SiO$_2$-nanocomposite film coating of CAD/CAM composite resin blocks improves surface hardness and reduces susceptibility to bacterial adhesion

Pranithida KAMONWANON$^1$, Nanako HIROSE$^2$, Satoshi YAMAGUCHI$^3$, Jun-ichi SASAKI$^3$, Haruaki KITAGAWA$^3$, Ranna KITAGAWA$^2$, Sroisiri THAWEBOON$^4$, Toemsak SRIKHIRIN$^3$ and Satoshi IMAZATO$^3$

1 Multidisciplinary Unit, Faculty of Science, Mahidol University, 272 Rama VI Road, Ratchathewi, Bangkok 10400, Thailand
2 Department of Restorative Dentistry and Endodontology, Osaka University Graduate School of Dentistry, 1-8 Yamadaoka, Suita, Osaka 565-0871, Japan
3 Department of Biomaterials Science, Osaka University Graduate School of Dentistry, 1-8 Yamadaoka, Suita, Osaka 565-0871, Japan
4 Department of Microbiology, Faculty of Dentistry, Mahidol University, 6 Yothi Road, Ratchathewi, Bangkok 10400, Thailand
5 Department of Physics, Faculty of Science, Mahidol University, 272 Rama VI Road, Ratchathewi, Bangkok 10400, Thailand

Corresponding author, Pranithida KAMONWANON; E-mail: namenunn@yahoo.com

Composite resin blocks for computer-aided design/computer-aided manufacturing (CAD/CAM) applications have recently become available. However, CAD/CAM composite resins have lower wear resistance and accumulate more plaque than CAD/CAM ceramic materials. We assessed the effects of SiO$_2$-nanocomposite film coating of four types of CAD/CAM composite resin blocks: Cerasmart, Katana Avencia block, Lava Ultimate, and Block HC on surface hardness and bacterial attachment. All composite blocks with coating demonstrated significantly greater Vickers hardness, reduced surface roughness, and greater hydrophobicity than those without coating. Adhesion of Streptococcus mutans to the coated specimens was significantly less than those for the uncoated specimens. These reduced levels of bacterial adherence on the coated surface were still evident after treatment with saliva. Surface modification by SiO$_2$-nanocomposite film coating has potential to improve wear resistance and susceptibility to plaque accumulation of CAD/CAM composite resin restorations.

**Keywords:** Bacterial adhesion, CAD/CAM composite resin blocks, Surface coating

---

**INTRODUCTION**

Composite resins have been the most commonly used material for both anterior and posterior direct restorations for the past 30 years. These materials have excellent mechanical and esthetic properties without the potential for mercury toxicity associated with dental amalgams. Composite resin blocks for computer-aided design/computer-aided manufacturing (CAD/CAM) applications have recently become available. Because CAD/CAM composite resins are stronger than conventional filling resins, they can be used for indirect crown restorations. However, these materials have lower wear resistance and inferior esthetic qualities than CAD/CAM ceramic materials. The mean vertical wear at occlusal contact areas after 3-years’ clinical service was reportedly 92.5 and 174.1 µm for ceramic crowns and CAD/CAM composite resin crowns, respectively. Therefore, further improvement of wear resistance of CAD/CAM composite crowns should be considered to improve their clinical effectiveness.

Another disadvantage of resin-based materials is greater plaque accumulation on their surfaces, which can lead to caries formation and restoration failure. Composite resin restorations are known to accumulate more plaque than enamel and other type of restorations. Ethylene glycol-based co-monomers, such as ethylene glycol dimethacrylate and triethylene glycol dimethacrylate (TEGDMA), that are included in composite resins can promote the proliferation of cariogenic microorganisms such as streptococci and lactobacilli. TEGDMA also stimulates glycosyltransferase activity in cariogenic bacteria. Streptococcus mutans has been specifically identified in dental plaque located at the margins of composite resin restorations. Moreover, the formation of a biofilm contributes to the chemical and mechanical degradation of composite resin restorations.

The surface modification of dental materials to improve their properties is currently receiving much attention. Thin film coatings of material surfaces are commonly used to improve biocompatibility, prevent the diffusion of allergenic elements, decrease the adhesion of pathogenic microorganisms, and change the roughness/surface energy, thereby retarding surface deterioration. Mori et al. examined the effects of TiO$_2$ coating to improve the appearance (color, gloss, and surface roughness) of polymethyl methacrylate resin dentures. The TiO$_2$ coating was found to afford high levels of glossiness while maintaining the color of denture base materials. Moreover, coating the surface with inorganic particles helped improve the bond strength and aging resistance of the adhesive interface between zirconia and the resin cement, thereby increasing the longevity of dental restorations. SiO$_2$ coating has been also used to resist Candida albicans adhesion to acrylic resin denture base by changing the hydrophilic surface properties.

Recently, SiO$_2$-nanocomposite film-coating technology was introduced for dental materials, e.g., denture base or artificial tooth materials. These

---

Received Apr 11, 2016; Accepted Aug 22, 2016
doi:10.4012/dmj.2016-135  JOI JST.JSTAGE/dmj/2016-135
studies showed that a SiO2-nanocomposite film could be used as a protective layer against **C. albicans** adhesion. Coating the denture base with a SiO2-nanocomposite film resulted in a more hydrophobic surface and decreased **C. albicans** accumulation. In addition, SiO2-nanocomposite coating enhanced the hardness of polymethyl methacrylate artificial teeth, thereby achieving high wear resistance equivalent to composite resin artificial teeth. The potential application of nanocomposite films to various dental materials is currently an active field of research. The aim of this study was to evaluate the effectiveness of such thin SiO2-nanocomposite film-coating techniques for improving surface hardness and reducing susceptibility to bacterial adhesion.

**MATERIALS AND METHODS**

Four commercially available CAD/CAM composite resin blocks were used (Table 1): Cerasmart (CM; GC, Tokyo, Japan), Katana Avencia block (AC; Kuraray Noritake Dental, Niigata, Japan), Lava Ultimate (LM; 3M ESPE, St.Paul, MN, USA), and Block HC (BC; Shofu, Kyoto, Japan). For comparison, an ultrafine compact filled composite resin for crowns (Solidex, Shofu, SL) was included in this study.

**Specimen preparation**

For the CAD/CAM composite resin blocks, rectangular specimens (12×14 mm) were fabricated by sectioning the commercial blocks to a thickness of 1.5 mm using a low-speed diamond saw (Isomet2000, Buehler, Lake Bluff, IL, USA) with water cooling.

For SL, a siloxane mold 12×14 mm with a depth of 1.5 mm was placed on a glass slab, and the paste was packed into the mold. The surface was covered with a glass slab, and the upper and lower surfaces of the specimen were light-cured for 160 s each using an LED light-curing unit (Pencure 2000, J. Morita, Kyoto, Japan). The light tip was held perpendicular to the surfaces of the specimen. The specimen was removed from the mold and further light-cured for 5 min in a curing machine (α-LIGHT II IN, J. Morita) on both sides.

All specimens were abraded using SiC abrasive paper with a particle size of 12.6±1 µm (P1500, Wingo, Osaka, Japan). For coated specimens, ten sectioned blocks of each type were coated with a silane-SiO2 nanocomposite film by the dip-coating process. Block surfaces were first treated by immersion in 10% KOH for 10 min. The coating solution was prepared by mixing 15.0 g of hydrolyzed methyltrimethoxysilane (Dow Corning, Bangkok, Thailand) with 1.8 mL of acetic acid (Lab Scan, Bangkok, Thailand) and 14 mL of solvent (Dowanol, Modern Chemical, Bangkok, Thailand). The solvent was evaporated by precuring at 65°C for 20 min and heating at 110°C for 2 h. Before testing, all specimens were cleaned by ultrasonication in distilled water for 10 min, followed by washing with ethanol for 5 min and then sterilization by ethylene oxide gas.

**Surface hardness measurement**

The Vickers hardness test was performed using a hardness testing machine (Mitutoyo America, Chicago, IL, USA) using a load of 50 gf and a loading time of 15 s. Five specimens of each type were prepared, and three indents were applied in random locations for each specimen.

**Bacterial adhesion tests**

**Streptococcus mutans** NCTC10449 was cultured in brain-heart infusion (BHI) broth and adjusted to approximately 10⁹ colony forming units (CFU)/mL (OD₆₀₀=0.2). The specimens were immersed under aseptic conditions in 1 mL of bacterial suspension and incubated for 4 h at 37°C with shaking at 100 rpm. The material was retrieved from the suspension and rinsed three times with 5 mL of phosphate buffered saline.

### Table 1  Composite resin materials used in this study

| Trade name         | Code | Manufacturer                        | Monomer        | Filler       | Filler wt% |
|--------------------|------|-------------------------------------|----------------|--------------|------------|
| Cerasmart          | CM   | GC, Tokyo, Japan                     | Bis-MEPP, UDMA | SiO₂, Baglass | 71%        |
| Katana Avencia     | AC   | Kuraray Noritake Dental, Niigata, Japan | UDMA          | SiO₂, Al₂O₃  | 62%        |
| Lava Ultimate      | LM   | 3M ESPE, St.Paul, MN, USA           | Bis-GMA, UDMA, Bis-EMA, TEGDMA | SiO₂, ZrO₂, aggregated ZrO₂/SiO₂ cluster | 80%        |
| Block HC           | BC   | Shofu, Kyoto, Japan                  | UDMA, TEGDMA  | SiO₂, microfumed SiO₂, zirconium silicate | 61%        |
| Solidex            | SL   | Shofu                               | UDMA          | SiO₂, Al₂O₃  | 53%        |

Bis-MEPP: 2,2-bis(4-methacryloxyphenyl)propane, UDMA: urethane dimethacrylate, DMA: dimethacrylate, Bis-GMA: bisphenol A-glycidyl methacrylate, Bis-EMA: ethoxylated bisphenol A dimethacrylate, TEGDMA: triethylene glycol dimethacrylate.
Bacterial attachment on each specimen was evaluated using a scanning electron microscope (SEM; Philips 505, Heidelberg, Germany). After a 4-h incubation in bacterial culture, the specimens were placed in 2% glutaraldehyde, washed in sodium cacodylate solution, and postfixed in osmium tetroxide. The specimens were dehydrated through a graded series of ethanol, gold-sputter coated, and observed under a SEM (5 kV, ×1,000 magnification).

To quantify the number of bacteria attached to the specimen surfaces after incubation, specimens were transferred to 1 mL of PBS in a sterile bottle and sonicated to detach bacteria at low power for 6 min in an ultrasonic bath operating at 34 kHz and 180 W. The number of bacteria in the PBS was calculated by plating them on BHI agar plates followed by anaerobic incubation for 48 h.

Surface characterization

The water contact angle for each specimen was measured by the sessile drop method. Water drops were deposited on solid surfaces with a micrometric syringe controlled by a camera. The contact angle was measured at room temperature in triplicate on each specimen.

Five specimens from each block type were prepared, and the surface roughness measurement was conducted using a portable surface roughness tester (Surftest SJ-400, Mitutoyo America). Surface roughness was evaluated in triplicate on each specimen in different directions. The data were filtered with a cutoff of 0.8 mm.

Bacterial adhesion to saliva-treated specimens

Unstimulated saliva was collected in a chilled tube from a single healthy donor. The saliva was then centrifuged at 4°C and 2,380×g for 20 min. The supernatant was filtered twice with a 0.2-µm sterile syringe filter. The composite resin specimens were incubated in the saliva supernatant for 2 h at 37°C and then rinsed twice with PBS. These specimens then underwent bacterial adhesion tests as described above. The attachment of bacteria was evaluated by SEM and bacterial number counting. Five specimens were examined for each resin type.

Statistical analysis

One-way analysis of variance (ANOVA) was used for the statistical analysis of surface hardness, surface roughness, water contact angle, and bacterial adherence. A post hoc Tukey’s honesty significant difference (HSD) test was used for multiple comparisons. Statistical significance was set at α<0.05.

RESULTS

Surface hardness

The Vickers hardness values are summarized in Fig. 1. The hardness values of specimens ranged from 29.44 to 46.27 under dry conditions. For all the materials tested, the hardness values of the coated specimens were significantly higher than those for the uncoated specimens (p<0.05).

Bacterial adhesion

SEM images of uncoated and coated specimens after incubation in a suspension of S. mutans are shown in Fig. 2. Less bacterial accumulation was observed on coated surfaces than on uncoated surfaces for all materials tested. As shown in Table 2, the number of bacteria adhered to the surface was significantly smaller for the coated specimens than for the uncoated specimens (p<0.05).

Surface characterization

The surface roughness values of the uncoated and coated specimens are presented in Table 3. The surface roughness of the uncoated specimens varied depending on the material. The surface roughness of SL was significantly higher than that of the four types of composite resin block (p<0.05). However, the values for all of the coated specimens were similar, and the values were significantly lower than that of any uncoated specimens (p<0.05).

The water contact angles of all specimens are shown in Table 4. The mean contact angles ranged from 60° to 94.6°. The mean contact angle of SL surfaces was significantly lower than that of any uncoated specimens (p<0.05). However, the contact angles of coated specimen surfaces were significantly higher than those of uncoated specimens (p<0.05).
Fig. 2  SEM images (×1,000) of the uncoated and coated specimen surfaces after incubation in *S. mutans* culture for 4 h. (a) Uncoated SL, (b) coated SL, (c) uncoated CM, (d) coated CM, (e) uncoated AC, (f) coated AC, (g) uncoated LM, (h) coated LM, (i) uncoated BC, (j) coated BC. The arrows indicate the area of bacteria accumulation.

Table 2  Amount of bacteria (CFU×10⁵) attached to the specimen surfaces (Mean±S.D.)

|        | CM           | AC           | LM           | BC           | SL           |
|--------|--------------|--------------|--------------|--------------|--------------|
| Uncoated | 234.4±51.6  | 176.8±22.5  | 49.0±12.0    | 89.2±14.2    | 367.2±64.3   |
| Coated  | 5.0±2.0      | 4.4±1.1     | 3.8±1.3      | 4.6±2.2      | 4.2±1.5      |

CFU: colony-forming unit. **No significant differences between the same letters (p>0.05).**

Table 3  Surface roughness of uncoated and coated composite resins

|        | Uncoated CM | Uncoated AC | Uncoated LM | Uncoated BC | Uncoated SL | Coated specimens |
|--------|-------------|-------------|-------------|-------------|-------------|------------------|
| Mean (µm) | 0.49 b | 0.26 b | 0.12 c | 0.16 c | 1.29 d | 0.049 g |
| S.D. | 0.10 | 0.01 | 0.04 | 0.02 | 0.15 | 0.02 |

**No significant differences between the same letters (p>0.05).**

Table 4  Water contact angles (degrees) of the specimens

|        | Uncoated CM | Uncoated AC | Uncoated LM | Uncoated BC | Uncoated SL | Coated specimens |
|--------|-------------|-------------|-------------|-------------|-------------|------------------|
| Mean | 63.4 b | 63.8 b | 76.4 b | 64.7 a | 60.0 c | 94.6 a |
| S.D. | 1.7 | 3.5 | 3.9 | 3.1 | 1.8 | 2.3 |

**No significant differences between the same letters (p>0.05).**

Table 5  Amount of bacteria (CFU×10⁵) attached to the specimen surfaces after saliva treatment (Mean±S.D.)

|        | CM           | AC           | LM           | BC           | SL           |
|--------|--------------|--------------|--------------|--------------|--------------|
| Uncoated | 92.4±7.0    | 68.6±7.1    | 38.6±10.5   | 44.2±8.9    | 46.6±9.6    |
| Coated | 0.62±0.04   | 0.65±0.06   | 0.63±0.05   | 0.65±0.05   | 0.63±0.06   |

CFU: colony-forming unit. **No significant differences between the same letters (p>0.05).**
Bacterial adhesion to saliva-treated specimens

Table 5 shows the amount of bacterial accumulation on the surfaces of uncoated and coated specimens after treatment with saliva. The numbers of adhered bacteria were significantly lower on the coated specimens than on the uncoated specimens for all materials tested (p<0.05).

DISCUSSION

We investigated the effects of surface modification of CAD/CAM composite resins with SiO2-nanocomposite film in terms of surface properties and bacterial adhesion. The coating consisted of a thin silane-nanocomposite film, and silicon-dioxide nanoparticles were added to increase the strength of the film. The strength of the nanocomposite film was enhanced by mixing the appropriate amount of reinforcement into the polymeric matrix, as is commonly done in hybrid coatings. Organofunctional silanes can react with various inorganic and organic materials. They react with inorganic surface materials and substrates via hydrolysable functional groups to form hydrogen bonds. During the polymerization process, covalent linkages are formed.

The depth-sensing indentation technique is commonly used to investigate the hardness of materials. Hardness is closely related to the long-term wear resistance. Many studies have revealed a relationship between the surface hardness and wear resistance of materials used for dental restoration20-22). Therefore, we measured the Vickers hardness of uncoated and coated specimens. For the five materials tested, coated specimens demonstrated significantly greater hardness values than uncoated specimens. It has been suggested that the hardness of coated specimens can be improved by increasing the amount of well-distributed filler (with an average of 24.0±1.7 nm23)) of a similar molecular network and enhances the bonding between the matrix and fillers23,24). The coated specimens in this study were sufficiently covered by a nanocomposite film containing nano-sized inorganic fillers that were well dispersed without agglomeration. Yodmongkol et al.18) reported that application of a SiO2-nanocomposite film successfully increased the hardness of acrylic resin denture base material. The present results confirmed that addition of a SiO2-nanocomposite film increased the surface hardness of CAD/CAM composite resin blocks, suggesting that such a coating might enhance wear resistance.

SEM observations (Fig. 2) demonstrated that the accumulation of S. mutans on the surfaces of uncoated specimens was greater than that on coated specimens. Quantitative analysis revealed that the numbers of bacteria on the coated specimen surfaces were significantly smaller than those on the uncoated specimen surfaces for all five materials. Differences in physicochemical characteristics could explain why some materials are more susceptible to bacterial adhesion and plaque formation than others. Each of the composite resin materials tested had a different matrix composition and filler fraction, and such differences may directly influence the susceptibility to bacterial adhesion.

Among the various physicochemical characteristics, the surface free energy is an important determinant of bacterial adhesion23-27). The water contact angle is an indication of the interface energy. Generally, if the water contact angle is larger than 90°, then the material surface is hydrophobic. Tanner et al.28) and Hahnel et al.29) reported that hydrophobic substrates exhibited less attachment of S. mutans than hydrophilic substrates. Moreover, the adhesion of S. mutans is also influenced by the surface roughness30,31). Even though the surfaces of the five types of specimens underwent the same polishing process, the resulting grooves, pits, and holes on the polished surfaces depended on the homogeneity and composition of each specimen. Quirynen et al.32) reported that a rough surface (R±=2.2 µm) significantly promoted supragingival plaque formation compared with a smooth surface (R±=0.1 µm). Roughening of a surface increases the area available for adhesion29). On a rough surface, bacteria can resist shear forces, thereby increasing the possibility of a reversible bonding interface becoming an irreversible bonding interface. Our results were in accordance with these previous findings. The measurement of the contact angle has been widely used to evaluate surface hydrophobicity. Buergers et al.33) reported that the silorane-based resin composite (92.1°) showed a higher water contact angle than the conventional methacrylate-based composites (59.7°–69.4°) and demonstrated a lower adhesion of streptococci, although no simple rule or correlation between hydrophobicity and the amount of adhering bacteria can be deduced. The contact angle of our coated specimens indicated that they were more hydrophobic (94.6°) than the uncoated specimens. This increased hydrophobicity resulted in lower adhesion of S. mutans on coated surfaces. Moreover, the coated specimens had lower levels of surface roughness, which also contributed to lower amounts of bacterial attachment than those of uncoated specimens. These findings suggested that the more hydrophobic and smoother surfaces of composite resins coated with SiO2-nanocomposite films could result in lower levels of S. mutans attachment than those of uncoated specimens.

Generally, the saliva treatment of dental restoration materials tends to lower the binding affinity of bacteria, possibly as a result of decreased surface hydrophobicity34). All five types of composite resins showed reduced attachment of S. mutans after being treated with saliva. However, for the five types of saliva-treated materials tested, the numbers of bacteria adhering to the coated specimens were significantly lower than those adhering to the uncoated specimens. Different amounts of salivary proteins were reportedly adsorbed on different surfaces, suggesting that the composition of attached salivary proteins was different on each surface35-37). The parameters influencing the adsorption of proteins...
on solid surfaces have not yet been clarified, and contradictory results have been previously reported. A study analyzing the specific ligands of salivary proteins suggested that some are involved in the initial bacterial adhesion on surfaces. For example, proline-rich proteins and salivary mucins were present in the acquired pellicle and provided adhesion sites for receptor proteins of oral bacteria. In contrast, many studies have suggested that the adsorption of salivary proteins on surfaces smoothes out the differences in surface properties of different materials, depending on the thickness, composition, and conformation of proteins in the adsorbed layer. Salivary adsorption on dental restoration materials is reportedly dependent on the surface physicochemical properties. Therefore, the reason for reduced bacterial attachment on coated specimens even after saliva treatment may be the different protein adsorption profiles on coated and uncoated specimens.

To fully explore the plaque inhibitory effects of the present coating technology, further studies using multiple-species biofilm systems are required. In addition, the biocompatibility of coated materials needs to be investigated in detail before conducting in situ or in vivo tests.

**CONCLUSION**

CAD/CAM composite resin blocks can be modified by coating them with a SiO$_2$-nanocomposite film, making their surfaces harder and less receptive to the attachment of S. mutans. The coated surfaces were smoother and more hydrophobic than those of uncoated specimens, which could explain the reduced bacterial adhesion. The adherence of S. mutans was inhibited even after the coated surfaces were treated with saliva. It is suggested that such a SiO$_2$-nanocomposite film coating may be clinically beneficial in terms of greater wear resistance and less plaque accumulation on CAD/CAM composite resin restorations.

**ACKNOWLEDGMENTS**

This study was supported in part by Grants-in-Aid for Scientific Research (JP26293409, JP16K15800, JP16K20497) from the Japan Society for the Promotion of Science and grant No. PHD/0092/2552 from the Thailand Research Fund through the Royal Golden Jubilee Ph.D. program and the National Nanotechnology Center, NSTDA, Ministry of Science and Technology, Thailand, through the Center of Excellence Network program.

**REFERENCES**

1) Vanoorbeek S, Vandamme K, Lijnen I, Naert I. Computer-aided designed/computer-assisted manufactured composite resin versus ceramic single-tooth restorations: a 3-year clinical study. Int J Prosthodont 2010; 23: 223-230.

2) Magne P, Schlüchting LH, Maia HP, Baratieri LN. In vitro fatigue resistance of CAD/CAM composite resin and ceramic posterior occlusal veneers. J Prostheth Dent 2010; 104: 149-157.

3) Ruse ND, Sadoun MJ. Resin-composite blocks for dental CAD/CAM applications. J Dent Res 2014; 93: 1232-1234.

4) Kunzelmann KH, Jelen B, Mehl A, Hickel R. Wear evaluation of MZ100 compared to ceramic CAD/CAM materials. Int J Comput Dent 2001; 4: 171-184.

5) Beyth N, Farah S, Domb AJ, Weiss EI. Antibacterial dental resin composites. React Funct Polym 2014; 75: 81-88.

6) Skjørland KK. Plaque accumulation on different dental filling materials. Scand J Dent Res 1973; 81: 538-542.

7) Skjærland KK, Sanju T. Effect of sucrose rinse on bacterial colonization on amalgam and composite. Acta Odontol Scand 1982; 40: 193-196.

8) Svanberg M, Möjr IA, Orstavik D. Mutans streptococci in plaque from margins of amalgam, composite, and glass-ionomer restorations. J Dent Res 1990; 69: 861-864.

9) Weitman RT, Eames WB. Plaque accumulation on composite surfaces after various finishing procedures. J Am Dent Assoc 1975; 91: 101-106.

10) Hansel C, Leyhausen G, Mai UE, Geurtsen W. Effects of various resin composite (co)monomers and extracts on two caries-associated micro-organisms in vitro. J Dent Res 1998; 77: 60-67.

11) Kaiwai K, Tsuchitani Y. Effects of resin composite components on glucosyltransferase of cariogenic bacterium. J Biomed Mater Res 2000; 51: 123-127.

12) Boullaguet S. Biological risks of resin-based materials to the dentin–pulp complex. Crit Rev Oral Biol Med 2004; 15: 47-50.

13) Beyth N, Yudovin-Fearber I, Domb AJ, Weiss EI. Long-term antibacterial surface properties of composite resin incorporating polyethyleneimine nanoparticles. Quintessence Int 2010; 41: 827-835.

14) Mori K, Tsuji M, Ueda T, Sakurai K. Color and gloss evaluation of titanium dioxide coating for acrylic resin denture base. J Prosthodont Res 2015; 59: 249-253.

15) Liu D, Pow EH, Tsai JK, Matlinlnna JP. Evaluation of four surface coating treatments for resin to zirconia bonding. J Mech Behav Biomed Mater 2014; 32: 300-309.

16) Azuma A, Akiba N, Minakuchi S. Hydrophilic surface modification of acrylic denture base material by silica coating and its influence on Candida albicans adherence. J Med Dent Sci 2012; 59: 1-7.

17) Ramonwanon P, Yodmongkol S, Chantarachindawong R, Thaweboon S, Thaweboon B, Srikhirin T. Wear resistance of a modified polyethylene methacrylate artificial tooth compared to five commercially available artificial tooth materials. J Prosthodont Res 2015; 114: 286-289.

18) Yodmongkol S, Chantarachindawong R, Thaweboon S, Thaweboon B, Amornsakchai T, Srikhirin T. The effects of silane-SiO$_2$ nanocomposite films on Candida albicans adherence and the surface and physical properties of acrylic resin denture base material. J Prosthodont 2014; 112: 1530-1538.

19) Kimyai S. Adherence of Streptococcus mutans to the specimen surfaces was determined by the plate counting method. Med Oral Patol Oral Cir Bucal 2011; 16: 561-567.

20) Yip KH, Smales RD, Kaidonis JA. Differential wear of teeth and restorative materials: clinical implications. Int J Prosthodont 2004; 17: 350-356.

21) Mandikos MN, McGivney GP, Davis E, Bush PJ, Carter JM. A comparison of the wear resistance and hardness of indirect composite resins. J Prosthodont 2001; 85: 386-395.

22) Ekfeldt A, Olof G. Wear mechanisms of resin and porcelain denture teeth. Acta Odontol Scand 1989; 47: 391-399.

23) Chantarachindawong R, Luangtip W, Chindaudom P, Osotchan T, Srikhirin T. Development of the scratch resistance on acrylic sheet with basic colloidal silica (SiO$_2$)
–methyltrimethoxysilane (MTMS) nanocomposite films by sol-gel technique. Can J Chem Eng 2012; 90: 888-896.
24) Bayne SC, Taylor DF, Heymann HO. Protection hypothesis for composite wear. Dent Mater 1992; 8: 305-309.
25) Teughels W, Slipe I, Quirynen M. Effect of material characteristics and/or surface topography on biofilm development. Clin Oral Implants Res 2006; 17: 68-81.
26) Busscher HJ, Weerkamp AH. Measurement of the surface free energy of bacterial cell surfaces and its relevance for adhesion. Appl Environ Microbiol 1984; 48: 980-983.
27) Uyen M, Busscher HJ, Weerkamp AH, Arends J. Surface free energies of oral streptococci and their adhesion to solids. FEMS Microbiol 1985; 30: 103-106.
28) Tanner J, Vallittu PK, Söderling E. Adherence of Streptococcus mutans to an E-glass fiber-reinforced composite and conventional restorative materials used in prosthetic dentistry. J Biomed Mater Res 2000; 49: 250-256.
29) Hahnel S, Rosentritt M, Bürgers R, Handel G. Adhesion of Streptococcus mutans NCTC 10449 to artificial teeth: an in vitro study. J Prosthet Dent 2006; 96: 309-315.
30) Eick S, Glockmann E, Brandl B, Pfister W. Adherence of Streptococcus mutans to various restorative materials in a continuous flow system. J Oral Rehabil 2004; 31: 278-285.
31) Taylor RL, Verran J, Lees GC, Ward AJ. The influence of substratum topography on bacterial adhesion to polymethylmethacrylate. J Mater Sci Mater Med 1998; 9: 17-22.
32) Quirynen M, Marechal M, Busscher HJ, Weerkamp AH, Darius PL, Van Steenberghhe D. The influence of surface free energy and surface roughness on early plaque formation. An in vivo study in man. J Clin Periodontol 1990; 17: 138-144.
33) Buergers R, Schneider-Brachert W, Hahnel S, Rosentritt M, Handel G. Streptococcal adhesion to novel low-shrink silorane-based restorative. Dent Mater 2009; 25: 269-275.
34) Satou J, Fukunaga A, Morikawa A, Matsumae I, Satou N, Shintani H. Streptococcal adherence to uncoated and saliva-coated restoratives. J Oral Rehabil 1991; 18: 421-429.
35) Svendsen IE, Lindh L. The composition of enamel salivary films is different from the ones formed on dental materials. Biofouling 2009; 25: 255-261.
36) Ahn SJ, Kho HS, Lee SW, Nahm DS. Roles of salivary proteins in the adherence of oral streptococci to various orthodontic brackets. J Dent Res 2002; 81: 411-415.
37) Sonju T, Glantz PO. Chemical composition of salivary integuments formed in vivo on solids with some established surface characteristics. Arch Oral Biol 1975; 20: 687-691.
38) Muller R, Hiller KA, Schmalz G, Ruhl S. Chemiluminescence-based detection and comparison of protein amounts adsorbed on differently modified silica surfaces. Anal Biochem 2006; 359: 194-202.
39) Walz A, Stohler K, Wattenberg A, Hawranke E, Meyer HE, SchmalzG, Blüggel M, Ruhl S. Proteome analysis of glandular parotid and submandibular–sublingual saliva in comparison to whole human saliva by two-dimensional gel electrophoresis. Proteomics 2006; 6: 1631-1639.