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Original Article

Enhanced antimicrobial and remineralizing properties of self-adhesive orthodontic resin containing mesoporous bioactive glass and zwitterionic material

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Received 1 September 2021; Final revision received 18 September 2021

Available online 7 October 2021

KEYWORDS

SARs;
MBNs;
MPCs;
Antimicrobial properties;
Remineralizing properties

Abstract Background/purpose: Self-adhesive resins (SARs) do not require additional restorative adhesives and provide adequate adhesion to mineralized dental structures by shortening the bonding time in clinics where moisture control and isolation are difficult. The aim of this study was to evaluate the mechanical and biological properties of SARs containing mesoporous bioactive glass nanoparticles (MBNs) and 2-methacryloyloxyethyl phosphorylcholine (MPC) and to determine their antibacterial and remineralization effects.

Materials and methods: MBNs and MPC were added to SARs to improve their physical properties and remineralization ability. The experimental resins assessed in this study were SARs mixed with 3%MPC, 5%MPC, 1%MBN+3%MPC, or 3%MBN+3%MPC. The shear bond strength, microhardness, adhesive remnant index, ion dissolution, degree of conversion, and antibacterial properties of the SARs were evaluated. To assess the remineralization properties, micro-computed tomography analysis was performed after pH cycling.

Results: Increasing the MBN content in SAR resulted in higher microhardness compared to the control SAR. The shear bond strength decreased in the SAR+5%MPC group and increased in the SAR+1%MBN+3%MPC and SAR+3%MBN+5%MPC groups.

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<https://doi.org/10.1016/j.jds.2021.09.029>

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Conclusion: Our findings suggest that SARs containing MBNs and MPC have antibacterial and remineralization effects on the enamel.

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Introduction

Bracket bonding procedures should be simple and time-efficient as the moist environment in the oral cavity may compromise the adhesion of dental materials. Self-adhesive orthodontic resin (SAR) is a material that combines priming and adhesive agents into a single application, eliminating the application of primers after etching the enamel surface. SAR makes the bonding procedure more effective by reducing the working time and decreasing the chances of saliva contamination while attaining clinically successful bond strength.

When a firm bonding to enamel is required, applying a primer prior to an adhesive allows the primer to infiltrate the space between the enamel prism tags and the bonding agents that need to be strongly attached to the tooth surface for long term stability. Thus, a well-infiltrated resin on the enamel surface increases the bond strength. A previous study reported that adding a primer layer to the adhesive material increases the shear bond strength (SBS) and decreases the remnants on the tooth after debonding.¹ However, Ok et al. showed that there was no statistically significant difference in bonding failures between a conventional adhesive system containing primers and a single-component adhesive system.²

Other studies have reported that SARs may cause higher microleakage than conventional restorative materials owing to low etching capacity, which leads to inadequate micromechanical retention between the restorative material and the tooth surface. Leftover acidic materials from SAR can prevent efficient polymerization of monomers, and unreacted monomers can decrease resin seal and increase microleakage.³ Microleakage can lead to the development of white spots or plaques around the margins of the brackets, where meticulous tooth brushing is difficult.

Complex orthodontic appliances can facilitate biofilm formation despite good oral hygiene. As the biofilm accumulates adjacent to the orthodontic brackets, the levels of *Streptococcus mutans* and lactobacilli increase, whereas the pH of the accumulated plaques decreases. This acidic environment promotes demineralization of tooth enamel at the margins of the brackets, known as white spot lesions.⁴ Inhibiting bacterial attachment to the biofilm is considered an effective strategy for decreasing the incidence of infectious diseases, as bacterial adherence and attachment are critical in the formation and maturation of biofilms.⁵ Numerous studies have been conducted on strategies to destroy biofilms in the oral cavity. Tooth brushing and tongue scraping are used to mechanically remove microorganisms.⁶ Mouth rinses and toothpastes containing antibacterial compounds, such as chlorhexidine, cetylpyridinium chloride, and triclosan, are used to chemically prevent bacterial growth

and biofilm formation.⁶ Disinfectants are useful; however, they can cause adverse effects, such as extrinsic brown staining of teeth and restorations, toxicity to mucous membranes, burning sensation, and mouth irritation. Considering the disadvantages of disinfectants, a novel strategy or material to inhibit bacterial adherence and plaque formation has been developed. As a kind of zwitterionic material, it has been shown that 2-methacryloyloxyethyl phosphorylcholine (MPC), which mimics a biomembrane, is harmless to humans and reduces protein adsorption and bacterial adhesion while inhibiting cell adhesion.⁶

Bioactive glasses release calcium and phosphorus ions and act as a source of various ions (SiO₂, CaO, Na₂O, and P₂O₅). The ions mentioned earlier released from the bioactive glasses act as buffers, which increase the pH of the dissolution medium and prevent demineralization of the enamel. They also promote remineralization by facilitating the formation of hydroxyapatite. In particular, mesoporous bioactive glass nanoparticles (MBNs) have the ability to load other biomolecules, and demonstrate increased bioactivity.⁷

A recent study by Park et al. proved that orthodontic adhesives containing MPC and MBNs possess clinically acceptable mechanical properties and biological stability. They demonstrated that the addition of MPC and MBNs improved the antibacterial and anti-demineralization effects of the material.⁸ The overall goal of this study was to develop a novel SAR containing MPC and MBN and investigate their mechanical properties, antibacterial effects, and anti-demineralization abilities.

Materials and methods

Synthesis of mesoporous bioactive glass

Mesoporous bioactive glass was synthesized using the modified sol–gel method.⁹ Briefly, 20 mL of ethanol (Samchun, Pyeongtaek, South Korea), 2 mL of aqueous ammonia (Samchun), 10 mL of 2-ethoxyethanol (Sigma–Aldrich, St. Louis, MO, USA), 3.12 g of calcium nitrate tetrahydrate (Sigma–Aldrich), and 1 g of hexadecyltrimethylammonium bromide (Sigma–Aldrich) were added to 150 mL distilled water at room temperature, and stirred for 30 min at 600 rpm. Thereafter, 5 mL of tetraethyl orthosilicate (Sigma–Aldrich) was added to the mixture and stirred for 30 min at room temperature. Next, 0.25 mL of triethyl phosphate (Sigma–Aldrich) was added, and the mixture was stirred at room temperature for 4 h. When white precipitates were formed, the solution was washed and subsequently dried for 24 h in an oven at 60 °C. Finally, it was heated for 5 h at 600 °C.

Preparation of experimental SARs containing MPC and MBN

To synthesize the experimental orthodontic bonding resins, previously synthesized MBNs and MPC (Sigma–Aldrich) were mixed with SARs (Ortho Connect Flow; GC Corp, Tokyo, Japan). Different amounts of MPC and MBNs were mixed with SAR for 10 s in a 2-mL black e-tube using a mixer (3M ESPE, Seefeld, Germany; Table 1). To evaluate the degree of conversion, dissolution, microhardness, and biological properties, resin disk samples of two different sizes (diameter of 5 mm and height of 1 mm to test the antibacterial activity and degree of conversion; diameter of 10 mm and height of 1 mm to test the microhardness and dissolution test) were fabricated by adding SAR to the disk molds, covering the top with slide glasses, and light-curing for 20 s (VALO; Ultradent, South Jordan, UT, USA).

Microhardness

To measure the mechanical hardness of each sample group, a microhardness tester (MVK-H1; Mitutoyo, Kanagawa, Japan) was used to perform Vickers test; the measurement was performed 20 times per group. Microhardness was defined as the load on the indented surface area of the resin disk (10 mm in diameter and 1 mm in height). A load of 100 g was used in this study.

Degree of conversion (DC)

The DC was analyzed using Fourier-transform infrared spectroscopy (FT-IR, Spectrum GX; PerkinElmer, Waltham, MA, USA) and calculated using the attenuated total reflectance (ATR) method. This method utilizes the peak ratios of double bonds in aliphatic compounds (1640 cm^{-1}) and aromatic compounds (1610 cm^{-1}) to determine the DC. The wavenumber of the spectrum was $650\text{--}4000\text{ cm}^{-1}$, and the spectrum of the FTIR was recorded as 32 scans per second with a resolution of 4 cm^{-1} . To determine the ratio of double bonds formed by polymerization, the number of methacrylate carbon double bonds (aliphatic carbon double bond; peak at 1634 cm^{-1}) before and after polymerization and the absorbance spectra of the internal standard (aromatic carbon double bond; peak at 1608 cm^{-1}) were measured.¹⁰ Three data trials were conducted for each group (10 mm disk).

Table 1 Groups of experimental self-adhesive orthodontic bonding resins.

Groups	SAR, wt%	MBN, wt%	MPC, wt%
SAR	100	0	0
SAR + 3% MPC	97	0	3
SAR + 5% MPC	95	0	5
SAR + 1% MBN + 3% MPC	96	1	3
SAR + 3% MBN + 3% MPC	94	3	3

SAR; self-adhesive resin, MBN; mesoporous bioactive glass nanoparticle, MPC; 2-methacryloyloxyethyl phosphorylcholine.

Dissolution test

Inductively coupled plasma-atomic emission spectroscopy (ICP-AES; Optima 8300, PerkinElmer) was used to evaluate ion release from SAR mixed with MPC and/or MBNs. The ICP-AES test requires a surface area of 3 cm^2 per milliliter when the thickness is greater than 0.5 mm (ISO 10993-12). In this study, six resin disks of 10 mm in diameter and 1 mm in thickness were required for 4 mL of distilled water (DW). Disks were submerged in DW for 1, 3, 7, 14, or 21 days per group. Calcium, phosphate, and silicon ion levels in DW were measured after removing the disks.

Antibacterial test

S. mutans (ATCC 25175; American Type Culture Collection (ATCC), Manassas, VA 201808, USA) was used for the antibacterial tests. *S. mutans* was cultured in brain heart infusion at $37\text{ }^\circ\text{C}$ and stored in an aerobic incubator. Each disk was sterilized with ethylene oxide (EO) gas and placed in a 96-well plate containing 1.0×10^5 CFU/mL of *S. mutans*; the plate was then cultured at $37\text{ }^\circ\text{C}$. Each of the control and four experimental groups was incubated for 24, 48, and 72 h, and the absorbance at 405 nm was measured using a microplate reader (SpectraMax, iD3, BioTek, Winooski, VT, USA).

Shear bond test

Twenty premolars extracted for orthodontic treatment were used per group. To bond brackets to the teeth, tooth surfaces were etched for 30 s with 35% phosphoric acid gel (Ultra Etch; Ultradent), rinsed, and dried. The transparent tapes were applied on the buccal of tooth, except for the $5\text{ mm} \times 5\text{ mm}$ area that was to be etched. The tapes were removed after the etching and washing process. After confirming a chalky surface on the tooth, the four experimental orthodontic bonding resins (SAR + 3% MPC, SAR + 5% MPC, SAR + 1% MBN + 3% MPC, SAR + 3% MBN + 3% MPC) were added to the bracket (3M Unitek, Monrovia, CA, USA), without applying orthodontic adhesives. The brackets were aligned with the long axis of the teeth. Excess resins were removed, and each group was light-cured for 20 s. Samples were stored in distilled water for 24 h, and the shear bond strength (SBS) was measured using a universal testing machine (Instron, Canton, MA, USA). The SBS (MPa) was calculated by measuring the maximum load (N) at the crosshead at a speed of 1 mm/

Table 2 Adhesive remnant index (ARI) score.

Score	Definition
1	All the adhesive remained on the tooth
2	More than 90% of the adhesive remained on the tooth
3	10%–90% of the adhesive remained on the tooth
4	Less than 10% of the adhesive remained on the tooth
5	No adhesive remained on the tooth

min divided by the surface area of the bracket. The remaining resins on the tooth surfaces were evaluated using the adhesive remnant index (ARI) score, as shown in Table 2.¹¹ This study was reviewed and approved by Institutional review board of Pusan National University Dental Hospital (PNUDH-2021-015).

Anti-demineralization test

The pH cycling method was used to test the anti-demineralization and remineralization effects.¹² The bracket attachment process was performed in the same way as in the SBS measurement. After the brackets were bonded, samples were stored in distilled water for 24 h, followed by a cycle of submerging the samples in demineralization solution (Biosesang, Seongnam, South Korea) for 6 h and in remineralization solution (Biosesang) for 18 h. The pH cycle was repeated for 14 days. Between the solution changes, the samples were transferred to distilled water for 1 min, washed, and dried. The solutions were replaced every seven days. After pH cycling, the samples were scanned using micro-computed tomography (micro-CT; InspXio SMX-90CT, Shimadzu, Kyoto, Japan) at 90 kV and 109 μ A. The micro-CT data were analyzed using ImageJ software (National Institutes of Health, Bethesda, MD, USA). Various sizes of CT scans were corrected using a scale bar. A brightness of 87% was defined as a sound enamel for analysis, and data exceeding the criteria were considered to have shown enamel loss. The remineralization length of each sample, defined as the distance between the end point of the orthodontic bonding resins and the sound enamel, was measured.

Statistical analysis

After mechanical and biological tests, one-way analysis of variance (ANOVA) and Tukey's post hoc comparison were performed. The ARI scores between groups were compared using the Kruskal–Wallis and Mann–Whitney tests. A p-value less than 0.05 was defined as statistically significant. All statistical analyses were performed using SPSS version 21.0 (IBM, Armonk, NY, USA).

Results

Shear bond strength

Compared to the untreated control (SAR, 10.09 ± 2.35 MPa), SAR + 5% MPC (7.39 ± 1.62 MPa) showed a slight decrease in SBS, while SAR + 1% MBN + 3% MPC (17.67 ± 2.97 MPa) and SAR + 3% MBN + 3% MPC (15.40 ± 2.39 MPa) showed an increase in SBS ($p < 0.05$, Fig. 1).

Adhesive remnant index score

There were no significant differences in the ARI scores between the groups ($p > 0.05$) (Table 3).

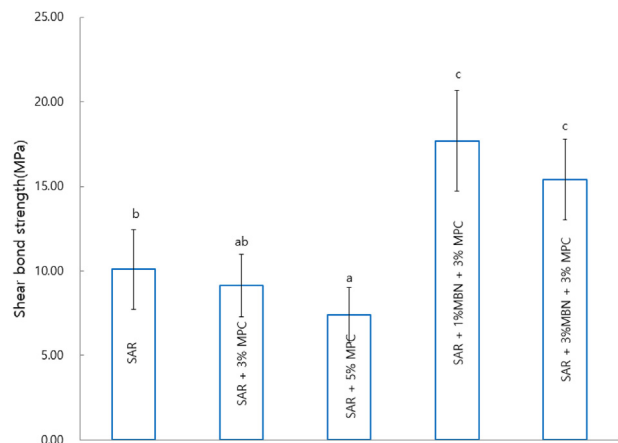


Figure 1 Comparison of shear bond (SBS) between the control SAR and MPC- and MBN-incorporated SARs. Labels with the same letters indicate no statistically significant differences between groups ($p > 0.05$). A one-way ANOVA was performed ($n = 20$). SAR; self-adhesive resin, MPC; 2-methacryloyloxyethyl phosphorylcholine, MBN; mesoporous bioactive glass nanoparticle.

Table 3 Adhesive remnant index (ARI) score.

Type	No. of Samples	ARI Scores					Statistics Kruskal–Wallis
		1	2	3	4	5	
Self-adhesive resin (SAR)	20			19		1	$p = 0.649$
SAR + 3% MPC	20		1	18		1	
SAR + 5% MPC	20		1	19			
SAR + 1% MBN + 3% MPC	20			20			
SAR + 3% MBN + 3% MPC	20			20			

SAR; self-adhesive resin, MBN; mesoporous bioactive glass nanoparticle, MPC; 2-methacryloyloxyethyl phosphorylcholine.

Microhardness

There were statistically significant increases in microhardness in all the experimental groups compared to the control (SAR). There was no significant difference in microhardness between the two groups with different MPC contents. However, there was a statistically significant difference between the MPC-added groups and the MBN- and MPC-added groups (Fig. 2).

Antibacterial test

For *S. mutans*, all experimental groups showed statistically reduced values compared to the control group (SAR) on days 1 and 3 (Fig. 3).

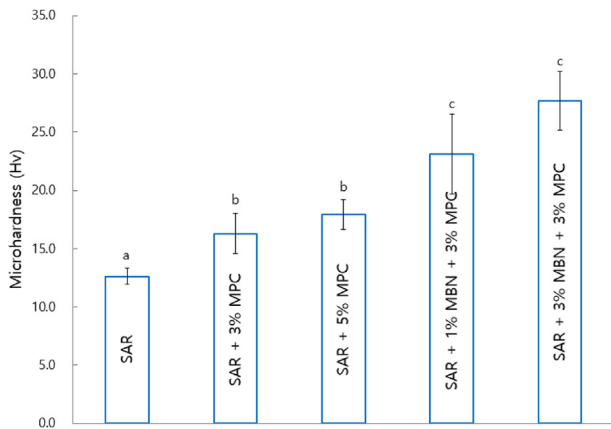


Figure 2 Comparison of microhardness between the control (SAR) and MBN-incorporated SARs. Labels with the same letters indicate no statistically significant difference between the groups ($p > 0.05$). A one-way ANOVA was performed ($n = 20$). SAR; self-adhesive resin, MPC; 2-methacryloyloxyethyl phosphorylcholine, MBN; mesoporous bioactive glass nanoparticle, ANOVA; analysis of variance.

Dissolution test

Changes in the concentrations of Ca, Si, and P released from the control (SAR), SAR + 3% MPC, SAR + 5% MPC, SAR + 1% MBN + 3% MPC, and SAR + 3% MBN + 3% MPC disks over 21 days are shown in Fig. 4. The Ca concentration was significantly increased in the groups containing both MBNs and MPC. For Si, all the groups displayed progressive increases over 14 days. The P concentration increased consistently until day 14 in all groups, except for the control (SAR), and then decreased subsequently (Fig. 4).

Degree of conversion

There were no statistically significant differences in the DC among the groups. The DC values for the groups are as

follows: control (SAR, $50.58\% \pm 2.17\%$), SAR + 3% MPC ($58.40\% \pm 10.59\%$), SAR + 5% MPC ($55.75\% \pm 8.32\%$), SAR + 1% MBN + 3% MPC ($53.66\% \pm 11.34\%$), SAR + 3% MBN + 3% MPC ($51.58\% \pm 10.77\%$).

Anti-demineralization test

Compared to the control (SAR, $96.1 \pm 19.5 \mu\text{m}$), all the groups showed a significant difference in remineralization length. The remineralization length increased as the MBN content of the sample increased (Fig. 5).

Discussion

Recently, numerous studies have attempted to use Bioactive glass (BAG) as a composite resin filler owing to its remineralization effects.^{13–15} Therefore, the mechanical and biological properties of MBN-incorporated SAR were investigated in this study.¹⁶ Through the addition of MBN, which has high chemical and mechanical stabilities and effective bioactive functions, SAR displayed improved test results and showed potential as a new class of orthodontic resin that can simplify clinical procedures with increased bonding and resin strengths. A previous study discovered that increasing the amount of MBNs (1%, 3%, 5%) added to SAR resulted in greater SBS.¹⁶ Interestingly, the 5% MBN group showed slightly decreased SBS compared to the 3% MBN group. This result indicates that a high MBN content may degrade the mechanical properties of the resin. Therefore, MBN concentrations of 1% and 3% were selected for this study.^{8,17}

Salivary protein adsorption is a prerequisite for plaque formation and bacterial attachment. Hence, preventing protein adsorption on the surfaces of dental composites is crucial for inhibiting biofilm formation and suppressing secondary caries. MPC can chemically bind to resin surfaces. MPC-treated surfaces show significant resistance to oral protein adsorption and bacterial adhesion even when the surface is brushed with a toothbrush.¹⁸ Based on

S. mutans

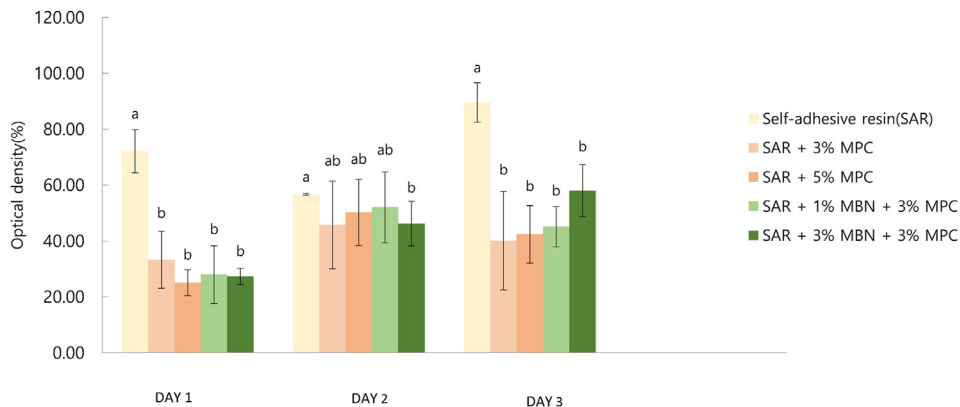


Figure 3 Results of antibacterial tests of the control (SAR) and MPC- and MBN-incorporated SARs against *Streptococcus mutans*. A one-way ANOVA was performed ($n = 3$). SAR; self-adhesive resin, MPC; 2-methacryloyloxyethyl phosphorylcholine, MBN; mesoporous bioactive glass nanoparticle, ANOVA; analysis of variance.

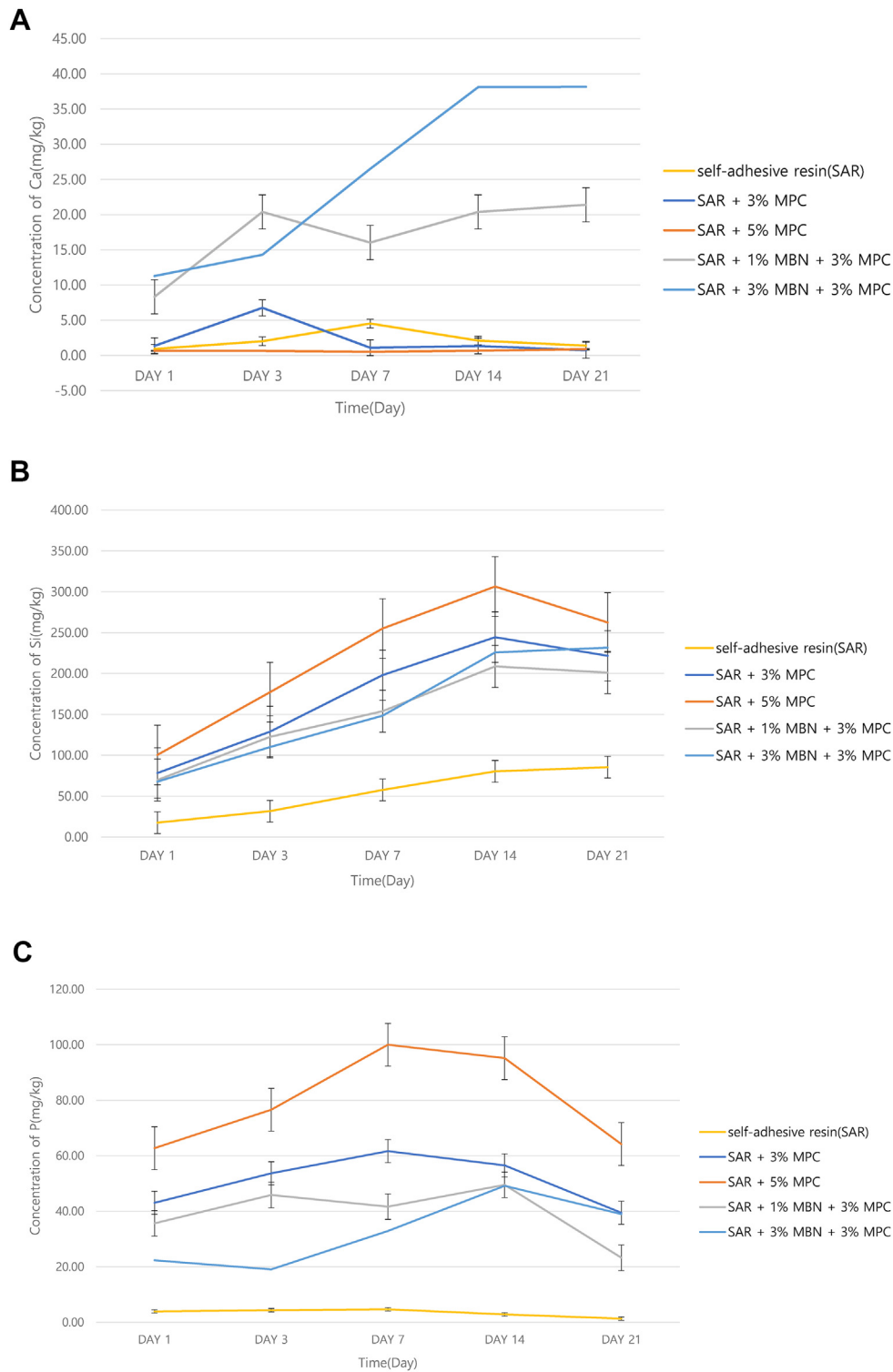


Figure 4 Concentrations of Ca (A), Si (B), and P (C) released for 1, 3, 7, 14, 21 days.

previous findings, the present study tested the biomechanical properties of SAR incorporated with MBNs and MPC. Kwon et al. observed that the antibacterial effect was greater when 3%, 5% MPC was contained than 1.5% MPC.¹⁹ Moreover, although the rate of MPC graft polymerization increased with increasing MPC content, the entire polymerization system began to show gelation at higher MPC

content, which resulted in a substantial decrease in protein-repellent efficiency.²⁰ In addition, Zhang et al. reported that an MPC content greater than 3% degraded its mechanical properties.^{4, 21} Based on these results, 3% was selected as the optimum MPC concentration, and MBNs at a concentration of 1% or 3% were added to observe which group showed maximal efficiency.

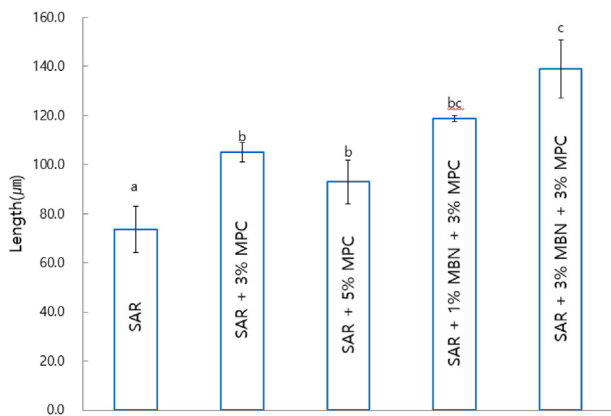


Figure 5 Anti-demineralization test results for the control (SAR) and MPC- and MBN-incorporated SARs. Labels with the same letters indicate no statistically significant difference between the groups ($p > 0.05$). A one-way ANOVA was performed ($n = 5$). SAR; self-adhesive resin, MPC; 2-methacryloyloxyethyl phosphorylcholine, MBN; mesoporous bioactive glass nanoparticle, ANOVA; analysis of variance.

The SBS of the 5% MPC group was significantly decreased and that of the MBN- and MPC-added groups was significantly increased when compared to the control. It can be seen that the excessive addition of MPC can reduce the mechanical properties of the resin, and in particular, when the MPC is 5% or more, the mechanical properties are significantly reduced. Microhardness in all the experimental groups was significantly higher than that in the control. Moreover, there was a statistically significant difference between the MPC-added and the MBN + MPC-added groups. There was no significant difference between the 3% and 5% MPC groups as well as between the MBN- and MPC-incorporated groups. Furthermore, there was no significant difference in ARI scores in all the groups, and resin residues (10%–90%) were evident on the tooth surfaces.

MPC- and MBN-containing SARs have promising antibacterial effects because MPC reduces bacterial adhesion and MBN increases the pH of the environment and induces alkaline stress on bacteria. All the experimental groups were effective in reducing the density of *S. mutans* cultures on day 1 and 3. On day 2, only the 3% MPC+3% MBN group showed a significant difference, but the other groups showed a decreased value. Results of this study support previous findings on the substantial decrease in the CFUs of total microorganisms, total streptococci, and mutans streptococci in the biofilm formed on MPC-incorporated materials.^{4,21}

Dissolution test results showed that the greatest Ca release was observed in the groups containing both MBNs and MPC. Ca concentration increased between days 1 and 3 in the 1% MBN + 3% MPC group and soared after day 3 in the 3% MBN + 3% MPC group. Si and P concentrations in all the experimental groups were higher than those in the control. Interestingly, Si and P levels decreased after day 14. Zhang et al. reported that S53P4, which is a type of BAG, can kill pathogens related to enamel caries (*S. mutans*), root caries (*Actinomyces naeslundii*, *S. mutans*), and periodontitis (*Actinobacillus actinomycetemcomitans*). S53P4 and high

concentrations of BAG compositions in 16 different bacterial cultures exhibited antibacterial properties due to pH increase.²² Based on these results, it could be assumed that Ca, P, and orthosilicate released from bioactive glasses act as buffers that increase the pH of the dissolution medium, leading to lower chances of demineralization and higher chances of remineralization.

All the experimental groups showed a significant difference in anti-demineralization compared to the control group. According to Zhang et al., MPC has no remineralization capability, and antibacterial and remineralization agents need to be incorporated into dental composites to inhibit biofilm formation more effectively.²¹ However, Lee et al. suggested that higher MPC content leads to greater ion release.²³ Park et al. showed that MPC-incorporated orthodontic bonding agents improved remineralization effects, which are potentiated when MBN is added.⁸ In this study, the remineralization length was higher in the MBN and MPC groups than in the MPC group. As the catalytic effect of MBN substantially induces the exchange of calcium and phosphate ions from BAG, it could likely enhance the anti-demineralization effect of MPC. In particular, the anti-demineralization effect was greatest in the 3% MBN group.

In conclusion, the incorporation of both MBN and MPC into SAR substantially enhanced the mechanical properties and antibacterial and anti-demineralization effects. Further studies should investigate the ideal mass fractions of MBNs and MPC while considering the polymerization shrinkage and coefficient of thermal expansion. Moreover, the clinical handling and bonding success rates of these orthodontic resins should be evaluated and analyzed. Nonetheless, the outcomes of this study are promising and serve as a screening tool for the clinical investigation of novel orthodontic materials.

This study conclusively showed that MBN- and MPC-containing SARs exert greater antibacterial and remineralization effects than conventional orthodontic bonding materials. This novel approach of adding MBNs and MPC to SAR may serve as a basis for developing an innovative material with excellent mechanical properties that would simplify the bonding procedure and overcome the limitations of existing bonding materials.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

Acknowledgements

This research was funded by the National Research Foundation of Korea (NRF) grant funded by the Korean government (2021R1A2C1003240).

References

- Shapinko Y, Eleftheriadi I, Brosh T, et al. Evaluation of an orthodontic adhesive with combined primer and composite. *J Stomatol* 2018;8:205–16.

2. Ok U, Aksakalli S, Eren E, Kechagia N. Single-component orthodontic adhesives: comparison of the clinical and in vitro performance. *Clin Oral Invest* 2021;1–13.
3. Hosseinipour ZS, Heidari A, Shahrabi M, Poorzandpoush K. Microleakage of a self-adhesive flowable composite, a self-adhesive fissure sealant and a conventional fissure sealant in permanent teeth with/without saliva contamination. *Front Dent* 2019;16:239.
4. Zhang N, Zhang K, Melo MAS, et al. H Novel protein-repellent and biofilm-repellent orthodontic cement containing 2-methacryloyloxyethyl phosphorylcholine. *J Biomed Mater Res B Appl Biomater* 2016;104:949–59.
5. Kolenbrander PE, Andersen RN, Blehert DS, Egland PG, Foster JS, Palmer Jr RJ. Communication among oral bacteria. *Microbiol Mol Biol Rev* 2002;66:486–505.
6. Fujiwara N, Yumoto H, Miyamoto K, et al. 2-Methacryloyloxyethyl phosphorylcholine (MPC)-polymer suppresses an increase of oral bacteria: a single-blind, crossover clinical trial. *Clin Oral Invest* 2019;23:739–46.
7. Lu X, Kolzow J, Chen RR, Du J. Effect of solution condition on hydroxyapatite formation in evaluating bioactivity of B2O3 containing 45S5 bioactive glasses. *Bioact Mater* 2019;4:207–14.
8. Park SY, Yoo KH, Yoon SY, Son WS, Kim YI. Synergetic effect of 2-methacryloyloxyethyl phosphorylcholine and mesoporous bioactive glass nanoparticles on antibacterial and anti-demineralisation properties in orthodontic bonding agents. *Nanomaterials* 2020;10:1282.
9. Xia W, Chang J. Preparation and characterization of nano-bioactive-glasses (NBG) by a quick alkali-mediated sol–gel method. *Mater Lett* 2007;61:3251–3.
10. Collares FM, Portella FF, Leitune VCB, Samuel SMW. Discrepancies in degree of conversion measurements by FTIR. *Braz Oral Res* 2014;28:9–15.
11. Bishara SE, Ajlouni R, Laffoon JF, Warren JJ. Comparison of shear bond strength of two self-etch primer/adhesive systems. *Angle Orthod* 2006;76:123–6.
12. Stookey GK. The Featherstone laboratory pH cycling model: a prospective, multi-site validation exercise. *Am J Dent* 2011;24:322.
13. Hashimoto M, Iijima M, Nagano F, Ohno H, Endo K. Effect of monomer composition on crystal growth by resin containing bioglass. *J Biomed Mater Res B Appl Biomater* 2010;94:127–33.
14. Manfred L, Covell DA, Crowe JJ, Tufekci E, Mitchell JC. A novel biomimetic orthodontic bonding agent helps prevent white spot lesions adjacent to brackets. *Angle Orthod* 2013;83:97–103.
15. Chatzistavrou X, Velamakanni S, DiRenzo K, et al. Designing dental composites with bioactive and bactericidal properties. *Mater Sci Eng* 2015;52:267–72.
16. Choi A, Yoo KH, Yoon SY, Park BS, Kim IR, Kim YI. Anti-microbial and remineralizing properties of self-adhesive orthodontic resin containing mesoporous bioactive glass. *Mater* 2021;14:3550.
17. Nam HJ, Kim YM, Kwon YH, et al. Fluorinated bioactive glass nanoparticles: enamel demineralization prevention and antibacterial effect of orthodontic bonding resin. *Mater* 2019;12:1813.
18. Koyama J, Fukazawa K, Ishihara K, Mori Y. In situ surface modification on dental composite resin using 2-methacryloyloxyethyl phosphorylcholine polymer for controlling plaque formation. *Mater Sci Eng* 2019;104:109916.
19. Kwon JS, Lee MJ, Kim JY, et al. Novel anti-biofouling bioactive calcium silicate-based cement containing 2-methacryloyloxyethyl phosphorylcholine. *PLoS One* 2019;14:e0211007.
20. Takahashi N, Iwasa F, Inoue Y, Morisaki H, Ishihara K, Baba K. Evaluation of the durability and antiadhesive action of 2-methacryloyloxyethyl phosphorylcholine grafting on an acrylic resin denture base material. *J Prosthet Dent* 2014;112:194–203.
21. Zhang N, Chen C, Melo MA, et al. A novel protein-repellent dental composite containing 2-methacryloyloxyethyl phosphorylcholine. *Int J Oral Sci* 2015;7:103–9.
22. Zhang D, Leppäranta O, Munukka E, et al. Antibacterial effects and dissolution behavior of six bioactive glasses. *J Biomed Mater Res* 2010;93:475–83.
23. Lee SM, Yoo KH, Yoon SY, et al. Enamel anti-demineralization effect of orthodontic adhesive containing bioactive glass and graphene oxide: an in-vitro study. *Mater* 2018;11:1728.