Food Science of Animal Resources

Food Sci. Anim. Resour. 2023 January 43(1):157~169
DOI https://doi.org/10.5851/kosfa.2022.e68

pISSN : 2636-0772 eISSN : 2636-0780
http://www.kosfaj.org

ARTICLE

Effects of *Lactobacillus reuteri* MG5346 on Receptor Activator of Nuclear Factor-Kappa B Ligand (RANKL)-Induced Osteoclastogenesis and Ligature-Induced Experimental Periodontitis Rats

Yu-Jin Jeong[1], Jae-In Jung[1], YongGyeong Kim[2], Chang-Ho Kang[2], and Jee-Young Imm[1,*]

[1]Department of Foods and Nutrition, Kookmin University, Seoul 02707, Korea
[2]Mediogen, Co., Ltd., Jecheon 27159, Korea

OPEN ACCESS

Received October 6, 2022
Revised November 13, 2022
Accepted November 18, 2022

***Corresponding author** : Jee-Young Imm
Department of Foods and Nutrition, Kookmin University, Seoul 02707, Korea
Tel: +82-2-910-4772
Fax: +82-2-910-5249
E-mail: jyimm@kookmin.ac.kr

***ORCID**
Yu-Jin Jeong
https://orcid.org/0000-0003-3833-325X
Jae-In Jung
https://orcid.org/0000-0002-4715-0669
YongGyeong Kim
https://orcid.org/0000-0003-1970-3315
Chang-Ho Kang
https://orcid.org/0000-0001-6466-8550
Jee-Young Imm
https://orcid.org/0000-0003-3152-7051

Abstract Effects of culture supernatants of *Lactobacillus reuteri* MG5346 (CS-MG5346) on receptor activator of nuclear factor-kappa B ligand (RANKL)-induced osteoclastogenesis were examined. CS-MG5346 treatment up to 400 μg/mL significantly reduced tartrate-resistant acid-phosphatase (TRAP) activity, the phenotype biomarker of osteoclast, without affecting cell viability. CS-MG5346 inhibited the expression of osteoclast specific transcriptional factors (c-fos and nuclear factor-activated T cells c1) and their target genes (*TRAP*, *cathepsin*, *and matrix metallo-proteinase-9*) in a dose-dependent manner ($p<0.05$). The administration of *L. reuteri* MG5346 (2×10^8 CFU/day) for 8 wks significantly improved furcation involvement, but no difference was observed in alveolar bone loss in ligature-induced experimental periodontitis rats. The elevated RANKL/osteoprotegerin ratio, the biomarker of periodontitis, was significantly lowered in the gingival tissue by administration of *L. reuteri* MG5346 ($p<0.05$). *L. reuteri* MG5346 showed excellent stability in simulated stomach and intestinal fluids and did not have antibiotic resistance. Based on the results, *L. reuteri* MG5346 has the potential to be a promising probiotic strain for oral health.

Keywords *Lactobacillus reuteri* MG5346, culture supernatant, osteoclastogenesis, osteoclast specific gene expression, ligature-induced experimental periodontitis

Introduction

Gingivitis and periodontitis are common chronic inflammatory diseases and these periodontal diseases occur in about 20%–50% of the world's population. Moreover, periodontal diseases increase the risk of systemic diseases, such as cardiovascular disease (Nazir, 2017). The surgical intervention and antibiotic treatment may not be sufficient to control periodontitis because of the complex etiology involved in oral microbiota (Gatej et al., 2017).

Probiotics are defined as safe live microorganism exerting health benefits and disease prevention when consumed in adequate amounts (Pineiro and Stanton, 2007). The composition of oral microbiota was significantly different between healthy and periodontitis patients, and adequate oral lactobacilli, such as *Lactobacillus paracasei* and *Lactobacillus plantarum*, were able to reduce the occurrence of dental caries by inhibiting the growth and colonization of cariogenic bacteria (Kõll-Klais et al., 2005). *Lactobacillus casei* 393 and *L. plantarum* B719-fermented milk increased osteoblast activity and prevented bone loss in ovariectomized rats (Kim et al., 2009; Lee et al., 2020). In addition to probiotics, postbiotics refer to non-viable bacterial components or metabolites of probiotics, mitigate various inflammatory diseases, such as inflammatory bowel disease, rheumatoid arthritis, and obesity (Bungau et al., 2021; Cristofori et al., 2021).

As an ongoing effort to develop oral probiotics, *Lactobacillus reuteri* MG5346 (MG5346) has been selected from our preliminary screening study. *L. reuteri* is a Gram-positive bacterium that inhabits various locations in the human body, including the gastrointestinal tract, urinary tract and skin (Mu et al., 2018). *L. reuteri* showed an immune modulation effect by inducing anti-inflammatory regulatory T cells while reducing pro-inflammatory cytokines (He et al., 2017; Hsieh et al., 2016). *L. reuteri* lozenges helped to treat chronic periodontitis as an adjuvant treatment and delayed recolonization for up to 6 months in the follow-up study (Tekce et al., 2015). In our previous study, probiotic culture supernatant (CS) inhibited both *Streptococcus mutans*-induced biofilm formation and receptor activator of the nuclear factor κB ligand (RANKL)-induced osteoclast formation (Jung et al., 2021). The inhibitory activity of CS on biofilm formation and osteoclastogenesis varied depending on the probiotic strain. These results suggested that the efficacy of oral probiotics, such as *L. reuteri*, are also strain-specific.

The objective of the present study was to examine the efficacy of MG5346 as an oral probiotic. To achieve this goal, the effects of the CS-MG5346 on RANKL-mediated osteoclastogenesis were analyzed. In addition, the effect of MG5346 administration on alveolar bone loss and tissue damage was evaluated using ligature-induced periodontitis rats.

Materials and Methods

Materials

Dulbecco's modified Eagle's medium (DMEM), α-minimum essential Eagle's medium (α-MEM), penicillin-streptomycin solution, and fetal bovine serum (FBS) were purchased from Welgene (Gyeongsan, Korea). TaqMan Gene Expression Master Mix, TaqMan probes (5'-fluorescein based reporter dye; 3'-TAMRA quencher), and High-Capacity RNA-to-cDNA Kit were purchased from Applied Biosystems (Foster City, CA, USA). RANKL was purchased from purchased ProSpec (Rehovot, Israel). All other reagents used in the experiment were purchased from Sigma-Aldrich (St. Louis, MO, USA).

Preparation of culture supernatant of *Lactobacillus reuteri* MG5346 (CS-MG5346)

MG5346 was originally isolated from fermented foods. CS-MG5346 was prepared by the method described previously (Jung et al., 2021) and kindly provided by Mediogen (Jecheon, Korea).

Gastrointestinal tolerance of *Lactobacillus reuteri* MG5346 (MG5346)

The gastrointestinal tolerance of MG5346 was determined by the method of Tokatlı et al. (2015) with slight modification. MG5346 was harvested (3,460×g, 10 min) after being cultured in MRS media at 37°C for 24 h. The MG5346 pellets were washed twice with sterile saline solution (0.85% NaCl, w/v) and resuspended to 10^7–10^8 CFU/mL in simulated gastric fluid

(SGF; 3 g/L of pepsin in sterile saline solution, pH 2.5) or simulated intestinal fluid (SIF; 1 g/L of pancreatin, 0.3% bile salt in sterile saline solution, pH 8.0). The survival rate of MG5346 was determined after incubation at 37℃ for 4 h in SGF and 6 h in SIF, respectively. The viable cells were counted on MRS agar and expressed by the following formula:

$$\text{Survival rate } (\%) = \frac{\text{Log CFU of survived viable cells}}{\text{Log CFU of initial inoculated cells}} \times 100 \quad (1)$$

Antibiotic susceptibility

The antibiotic susceptibility of MG5346 was determined by the minimum inhibitory concentration (MIC) test strip method described previously (Jung et al., 2022).

Osteoclast differentiation from RAW 264.7 cells

The murine RAW 264.7 cell line was purchased from the American Type Culture Collection (ATCC, Manassas, VA, USA). The cells were cultured in DMEM supplemented with 10% FBS and penicillin-streptomycin (100 untis/mL) at 37℃ in a 5% CO_2 humidified atmosphere. Osteoclastogenesis was induced by replacing the α-MEM medium with the medium containing RANKL (100 ng/mL) and M-CSF (50 ng/mL). Cytotoxicity of CS-MG5346 was measured using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay (Lee and Imm, 2017).

Tartrate-resistant acid phosphatase (TRAP)-positive activity

RAW 264.7 cells were seeded in 96-well plates at a density of 3×10^3 cells/well for 24 h and were cultured in the presence of RANKL (100 ng/mL), M-CSF (50 ng/mL), and CS-MG5346 for another 7 days. The cells were lysed using 0.05% Triton X-100/saline solution and were dispersed in 50 mM citrate buffer (pH 4.7) containing 10 mM sodium tartrate and 10 mM *p*-nitrophenylphosphate. TRAP activity was determined according to the method of Kim et al. (2019).

Animal experiment

Animal experiments were conducted according to the guideline of the Institutional Animal Care and Use Committee (approval number: KNOTUS 21-KE-032). Male Sprague-Dawley rats (6 wks old; Orient Bio, Seongnam, Korea) were housed in an animal facility and maintained under the conditions of a 12-h light-dark cycle at 23±3℃, 55±15% humidity. After acclimation for 7 days, rats were randomly divided into three groups: 1) untreated control (n=10), 2) ligature+vehicle (n=10), 3) ligature+MG5346 (2×10^8 CFU/day; n=10). The ligature was placed around the right second molar of the mandible using a sterile 4-0 silk under anesthesia with zoletil 50 (Virbac, Carros, France) and xylazine (Rompun, Bayer AG, Leverkusen, Germany). Maintenance of the ligature was checked regularly during the entire experimental period (8 wk).

Alveolar bone loss and tissue damage measurement using micro-CT analysis

Mandibular jaws of all rats were scanned using a micro-CT (vivaCT 80, Scanco Medical AG, Brüttisellen, Switzerland) after 8 wk of ligation induction and MG5346 administration. The cement–enamel junction (CEJ)–alveolar bone crest (ABC) distance and degree of maxillary molar furcation involvement were used as an index of alveolar bone loss and periodontal tissue damage.

Quantitative real-time PCR (qRT-PCR)

Total RNA was extracted using NucleoZOL reagent (Macherey-Nagel, Düren, Germany), and qRT-PCR analysis was performed using cell lysates [nuclear factor-activated T cells c1 (NFATc1), TRAP, c-Fos, TRAP, and cathepsin K] and rat gingival tissue [RANKL and osteoprotegerin (OPG)] as described previously (Jung et al., 2022). The relative expression of osteoclast-specific transcriptional factor and target genes were analyzed using the following probes: β-actin (Mm00607939_s1), TRAP (Mm00475698_m1), cathepsin K (Mm00484039_m1), NFATc1 (Mm00479445_m1), c-Fos (Mm00487425_m1), RANKL (Rn00589289_m1), and OPG (Rn00563499_m1). qRT-PCR was performed using the StepOne Plus Real-Time PCR System (Applied Biosystems), and the expression of target genes was normalized to the housekeeping gene, β-actin.

Statistical analysis

All analytical experiments were performed in triplicate, and SPSS Statistics (SPSS 26; SPSS, Chicago, IL, USA) software was used for statistical analysis. Data were expressed as mean±SD. Significant differences ($p<0.05$) were assessed using a one-way analysis of variance (ANOVA), followed by Duncan's post-hoc test.

Results and Discussion

Gastrointestinal tolerance of *Lactobacillus reuteri* MG5346 (MG5346)

The acid resistance and bile salt tolerance of probiotics are the most important requirements to ensure health benefits to the host (Tokatlı et al., 2015). As shown in Table 1**,** MG5346 showed 91% and 92% survival rates in SGF and SIF, respectively. *L. reuteri* is one of the few resident *Lactobacillus* species found in various sites in the human body human body, including the gastrointestinal tract (Valeur et al., 2004). This high adaptability of *L. reuteri* might be related to its tolerance in the gastrointestinal environment. Chen et al. (2019) reported that *L. reuteri* WHH1689 contained various stress-resistant genes related to acid (FoF1-ATP synthase and the sodium proton antiporter) and bile (choloylglycine hydrolase and inorganic pyrophosphatae) tolerance.

Antibiotic resistance of *Lactobacillus reuteri* MG5346 (MG5346)

The antibiotic resistance of probiotics is a principal safety consideration because probiotics can be a source of transferable resistance genes to pathogens (Li et al., 2020). Thus, the MIC of eight antibiotics against MG5346 was determined. MG5346 showed much lower MIC values for eight antibiotics than corresponding cut-off MIC values. This result indicates that MG5346 does not have antibiotic resistance (Table 2). According to the report of Jose et al. (2015), probiotics generally show resistance to vancomycin, ciprofloxacin, gentamicin and streptomycin. Similar to the result of this study, 32 representative *L.*

Table 1. Survival rate of *Lactobacillus reuteri* MG5346 under simulated gastrointestinal conditions

Strain	Initial count[1)] (Log CFU/mL)	Survival in SGF[2)]		Survival in SIF[3)]	
		Log CFU/mL	%	Log CFU/mL	%
L. reuteri MG5346	7.55±0.19	6.85±0.07	90.74	6.94±0.03	91.87

The results are expressed as means±SD.
[1)] Initial counts evaluated at 0 h.
[2)] Survival rate in simulated gastric fluid (SGF, pH 2.5) was determined at 37°C after 4 h.
[3)] Survival rate in simulated intestinal fluid (SIF, pH 8.0) was determined at 37°C after 6 h.

Table 2. MIC of antibiotics for *Lactobacillus reuteri* MG5346

Antibiotics	Microbiological cut-off values (mg/L)	
	EFSA	*L. reuteri* MG5346
Ampicillin	2	0.06
Chloramphenicol	4	1
Clindamycin	4	<0.016
Erythromycin	1	0.03
Gentamycin	8	0.38
Kanamycin	64	8
Streptomycin	64	4
Tetracycline	32	2

MIC (minimum inhibitory concentration) indicates the lowest concentration of antibiotic that prevents visible bacterial growth. Antibiotic resistance was determined according to the European Food Safety Authority (EFSA) guidelines.

reuteri strains did not have any transferable or acquired antibiotic resistance. In addition, they did not show virulence potential in the gelatinase activity, and hemolysis test (Singh et al., 2012).

Effects of culture supernatant of *Lactobacillus reuteri* MG5346 (CS-MG5346) on tartrate-resistant acid phosphatase (TRAP) activity in receptor activator of the nuclear factor κB ligand (RANKL)-stimulated RAW 264.7 macrophages

RANKL mediates the conversion of hematopoietic precursors, such as monocytes and macrophages into osteoclasts with the cooperation of M-CSF (Kong et al., 1999). TRAP is highly expressed in response to the conversion of macrophages to multinucleated osteoclasts, and increased TRAP activity is often used as a phenotype marker for osteoclasts (Tanaka et al., 2005). TRAP activity was significantly increased by RANKL stimulation, while the addition of CS-MG5346 decreased TRAP activity in a dose-dependent manner (Fig. 1A). This suggests that CS-MG5346 is able to inhibit osteoclast formation.

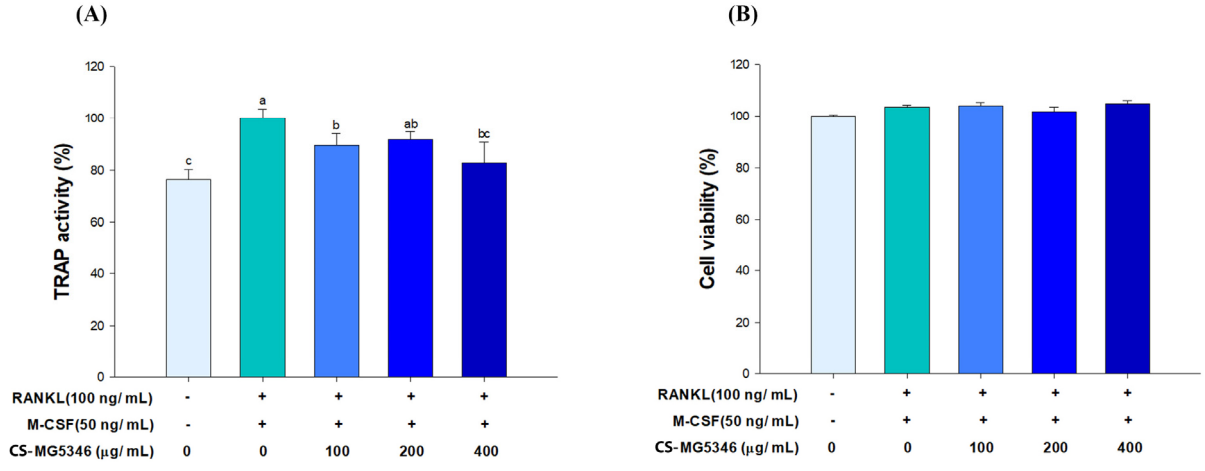

Fig. 1. Effects of CS-MG5346 on (A) TRAP activity and (B) cell viability in RANKL-stimulated RAW 264.7 macrophages. [a–c] Different letters indicate significant differences at $p<0.05$. TRAP, tartrate-resistant acid-phosphatase; RANKL, receptor-activator of nuclear factor-kappa B ligand; CS-MG5346, culture supernatant of *Lactobacillus reuteri* MG5346.

Britton et al. (2014) reported that *L. reuteri* ATCC 6475 released compounds inhibiting RANKL-induced osteoclastogenesis. Although the exact nature of the inhibitory compounds for osteoclastogenesis was not clarified, histamine might be associated with the suppression of osteoclast differentiation. Thomas et al. (2012) demonstrated that histamine released from *L. reuteri* inhibited TNF-α activity, which promotes osteoclastogenesis. In addition, CS-MG5346 did not show a cytotoxic effect in the MTT assay up to 400 μg/mL. Thus, a further experiment proceeded within this non-cytotoxic concentration range (Fig. 1B).

Effect of culture supernatant of *Lactobacillus reuteri* MG5346 (CS-MG5346) on osteoclastogenesis-associated gene expression

Osteoclast differentiation requires transcription factors essential for the induction of target genes (Kim and Kim, 2014). The effects of CS-MG5346 on the gene expression of two key osteoclast-specific transcriptional factors (*c-Fos* and *NFATc1*) were analyzed. CS-MG5346 treatment significantly downregulated RANKL-mediated elevated *c-Fos* and *NFATc1* gene expression in a dose-dependent manner (Figs. 2A and B). The binding of RANKL to RANK on the surface of osteoclast precursor cells recruits c-Fos at the early osteoclast differentiation stage, which in turn, activates NFATc1, a master regulator of osteoclastogenesis (Zhao et al., 2010). It has been reported that *c-Fos*-knock-out mice failed to undergo osteoclast differentiation (Wang et al., 1992). Thus, the downregulation of *c-Fos* and *NFATc1* can be a major contributor to the inhibition of osteoclastogenesis.

Stimulation of *NFATc1* promotes the expression of osteoclast-specific genes, such as *TRAP*, *cathepsin K*, and *metallo-proteinase-9* (*MMP-9*), that causing the degradation of bone extracellular matrix proteins (Asagiri and Takayanagi, 2007; Sundaram et al., 2007). Consistent with these reports, CS-MG5346 treatment significantly suppressed the expression of TRAP, cathepsin K, and MMP-9 ($p<0.05$; Figs. 2C, D, and E). The mRNA levels of TRAP, cathepsin K, and MMP-9 showed a high correlation with the level of bone resorption in patients with osteoarthritis and osteoporosis (Logar et al., 2007).

Effects of *Lactobacillus reuteri* MG5346 (MG5346) on alveolar bone loss and furcation involvement in ligature-induced periodontitis rat model

The mechanisms for the initiation and progression of periodontitis are still unclear and a large number of oral bacteria are involved in etiology of chronic periodontitis (Graves et al., 2008). The rat ligature model is one of the most frequently used non-primate animal periodontitis models. The ligatures around teeth cause plaque accumulation and induce periodontal inflammation and subsequent alveolar bone loss (Xu and Wei, 2006).

The effect of MG5346 administration for 8 wks on alveolar bone loss was determined in ligature-induced experimental periodontitis rats. The periodontal destruction was observed in both vertical (CEJ-ABC) and horizontal (furcation involvement) direction in multi-rooted teeth (Pilloni and Rojas, 2018). Micro-CT tomography indicated that ligation significantly increased both CEJ-ABC distance and furcation involvement. Although a decreasing tendency was observed in the CEJ-ABC distance by *L. reuteri* MG5346 administration, there was no significant difference between the ligation control and *L. reuteri* MG5346 group (1.60±0.22 vs.1.44±0.19). Conversely, furcation involvement was significantly decreased by administration of MG5346 (0.58±0.15 vs. 0.46±0.0.9; $p<0.05$; Fig. 3). The prolonged inflammation by periodontitis leads to bone resorption and furcation defect, and reduced furcation involvement significantly reduces the risk of bone loss (Parihar and Katoch, 2015). The adjuvant use of *L. reuteri* DSM 17938 (1×10^8 CFU/lozenge) for 21 days ameliorated chronic periodontitis by reducing gingival inflammation and deep periodontal pockets in smokers (Theodoro et al., 2019).

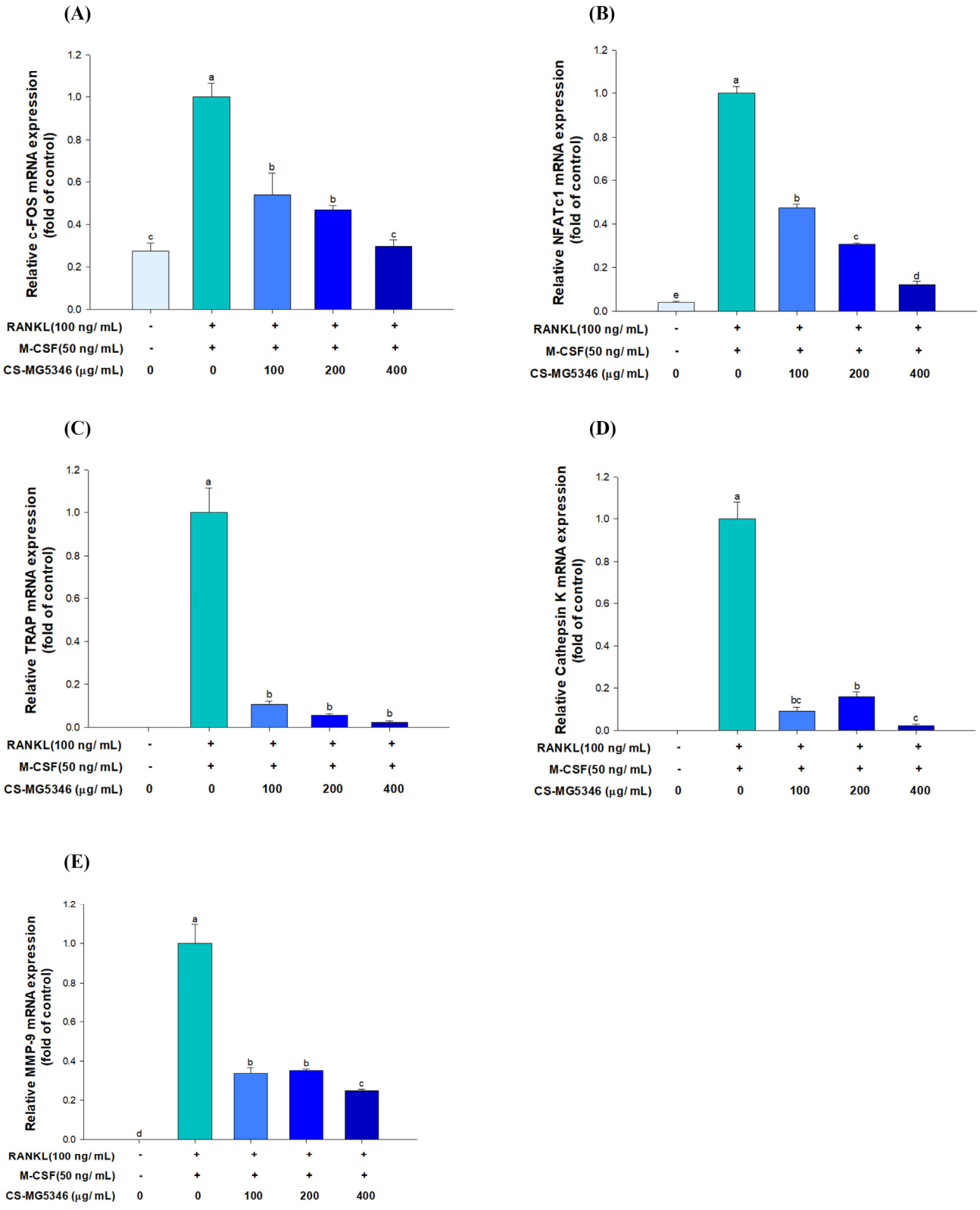

Fig. 2. Effects of CS-MG5346 on gene expression of (A) c-fos, (B) NFATc1, (c) TRAP, (D) cathepsin K, and (E) MMP-9 in RANKL-stimulated RAW 264.7 macrophages. [a–e] Different letters indicate significant differences at $p<0.05$. RANKL, receptor-activator of nuclear factor-kappa B ligand; CS-MG5346, culture supernatant of *Lactobacillus reuteri* MG5346; NFATc1, nuclear factor-activated T cells c1; TRAP, tartrate-resistant acid-phosphatase; MMP-9, matrix metallo-proteinase-9.

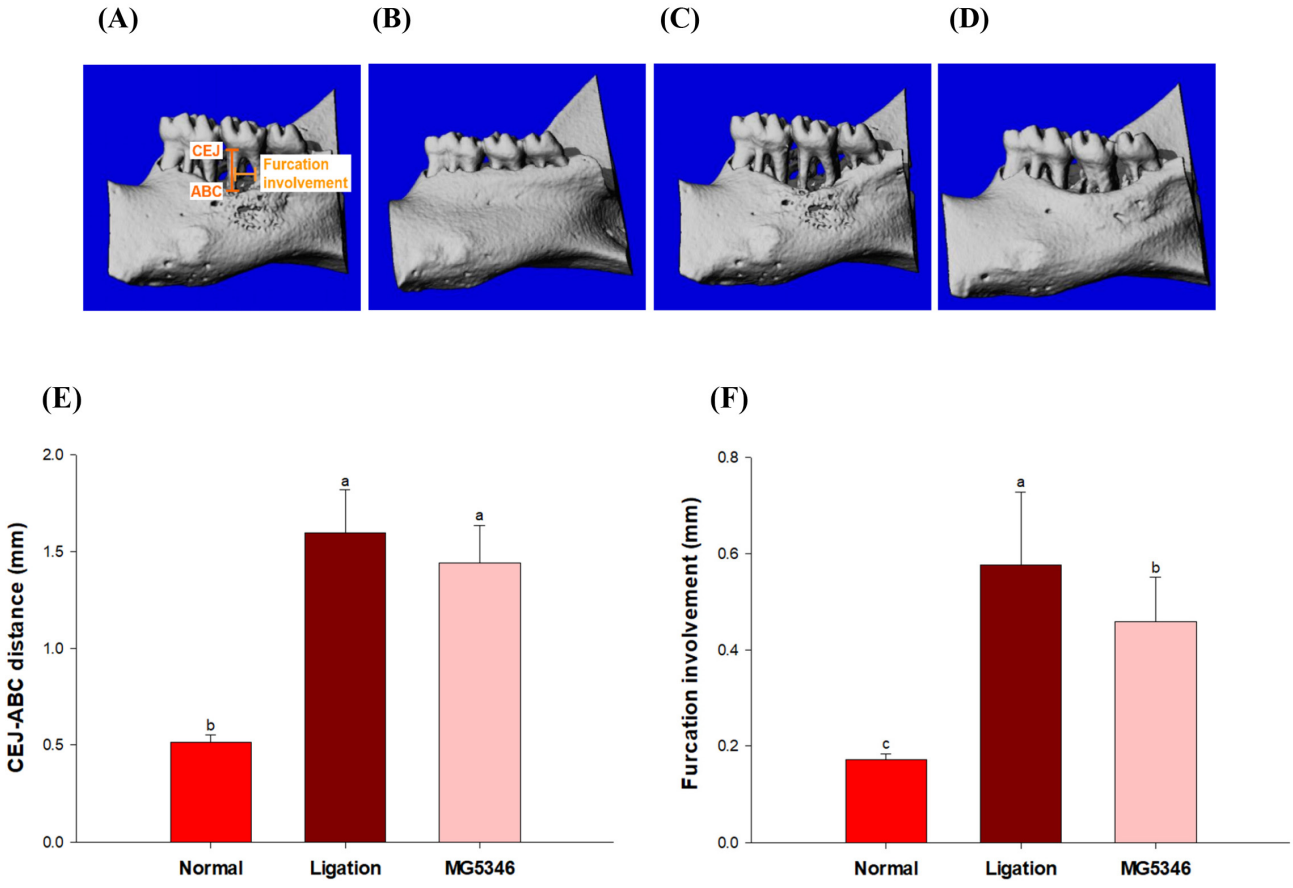

Fig. 3. Effects of MG5346 on CEJ-ABC distance and furcation involvement in experimental periodontitis rats. (A) Indication of cemento enamel junction-alveolar bone crest (CEJ-ABC) and furcation involvement, (B) representative image of untreated control group, (C) representative image of ligature control group, (D) representative image of ligature+*Lactobacillus reuteri* MG5346 group, (E) CEJ-ABC distance, and (F) furcation involvement. The cement–enamel junction (CEJ)–alveolar bone crest (ABC) distance and degree of maxillary molar furcation involvement were used as an index of alveolar bone loss and periodontal tissue damage. $^{a-c}$ Different letters indicate significant differences at $p<0.05$.

Effects of *Lactobacillus reuteri* MG5346 (MG5346) on receptor activator of the nuclear factor κB ligand (RANKL) and osteoprotegerin (OPG) gene expression in gingival tissue

RANKL-RANK is a key pathway modulating the formation and differentiation of osteoclasts (Wada et al., 2006). OPG competitively binds to RANKL, subsequently interfering with the binding of RANKL with RANK. The imbalance in RANKL/OPG led to increased bone resorption (Boyce and Xing, 2008). Periodontal tissue was isolated from rats, and the expression of *RANKL* and *OPG* was analyzed using qRT-PCR. The expression of *RANKL* increased by ligation while it was decreased by MG5346 administration (Fig. 4A). The expression of *OPG*, which was decreased by periodontitis induction was significantly recovered by administration of MG5346 ($p<0.05$; Fig. 4B). The RANKL/OPG ratio in MG5346-fed groups was close to the non-ligation control group (Fig. 4C).

Although the modulation of bone metabolism by administration of probiotics has been reported (Britton et al., 2014; Jung et al., 2022; Yousf et al., 2015), the evidence is still inconclusive. Hu et al. (2021) reported that extracellular vesicles (EVs) released from *L. reuteri* might be involved in the mitigation of periodontitis. The administration of EVs from *L. reuteri* BBC3 exerted an anti-inflammatory effect in lipopolysaccharide-stimulated chicken macrophages and improved intestinal injury in

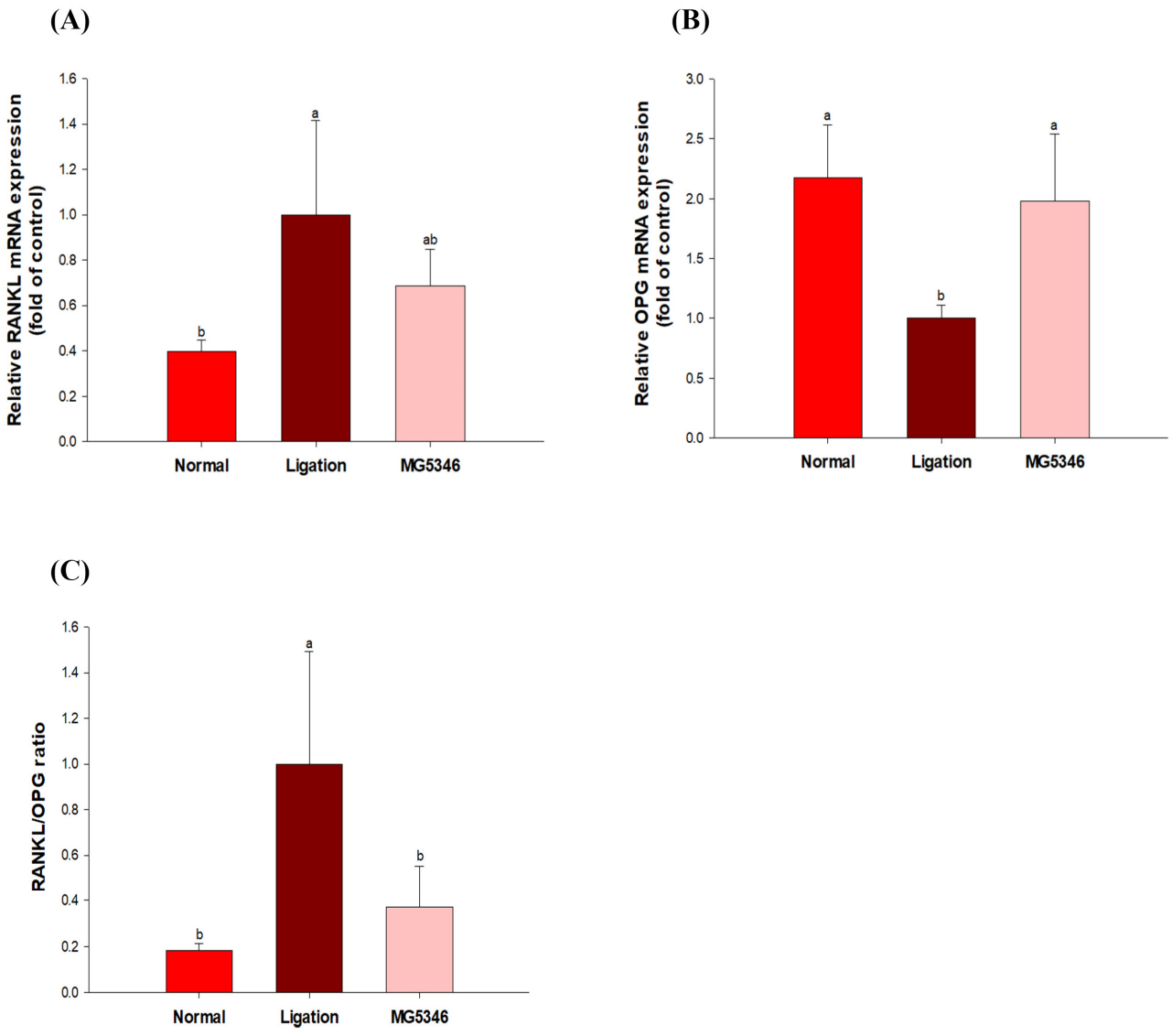

Fig. 4. Effects of MG5346 on gene expression of (A) RANKL, (B) OPG, and (C) RANKL/OPG ratio in gingival tissue of experimental periodontitis rats. [a,b] Different letters indicate significant differences at $p<0.05$. RANKL, receptor activator of nuclear factor-kappa-B ligand; MG5346, *Lactobacillus reuteri* MG5346; OPG, osteoprotegerin.

chickens. Alternatively, the ability of probiotics to modulate C-X-C motif chemokine (CXCL8) was suggested as a potential mechanism of probiotic immune modulation (Mendi et al., 2016). CXCL8 is a chemokine released from various cell types, such as gum epithelial cells, and it recruits neutrophils to the site of infection (Yamamoto and Aizawa, 2021). *Porphyromonas gingivalis*-mediated CXCL8 inhibition reduced the host immune response and enhanced periodontal tissue damage (Sochalska and Potempa, 2017). Probiotics, such as *L. rhamnosus* ATCC 9595, *L. casei* 324 m, and *L. reuteri* upregulated CXCL8 gene expression and counteracted *P. gingivalis*-mediated CXCL8 suppression (Albuquerque-Souza et al., 2021; Allaker and Stephen, 2017; Mendi et al., 2016). Oral administration of *L. reuteri* tablet significantly reduced proinflammatory cytokine levels (TNF-α, IL-1β, and IL-17) in 18 out of 24 patients with chronic periodontitis. The clinical indices, such as bleeding index, periodontal probe depth, and clinical adhesion level, were also significantly improved (Szkaradkiewicz et al., 2014).

Conclusion

Probiotics are generally regarded as safe, except for specific health conditions, such as patients with immune-compromisation. The development of oral probiotics/postbiotics offers valuable options to prevent or alleviate periodontitis. Based on results in osteoclastogenesis and the ligature-induced periodontitis rat model, MG5346 can be a promising probiotic strain for oral health. Carefully designed clinical studies are required to warrant the efficacy of oral probiotics/postbiotics.

Conflicts of Interest

YongGyeong Kim and Chang-Ho Kang are employees of Mediogen. Industry employees are involved in the study probiotic characterization, but they did not play a role in other data collection, analyses, or interpretation of data, writing of the manuscript, or in the decision to publish the results.

Acknowledgments

This research was financially supported by the Ministry of Small and Medium Sized Enterprises (SEMs) and Startups (MSS), Korea, under the "Regional Star-Enterprise Development Program (R&D, S2908142)" supervised by the Korea Institute for Advancement of Technology (KIAT).

Author Contributions

Conceptualization: Kang CH, Imm JY. Data curation: Jeong YJ, Jung JI, Kim YG. Investigation: Jeong YJ, Jung JI, Kim YG. Writing - original draft: Jeong YJ, Kim YG. Writing - review & editing: Jeong YJ, Jung JI, Kim YG, Kang CH, Imm JY.

Ethics Approval

Animal experiments were carried out after approval from the Institutional Animal Care and Use Committee of KNOTUS, Korea (KNOTUS 21-KE-032).

References

Albuquerque-Souza E, Ishikawa KH, Amado PP, Nicoli JR, Holzhausen M, Mayer MPA. 2021. Probiotics improve re-epithelialization of scratches infected by *Porphyromonas gingivalis* through up-regulating CXCL8-CXCR1/CXCR2 axis. Anaerobe 72:102458.

Allaker RP, Stephen AS. 2017. Use of probiotics and oral health. Curr Oral Health Rep 4:309-318.

Asagiri M, Takayanagi H. 2007. The molecular understanding of osteoclast differentiation. Bone 40:251-264.

Boyce BF, Xing L. 2008. Functions of RANKL/RANK/OPG in bone modeling and remodeling. Arch Biochem Biophys 473:139-146.

Britton RA, Irwin R, Quach D, Schaefer L, Zhang J, Lee T, Parameswaran N, McCabe LR. 2014. Probiotic *L. reuteri* treatment prevents bone loss in a menopausal ovariectomized mouse model. J Cell Physiol 229:1822-1830.

Bungau SG, Behl T, Singh A, Sehgal A, Singh S, Chigurupati S, Vijayabalan S, Das S, Palanimuthu VR. 2021. Targeting

probiotics in rheumatoid arthritis. Nutrients 13:3376.

Chen L, Gu Q, Li P, Chen S, Li Y. 2019. Genomic analysis of *Lactobacillus reuteri* WHH1689 reveals its probiotic properties and stress resistance. Food Sci Nutr 7:844-857.

Cristofori F, Dargenio VN, Dargenio C, Miniello VL, Barone M, Francavilla R. 2021. Anti-inflammatory and immunomodulatory effects of probiotics in gut inflammation: A door to the body. Front Immunol 12:578386.

Gatej S, Gully N, Gibson R, Bartold PM. 2017. Probiotics and periodontitis: A literature review. J Int Acad Periodontol 19:42-50.

Graves DT, Fine D, Teng YTA, Van Dyke TE, Hajishengallis G. 2008. The use of rodent models to investigate host–bacteria interactions related to periodontal diseases. J Clin Periodontol 35:89-105.

He B, Hoang TK, Wang T, Ferris M, Taylor CM, Tian X, Luo M, Tran DQ, Zhou J, Tatevian N, Luo F, Molina JG, Blackburn MR, Gomez TH, Roos S, Rhoads JM, Liu Y. 2017. Resetting microbiota by *Lactobacillus reuteri* inhibits T reg deficiency–induced autoimmunity via adenosine A_{2A} receptors. J Exp Med 214:107-123.

Hsieh FC, Lan CCE, Huang TY, Chen KW, Chai CY, Chen WT, Fang AH, Chen YH, Wu CS. 2016. Heat-killed and live *Lactobacillus reuteri* GMNL-263 exhibit similar effects on improving metabolic functions in high-fat diet-induced obese rats. Food Funct 7:2374-2388.

Hu R, Lin H, Wang M, Zhao Y, Liu H, Min Y, Yang X, Gao Y, Yang M. 2021. *Lactobacillus reuteri*-derived extracellular vesicles maintain intestinal immune homeostasis against lipopolysaccharide-induced inflammatory responses in broilers. J Anim Sci Biotechnol 12:25.

Jose NM, Bunt CR, Hussain MA. 2015. Implications of antibiotic resistance in probiotics. Food Rev Int 31:52-62.

Jung JI, Baek SM, Nguyen TH, Kim JW, Kang CH, Kim S, Imm JY. 2021. Effects of probiotic culture supernatant on cariogenic biofilm formation and RANKL-induced osteoclastogenesis in RAW 264.7 macrophages. Molecules 26:733.

Jung JI, Kim YG, Kang CH, Imm JY. 2022. Effects of *Lactobacillus curvatus* MG5246 on inflammatory markers in *Porphyromonas gingivalis* lipopolysaccharide-sensitized human gingival fibroblasts and periodontitis rat model. Food Sci Biotechnol 31:111-120.

Kim JG, Lee E, Kim SH, Whang KY, Oh S, Imm JY. 2009. Effects of a *Lactobacillus casei* 393 fermented milk product on bone metabolism in ovariectomised rats. Int Dairy J 19:690-695.

Kim JH, Kim N. 2014. Regulation of NFATc1 in osteoclast differentiation. J Bone Metab 21:233-241.

Kim S, Kang SS, Choi SI, Kim GH, Imm JY. 2019. *Ecklonia cava* extract containing dieckol suppresses RANKL-induced osteoclastogenesis via MAP kinase/NF-κB pathway inhibition and heme oxygenase-1 induction. J Microbiol Biotechnol 29:11-20.

Kõll-Klais P, Mändar R, Leibur E, Marcotte H, Hammarström L, Mikelsaar M. 2005. Oral lactobacilli in chronic periodontitis and periodontal health: Species composition and antimicrobial activity. Oral Microbiol Immunol 20:354-361.

Kong YY, Yoshida H, Sarosi I, Tan HL, Timms E, Capparelli C, Morony S, Oliveira-dos-Santos AJ, Van G, Itie A, Khoo W, Wakeham A, Dunstan CR, Lacey DL, Mak TW, Boyle WJ, Penninger JM. 1999. OPGL is a key regulator of osteoclastogenesis, lymphocyte development and lymph-node organogenesis. Nature 397:315-323.

Lee CS, Lee SH, Kim SH. 2020. Bone-protective effects of *Lactobacillus plantarum* B719-fermented milk product. Int J Dairy Technol 73:706-717.

Lee D, Imm JY. 2017. AMP kinase activation and inhibition of nuclear factor-kappa B (NF-κB) translocation contribute to the anti-inflammatory effect of tricin. J Food Biochem 41:e12293.

Li T, Teng D, Mao R, Hao Y, Wang X, Wang J. 2020. A critical review of antibiotic resistance in probiotic bacteria. Food Res Int 136:109571.

Logar DB, Komadina R, Preželj J, Ostanek B, Trošt Z, Marc J. 2007. Expression of bone resorption genes in osteoarthritis and in osteoporosis. J Bone Miner Metab 25:219-225.

Mendi A, Köse S, Uçkan D, Akca G, Yilmaz D, Aral L, Gültekin SE, Eroğlu T, Kiliç E, Uçkan S. 2016. *Lactobacillus rhamnosus* could inhibit *Porphyromonas gingivalis* derived CXCL8 attenuation. J Appl Oral Sci 24:67-75.

Mu Q, Tavella VJ, Luo XM. 2018. Role of *Lactobacillus reuteri* in human health and diseases. Front Microbiol 9:757.

Nazir MA. 2017. Prevalence of periodontal disease, its association with systemic diseases and prevention. Int J Health Sci 11:72-80.

Parihar AS, Katoch V. 2015. Furcation involvement & its treatment: A review. J Adv Med Dent Sci Res 3:81-87.

Pilloni A, Rojas MA. 2018. Furcation involvement classification: A comprehensive review and a new system proposal. Dent J 6:34.

Pineiro M, Stanton C. 2007. Probiotic bacteria: Legislative framework—requirements to evidence basis. J Nutr 137:850S-853S.

Singh TP, Kaur G, Malik RK, Schillinger U, Guigas C, Kapila S. 2012. Characterization of intestinal *Lactobacillus reuteri* strains as potential probiotics. Probiotics Antimicrob Proteins 4:47-58.

Sochalska M, Potempa J. 2017. Manipulation of neutrophils by *Porphyromonas gingivalis* in the development of periodontitis. Front Cell Infect Microbiol 7:197.

Sundaram K, Nishimura R, Senn J, Youssef RF, London SD, Reddy SV. 2007. RANK ligand signaling modulates the matrix metalloproteinase-9 gene expression during osteoclast differentiation. Exp Cell Res 313:168-178.

Szkaradkiewicz AK, Stopa J, Karpiński TM. 2014. Effect of oral administration involving a probiotic strain of *Lactobacillus reuteri* on pro-inflammatory cytokine response in patients with chronic periodontitis. Arch Immunol Ther Exp 62:495-500.

Tanaka S, Nakamura K, Takahasi N, Suda T. 2005. Role of RANKL in physiological and pathological bone resorption and therapeutics targeting the RANKL–RANK signaling system. Immunol Rev 208:30-49.

Tekce M, Ince G, Gursoy H, Dirikan Ipci S, Cakar G, Kadir T, Yılmaz S. 2015. Clinical and microbiological effects of probiotic lozenges in the treatment of chronic periodontitis: A 1-year follow-up study. J Clin Periodontol 42:363-372.

Theodoro LH, Cláudio MM, Nuernberg MAA, Miessi DMJ, Batista JA, Duque C, Garcia VG. 2019. Effects of *Lactobacillus reuteri* as an adjunct to the treatment of periodontitis in smokers: Randomised clinical trial. Benef Microbes 10:375-384.

Thomas CM, Hong T, van Pijkeren JP, Hemarajata P, Trinh DV, Hu W, Britton RA, Kalkum M, Versalovic J. 2012. Histamine derived from probiotic *Lactobacillus reuteri* suppresses TNF via modulation of PKA and ERK signaling. PLOS ONE 7:e31951.

Tokatlı M, Gülgör G, Bağder Elmacı S, Arslankoz İşleyen N, Özçelik F. 2015. *In vitro* properties of potential probiotic indigenous lactic acid bacteria originating from traditional pickles. BioMed Res Int 2015:315819.

Valeur N, Engel P, Carbajal N, Connolly E, Ladefoged K. 2004. Colonization and immunomodulation by *Lactobacillus reuteri* ATCC 55730 in the human gastrointestinal tract. Appl Environ Microbiol 70:1176-1181.

Wada T, Nakashima T, Hiroshi N, Penninger JM. 2006. RANKL–RANK signaling in osteoclastogenesis and bone disease. Trends Mol Med 12:17-25.

Wang ZQ, Ovitt C, Grigoriadis AE, Möhle-Steinlein U, Rüther U, Wagner EF. 1992. Bone and haematopoietic defects in

mice lacking *c-fos.* Nature 360:741-745.

Xu Y, Wei W. 2006. A comparative study of systemic subantimicrobial and topical treatment of minocycline in experimental periodontitis of rats. Arch Oral Biol 51:794-803.

Yamamoto M, Aizawa R. 2021. Maintaining a protective state for human periodontal tissue. Periodontol 2000 86:142-156.

Yousf H, Tomar G, Srivastava RK. 2015. Probiotics and bone health: It takes GUTS to improve bone density. Int J Immunother Cancer Res 1:18-22.

Zhao Q, Wang X, Liu Y, He A, Jia R. 2010. NFATc1: Functions in osteoclasts. Int J Biochem Cell Biol 42:576-579.