLSM images of a plane view with two orthogonal cross-sectional views also clearly demonstrated that PSLs localized in ED1-positive lysosomes of mononuclear cells (Fig. 5Ab). The paw volume increase of AA rats occurred in two stages, an acute inflammation stage thereafter (31, 32). As shown in Fig. 5B, systemic treatment with PSLs or treatment with TGF-β1 and PGE₂ together significantly reduced the paw volume of AA rats during the bone/joints destruction stage. However, treatment with PCLs did not reduce the paw volume of AA rats. Furthermore, treatment with anti-TGF-β1 Ab and SQ22536 together completely reversed the inhibitory effects of PS on the paw volume of AA rats. At day 2 posttreatment with PSLs, the mRNA expression levels of RANKL and RANK significantly increased in the skeletal tissues of the AA rats from 21 d after CFA injection. Treatment with PSLs for 7 d significantly decreased the mean expression levels of both RANKL and RANK in the AA rats; however, treatment with PCLs did not decrease the expression level of either RANKL or RANK in the AA rats (Fig. 5D). Furthermore, the number of ICAM-1-positive mononuclear cells, which were identified as CTR-positive OP cells, increased in the BM cavities of the AA rats from 21 d after CFA injection. Treatment with PSLs for 7 d markedly decreased the number of ICAM-1-positive OP cells in the AA rats (Fig. 5E). These observations obtained in the AA rats were closely consistent with those obtained in the cultured cells. Therefore, a possible decrease in osteoclast formation was examined in the tibia BM cavity of the AA rats. Consistent with previous observations (32), the number of TRAP-positive MNCs in the BM cavity of the distal epiphysis increased from 21 d, and numerous TRAP-positive MNCs were found at 28 d after CFA injection. Systemic treatment with PSLs significantly decreased the mean number of TRAP-positive MNCs in the tibia BM cavity of the AA rats; however, PCLs did not decrease the mean number of TRAP-positive MNCs (Fig. 5F).

To further prove the essential roles of TGF-β1 and PGE₂ in PSL-induced inhibitory effects on the trabecular bone loss in AA rats, we finally quantified the trabecular bone network of the bones in the ankle joints at 14 d posttreatment with PSLs or TGF-β1 and PGE₂ together on AA rats (28 d after CFA injection) using μCT analysis. The μCT analysis was conducted in the calcaneus, because trabecular bone losses within the tibia and talus in the AA rats were too severe to quantify. In comparison with the sham rats

**FIGURE 2.** Effects of PSLs, TGF-β1, and PGE₂ on the protein expression of RANKL, RANK, and OPG in the rat culture cells. A, Immunoblot analyses of RANKL, OPG, and RANK posttreatment with PSLs, PCLs, TGF-β1, and PGE₂. **B–D,** The time course changes of RANKL and OPG in BM cell cultures and RANK in OP cell cultures. The mean protein levels of RANKL (B), OPG (C), and RANK (D) posttreatment with PSL, PCL, TGF-β1, and PGE₂. The mean relative immunoreactivity for RANKL, OPG, and RANK in untreated and PSL-treated BM or OP cell cultures was determined by comparison with that for actin. Each column and bar represents the mean ± SD of three experiments. Asterisks indicate significant differences among the PSL-, TGF-β1-, and PGE₂-treated and untreated BM or OP cell cultures at each time points (*p < 0.05; **p < 0.01; Student t test).
A severe trabecular bone loss was observed in the AA rats (Fig. 6B). The AA-induced trabecular bone loss was markedly inhibited by treatment with PSLs (Fig. 6C) as well as treatment with TGF-β1 and PGE2 together (Fig. 6D). However, the AA-induced trabecular bone loss was not inhibited by treatment with PCLs (Fig. 6E). Furthermore, the AA-induced trabecular bone loss was not inhibited by treatment with PSLs and simultaneous treatment with anti–TGF-β1 Ab and SQ22536 (Fig. 6F). In analysis of the parameters of trabecular bone shown in Fig. 6G–I, PSLs, as well as TGF-β1 and PGE2 together, significantly inhibited the AA-induced decrease of trabecular bone volume per unit of metaphysis (BV/TV, Fig. 6G), trabecular thickness (Tb/Th, Fig. 6H), and trabecular numbers (Tb/N, Fig. 6I). On the other hand, PCLs showed no effect on any parameters in AA-induced trabecular bone loss. Moreover, TGF-β1 Ab and SQ22536 significantly blocked the inhibitory effects of PSLs on AA-induced trabecular bone loss.

**Discussion**

The major finding of this study is that PSLs inhibit osteoclastogenesis and AA-induced trabecular bone loss in rats. This is the first report to clarify the effects of PSLs on osteoclasts. However, the effects of PSLs on macrophages and dendritic cells, which are differentiated from the common myeloid precursors with osteoclasts, have been described elsewhere (18, 19). The current findings are consistent with a recent observation that PSLs inhibit the maturation of myeloid dendritic cells (17).

TGF-β1 and PGE2 secreted from PSL-engulfed OP cells were thought to be closely associated with the inhibitory effects of PSLs on osteoclastogenesis and AA-induced bone loss for two reasons.
First, addition of either TGF-β1 or PGE2 alone significantly inhibited osteoclastogenesis (the formation of TRAP-positive MNCs) in both rat culture systems at the concentration of 500 pg/ml. Second, the inhibitory effect of PSLs on osteoclastogenesis was significantly reversed by an Ab against TGF-βRII, the receptor for the signaling of response to TGF-β1 (43). The effect of PSLs on osteoclastogenesis was also significantly antagonized by SQ22536, an adenylate cyclase inhibitor, thus suggesting the involvement of EP2 and/or EP4 receptors that are coupled to adenylate cyclase (44). The substantial concentration of TGF-β1, which alone could suppress the osteoclastogenesis in BM and OP cell cultures, was estimated to be 800 pg/ml and 650 pg/ml, respectively, because of the relatively high basal level of TGF-β1 in the culture medium (i.e., 300 pg/ml in BM cells, 150 pg/ml in OP cells). On the other hand, the substantial concentration of PGE2, which alone could suppress osteoclastogenesis, was estimated to be 650 pg/ml and 580 pg/ml in BM and OP cell cultures, respectively, because of relatively high basal level of PGE2 in the culture medium (i.e., 150 pg/ml in BM and 80 pg/ml OP cells). PSL-induced secretion of either TGF-β1 or PGE2 in the culture medium did not reach the concentration to inhibit osteoclastogenesis in BM and OP cell cultures. Either TGF-β1 or PGE2 alone at the concentration of 50 pg/ml had no effect on osteoclastogenesis; however, their combined treatment significantly suppressed it. Therefore, it is reasonable to consider that PSLs inhibited the osteoclastogenesis by a synergistic effect of TGF-β1 and PGE2. This can explain why anti–TGF-β1 Ab alone or SQ22536 alone can suppress the PSL-induced inhibitory effect on osteoclastogenesis. The effects of TGF-β1 and PGE2 on bone metabolism are still matters of controversy. TGF-β1 enhances osteoclastogenesis even at low concentrations (<100 pg/ml), whereas it inhibits it at a high dose (e.g., 2 ng/ml) (34, 35). Although PGE2 is generally believed to stimulate osteoclastogenesis in murine-cultured cells at a relatively high concentration (36–38), it also inhibit osteoclastogenesis in human and rat culture systems (39–44). Therefore, it is conceivable that the effects of PGE2 depend on experimental conditions, including the cell types, species, and concentrations. Additional experiments are necessary to elucidate the effect of PSLs on human osteoclast formation.

PSLs could be phagocytosed by OP cells, thus inhibiting osteoclastogenesis. These results indicate that PSLs affect the destiny of OP cells by generating TGF-β1 and PGE2, which may act in an autocrine manner. On the other hand, PSLs also inhibit

FIGURE 4. Involvement of TGF-β1 and PGE2 in PSL-induced inhibition of osteoclastogenesis in rat BM and OP cell cultures. Release of TGF-β1 (A) and PGE2 (B) from the cultured cells following treatment with PSLs and PCLs. Each column and bar represents the mean ± SD of three experiments. Asterisks indicate significant differences between the PSL-treated and untreated BM cell cultures (p < 0.05; **p < 0.01; Student t test). Daggers indicate significant differences between the PSL-treated and untreated OP cell cultures (††† p < 0.001; Student t test). C, The number of TRAP-positive MNCs was decreased in a dose-dependent posttreatment with TGF-β1 or PGE2. TGF-β1– and PGE2-induced inhibition was reversed by anti–TGF-βRII Ab (Anti-RII) and SQ22536 (SQ), a specific inhibitor for adenylate cyclase, respectively, but was not reversed by control rabbit IgG. Each column and bar represents the mean ± SD of three experiments. Asterisks indicate a significant difference between the PSL-treated and untreated BM cells (p < 0.05; Student t test). Daggers indicate a significant difference between the PSL-treated and untreated OP cell cultures (††† p < 0.001; Student t test). D, The inhibitory effect of PSL (100 μM) on TRAP-positive MNC formation was reversed by either anti–TGF-β1 (Anti-T) or SQ22536 (SQ), but was not reversed by control rabbit IgG. Each column and bar represents the mean ± SD of three experiments. Asterisk indicates a significant difference between the PSL-treated and untreated BM cell cultures (p < 0.05; Student t test). Daggers indicate a significant difference between the PSL-treated and untreated OP cell cultures (††† p < 0.001; Student t test).
osteoclastogenesis from BM cell cultures. This suggests that PSLs also affect the functions of osteoblasts and stromal cells in a paracrine manner because they have receptors for both TGF-β1 and PGE2 (45, 46). PSLs activate p44/p42 ERK but not p38 MAPK in primary cultured rat microglia (16) and macrophages (15). In addition, the PSL-induced PGE2 production is mediated by cyclooxygenase-1 and its functionally coupled upregulated terminal PGE synthases, especially microsomal PGE synthase 2 (16). Furthermore, bafilomycin A1, a specific inhibitor of vacuolar-type H+-ATPase, almost completely inhibited PSL-induced PGE2 generation, thus suggesting the involvement of lysosomal proteolytic functions in the PGE2 generation following phagocytosis of PSLs. It is reasonable to consider that PSLs affect the proximal signaling of osteoclastogenesis. PSLs inhibited the formation of mature osteoclasts but not that of OP cells, suggesting that PSLs may consequently inhibit cell-to-cell contact and/or cell fusion during osteoclastogenesis. These observations prompted us to further examine the effect of PSLs on the expression level of ICAM-1 and CD44, which are the important adhesion molecules for the fusion of OP cells during differentiation (25–27). Consistent with published reports (26, 27, 50), ICAM-1 and CD44 are expressed on the OP cells. Furthermore, PSLs decreased ICAM-1 and CD44 expression on OPs at the early stage of osteoclastogenesis in rat BM cell cultures. Therefore, another potential mechanism underlying the inhibitory effect of PSLs on osteoclastogenesis is the inhibition of OP cell fusion through the reduction of ICAM-1 and CD44 expression. Moreover, TGF-β1 and PGE2 reduced ICAM-1 and CD44 expression, respectively, in OP cell cultures during the early stage of osteoclastogenesis. These are in line with the previous findings that
both TGF-β1 and PGE2 inhibit ICAM-1 expression in monocytes (51–54). Taken together, these observations strongly suggest that TGF-β1 and PGE2 are major causative factors for PSL-induced inhibition of rat osteoclastogenesis through reduction of the expression of RANK, RANKL, ICAM-1, and CD44 at the early stage of osteoclastogenesis.

In parallel with the in vitro experiments, the effects of PSLs were further examined on the bone destruction associated with AA, which is widely used in research of inflammation and bone destruction (55, 56). We have noted previously that the inflammation of the synovial tissues peaks at 14 to 21 d after CFA injection, and the trabecular bone loss in the bone cavities occurs thereafter (31, 32). To focus on the effects of PSLs on AA-induced trabecular bone loss, systemic treatment with PSLs was started at 14 d after CFA injection, when the inflammation is established without bone destruction in the ankle joints. The following sequential events were observed after systemic treatment of PSLs in the AA rats: 1) phagocytosis of PSLs by OP cells in BM and monocytes in blood; 2) a significant increase in the plasma level of both TGF-β1 and PGE2; 3) a significant decrease in AA-induced elevated expression of RANKL, RANK, and ICAM-1 in the skeletal tissues with the decrease in TRAP-positive osteoclast formation; and 4) a significant inhibition of the AA-induced trabecular bone loss. Furthermore, systemic treatment with TGF-β1 and PGE2 significantly reduced the AA-induced trabecular bone loss, and with anti–TGF-β1 Ab and SQ22536, completely reversed the inhibitory effects of PSL and the AA-induced trabecular bone loss. These in vivo findings further support the hypothesis that PSLs inhibit osteoclastogenesis by generating TGF-β1 and PGE2. The deficit of osteoclastogenesis may further lead to the inhibition of AA-induced bone loss. Moreover, in addition to the regulation of osteoclastic bone resorption, TGF-β1 and PGE2 are potent stimulators of osteoblastic bone formation. In the present study, we confirmed that systemic treatment with TGF-β1 and PGE2 markedly improved the AA-induced decrease of trabecular bone network, especially in trabecular numbers. Those results were in accordance with the previous reports, which showed that local s.c. injection of either TGF-β1 or PGE2 increases the activity of osteoblasts to cause bone formation (57, 58). Therefore, increased TGF-β1 and PGE2 levels at the early stage posttreatment with PSLs contribute not only to the prevention of trabecular bone loss, but also to the facilitation of trabecular bone formation in the AA rats.

In conclusion, the current findings strongly suggest that PSLs potently inhibit rat osteoclastogenesis and AA-induced trabecular
bone loss in rats by generating TGF-β1 and PGE2. Because PS is a component of mammalian cell membranes, PSLs can be used as potential pharmacological interventions against abnormal bone loss such as osteoporosis without any deleterious side effects.

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Disclosures

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