Effect of differences in the type of restoration and adhesive resin cement system on the bonding of CAD/CAM ceramic restorations

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The effect of differences in the type of restoration and adhesive resin cement system on the bonding of CAD/CAM ceramic restoration after cyclic loading was examined quantitatively and qualitatively. Seventy-two human maxillary first molars were divided into three restoration groups: MOD-inlay, MODP-onlay, and crown. Immediate dentin sealing was applied to the exposed dentin of all prepared specimens. The 24 specimens of each restoration group were further divided into another three groups, and a different adhesive resin cement system was applied to each group for cementation. All restoratives were fabricated from feldspathic-ceramic-blocks and cemented with each adhesive resin cement system according to the manufacturer’s instructions. The microtensile bond-strength was measured after cyclic loading and was not significantly affected by differences in the type of restoration or adhesive resin cement system. However, the type of restorations and adhesive resin cement systems did show significant differences in terms of the bonding reliability.

Keywords: CAD/CAM restoration, Microtensile bond strength, Weibull analysis, Inlay/onlay/crown restoration, Adhesive resin cement system

INTRODUCTION

Recently, metal-free esthetic restoration has been widely applied in dental treatment. Reducing the invasiveness of dental treatment based on the concept of minimal intervention1) is also desired in clinical practice and is an essential part of present dental treatment. Indirect restoration is often selected clinically for cases with extensive tooth substance decay and is classified as inlay, onlay, or crown restoration depending on the state of the restored tooth surface. CAD/CAM systems have rapidly improved with vastly simplified procedures for indirect restoration and gained worldwide usage. Since then, digital technology and dental materials including resin adhesive systems and metal-free esthetic restoratives have progressed dramatically and also spread throughout the world. Metal-free indirect restoration requires robust adhesion between the tooth substance and fabricated restorative to obtain an excellent prognosis2). Burke et al.3) concluded that using an adhesive resin cement system as luting material for metal-free ceramic restoration is required to obtain robust bonding. There are two types of adhesive resin cement systems: a non-filler-containing 4-META/MMA-TBB cement system and filler-containing adhesive resin composite cement. Both are useful as luting materials for not only metal-free but also metal restoratives. Previous studies focused on the tensile bond strength have reported that both cement systems demonstrate different bonding behaviors to human dentin4) and CAD/CAM composite blocks5). The microtensile bond strength (μ-TBS) test developed by Sano et al.6) is an effective means of investigating the internal bond strength that is influenced by various intraoral stresses, such as thermal and cyclic load stresses. In addition, the International Organization for Standardization (ISO) 11405 standard7) states that calculating the failure probability with the Weibull distribution function is a suitable approach for comparing many materials8).

In order to clarify the effect of differences in both the type of restoration and adhesive resin cement system on the bonding of CAD/CAM ceramic restoration, this study measured the μ-TBS of glass ceramic inlay, onlay, and crown restorations cemented with a 4-META/MMA-TBB adhesive resin cement system or adhesive resin composite cement system for quantitative determination. In order to characterize the bond strength of each type of restoration, the bonding reliability was also evaluated through Weibull analysis for qualitative determination. The null hypotheses of this study were as follows: 1) Both the type of restoration and adhesive resin cement system do not influence the intra-cavity bond strength of CAD/CAM ceramic restoration and 2) both the type of restoration and cement system do not influence the bonding reliability.

MATERIALS AND METHODS

Experimental materials

The product name, composition, lot number, and manufacturer of each material used in this study are presented in Table 1. The experimental codes assigned to the products are also given in the Table. For cementation, a non-filler-containing 4-META/MMA-TBB resin cement system and two filler-containing adhesive resin composite cement systems were used. Super-Bond (SB) was used for the non-filler-containing self-cure 4-META/MMA-TBB adhesive resin cement system and
Table 1 Materials used in this study

| Materials Used in this Study                                      | Composition                                                                 | Lot no.  | Manufacturer       |
|------------------------------------------------------------------|-----------------------------------------------------------------------------|----------|--------------------|
| 4-META/MMA-TBB type adhesive resin cement system                 |                                                                             |          |                    |
| Polymer                                                          | PMMA                                                                        |          |                    |
| Quick Monomer                                                    | MMA, 4-META, Multifunctional methacrylate                                   |          |                    |
| Super-Bond (Teeth color) [Code: SB]                             | TBB, solvent                                                                |          |                    |
| Catalyst V                                                       |                                                                             |          |                    |
| Super-Bond PZ Primer Liquid A [Code: SB]                         | MMA, Functional monomer                                                     |          |                    |
| Liquid B                                                         | MMA, Silane                                                                 |          |                    |
| Teeth Primer                                                     | 4-META, Water, acetone, sodium sulfite                                       |          |                    |
| Resin composite-type adhesive resin cement system                |                                                                             |          |                    |
| Calibra Ceram (Medium) [Code: CC]                               |                                                                             |          |                    |
| Base Paste                                                       | Bariumfluoroaluminoborosilicate glass, HEMA, EBPADMA urethane resin, Silica, Urethane dimethacrylate, Trimethylolpropane trimethacrylate, Triethyleneglycol dimethacrylate | 180109   | Dentsply Sirona    |
| Catalyst Paste                                                   | Bariumfluoroaluminoborosilicate glass, Dipentaerythritol pentacrylatephosphate, Silica, EBPADMA urethane resin, Urethane dimethacrylate, Trimethylolpropane trimethacrylate, Triethyleneglycol dimethacrylate |          |                    |
| Calibra Silane Coupling Agent                                   | MPTMS, Ethanol, Acetone                                                     | 1611012  |                    |
| Prime&Bond Universal                                             | Polymethacrylate, Hydrophilic amide monomers, 2-propanol, Water, Camphorquinone | 1710000415 |                    |
| PANAVIA V5 (Universal) [Code: PV]                                | Bis-GMA, TEGDMA, Silanated barium glass filler, Silanated fluoroaluminosilicate glass filler, Initiators, Hydrophobic aromatic dimethacrylate, Hydrophilic aliphatic dimethacrylate, Colloidal silica, Accelerators | 6N0081   | Kuraray Noritake Dental |
| Paste A                                                          | Bis-GMA, Silanated barium glass filler, Hydrophilic aliphatic dimethacrylate, Di-Camphorquinone, Pigments, Hydrophobic aromatic dimethacrylate, Silanated aluminum oxide filler, Accelerators |          |                    |
| Paste B                                                          | 3-trimethoxysilylpropyl methacrylate, MDP, Ethanol                           | 8X0019   |                    |
| PANAVIA V5 Tooth Primer                                          | MDP, HEMA, Hydrophilic aliphatic dimethacrylate, Accelerators, Water        | 7K0042   |                    |
| Chair-side CAD/CAM system                                       |                                                                             |          |                    |
| CEREC AC Omnicam                                                 | CEREC operating system software version 4.5                                  |          | Dentsply Sirona    |
| CEREC MC XL                                                     |                                                                             |          |                    |
| CAD/CAM restorative block                                       |                                                                             |          |                    |
| VITABLOCS MarkII (A3C)                                          | Silicon dioxide, Aluminum oxide, Sodium oxide, Potassium oxide, Calcium oxide, Titanium dioxide | 63341    | VITA               |
| Immediate dentin sealing materials                              |                                                                             |          |                    |
| Clearfil Universal Bond Quick                                   | HEMA, Bis-GMA, MDP, Hydrophilic amide monomers, Colloidal silica, Sodium fluoride, Ethanol, Water | CR0102   | Kuraray Noritake Dental |
| Clearfil Majesty ES Flow (A3)                                   | Barium grass filler, Silica filler, TEGDMA, Hydrophobic-aromatic dimethacrylate, Di-Camphorquinone, Photo initiator | 970222   |                    |
| Pretreatment materials for cementation                          |                                                                             |          |                    |
| Porcelain Etchant                                               | Polycarboxylmethoxypropene sulfonic acid, Hydrofluoroc acid                  | 1800000384 | BISCO             |

PMMA, polymethyl methacrylate; MMA, methyl methacrylate; 4-META, 4-methacryloxyethyl trimellitate anhydride; TBB, tributylborane; HEMA, 2-hydroxyethyl methacrylate; EBPADMA, ethoxylated bisphenol A dimethacrylate; MPTMS, 3-mercaptopropyltrimethoxysilane; Bis-GMA, bisphenol A-glycidyl methacrylate; TEGDMA, triethyleneglycol dimethacrylate; MDP, 10-methacryloxydecyl dihydrogen phosphate.
consisted of a silane coupling agent (Super-Bond PZ Primer, Sun Medical, Shiga, Japan), self-etching primer (Teeth Primer, Sun Medical), polymer powder (Polymer, Sun Medical), monomer liquid (Quick Monomer, Sun Medical), and catalyst (Catalyst V, Sun Medical). The first adhesive resin composite cement system for the filler-containing dual-cure dimethacrylate based cement system was Calibra Ceram (CC), which consisted of a silane coupling agent (Calibra Silane Coupling Agent, Dentsply Sirona, York, PA, USA), bonding agent for pretreatment of the tooth surface (Prime&Bond Universal, Dentsply Sirona), and cement paste (Calibra Ceram, Dentsply Sirona). The second adhesive resin composite cement system for the filler-containing dual-cure dimethacrylate based system was PANAVIA V5 (PV), which consisted of a silane coupling agent (Clearfil Ceramic Primer Plus, Kuraray Noritake Dental, Tokyo, Japan), self-etching primer (PANAVIA V5 Tooth Primer, Kuraray Noritake Dental), and cement paste (PANAVIA V5, Kuraray Noritake Dental). A typical chairside CAD/CAM system (CEREC AC Omnicam software version 4.5 and CEREC MC XL, Dentsply Sirona) was used for the optical impression, restorative design and fabricating. A typical feldspathic ceramic block (VITABLOCS Mark II, VITA Zahnfabrik, Bad Säckingen, Germany) was selected as the CAD/CAM restorative block. An all-in-one adhesive system (Clearfil Universal Bond Quick, Kuraray Noritake Dental) and flowable resin composite (Clearfil Majesty ES Flow, Kuraray Noritake Dental) were used for immediate dentin sealing (IDS). For the pretreatment of the inner surfaces of the glass ceramic restorative prior to cementation, 9.5% hydrofluoric acid (Porcelain Etchant, BISCO, Schaumburg, IL, USA) was applied. For all light irradiation, a light-emitting diode (LED) curing unit (G-Light Prima II, GC, Tokyo, Japan) was used. A schematic experimental flowchart is shown in Fig. 1. Each tooth was embedded in a standardized cylindrical mold filled with an acrylic resin (PROVINICE, Shofu, Kyoto, Japan) to 1.0 mm below the lowest point of anatomical cervical line through the establishment of a plane set by the three apaxes of the buccomesial, buccodistal, and mesiopalatal cusps parallel to the base plane of the mold [Fig. 1(a)]. The non-prepared coronal form of each embedded tooth was scanned with a CEREC AC Omnicam to reproduce the original form onto each fabricated crown restorative [Fig. 1(b)]. All embedded tooth specimens were divided into three groups: MOD inlay restoration (Inlay), MODP onlay restoration (Onlay), and crown restoration (Crown) [Fig. 1(c)]. A straight cylinder diamond bur (FG211, ISO #: 110 070 014, mean grit size: 100 µm; Shofu) for occlusal preparation and a round-end diamond bur (FG107RD, ISO #: 198 090 023, mean grit size: 100 µm; Shofu) for pulp and axial wall preparation were equipped in a custom-made cavity duplicator (Tokyo Giken, Tokyo, Japan) and used for the standardized preparation. For the inlay group, the pulpal wall was prepared first at a depth of 2.0 mm from the deepest part of the central fossa with FG107RD. Both buccal and palatal walls were established 2.0 mm away from the central fossa. Then, both mesial and distal proximal boxes of a 1.5 mm width were prepared 1.0 mm above the lowest point of the anatomical cervical line. For the onlay group, first the inner and outer inclined surfaces of the palatal cusp were prepared with FG211 at a depth of 1.7 mm. Then, the buccal wall was established 0.8 mm away from the central fossa. After that, an axial wall with a rounded shoulder of 1.5 mm width was prepared with FG107RD. For the crown group, the tooth structure of the occlusal surface was removed first with FG211 to a depth of 1.7 mm. Then, an axial wall with a rounded shoulder of 1.5 mm width was prepared with FG107RD [Fig. 1(d)]. The exposed dentin surfaces of all prepared specimens were treated with Clearfil Universal Bond Quick and Clearfil Majesty ES Flow was applied with a small brush to control the thickness. Both materials were light-cured for 20 s individually. The unpolymerized superficial layer of IDS was removed with a cotton pellet soaked in 70% ethanol [Fig. 1(e)]. All specimens were scanned with a CEREC AC Omnicam according to the manufacturer's instructions. Each ceramic restorative was designed by using the duplicate function of CEREC AC Omnicam and the data of the intact coronal form, and all restoratives were fabricated with the CEREC MC XL [Fig. 1(f)]. Prior to cementation, each inner surface of the fabricated restorative was etched with porcelain etchant for 90 s, rinsed with sprayed water, and air-dried. The 24 specimens of each type of restoration group were further divided into three groups using different cements: SB, CC, and PV [Fig. 1(g)]. The internal surfaces of the three types of restorative, prepared cavity walls, and abutment surfaces were pretreated according to the manufacturer's instructions. For the SB group, cement paste was prepared with a standardized powder/liquid ratio and bulk-mix method and applied to the inner surface of restorative. For the CC and PV group, cement paste was applied directly from the auto-mixing tip to the inner surface of the restorative. All restoratives with the three type of restorations were placed in the cavity/abutment under a set force of 900 g. For SB group, a 900 g static load was applied for 2 min, and the excess cement was removed. Then, the restored specimens were left for 8 min. For the CC and PV groups, each restored specimen was light-irradiated from the occlusal, mesial, distal, buccal, and palatal directions with G-Light Prima II for 10 s each for a total irradiation period of 50 s. They were then pressed for 1 min, and excess cement
was removed. All restored specimens were polished with a series of polishing disks (Sof-Lex XT, 3M, Seefeld, Germany) from coarse (#400 grit, 12.7 mm diameter, 5,000 rpm) to superfine (#1200 grit, 12.7 mm diameter, 5,000 rpm) and stored in 37°C water for 1 h [Fig. 1(h)].

**Cyclic load and µ-TBS testing**

For each restored specimen, an opposing object was fabricated individually with an acrylic resin (PROVINICE, Shofu) to load stress against the inner and outer inclined surfaces of the functional cusps and the inner inclined surface of the non-functional cusp. All restored specimens were subjected to a cyclic load of 157 N at 90 cycles/min for $3 \times 10^5$ cycles in total [Fig. 1(i)]. This process was performed in 37°C water with a custom-made multifunction apparatus (Tokyo Giken). All restored specimens were sectioned three times along the bucco-palatal dimension into two slab specimens of 1.05 mm thickness with a precision sectioning machine (IsoMet 1000, Buehler, Lake Bluff, IL, USA) [Fig. 1(j)].

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**Fig. 1** Schematic flowchart of the experimental procedures.
The obtained slab specimens were polished with a series of silicone carbide papers up to #2000 and adjusted to a thickness of 1.0 mm [Fig. 1(k)]. Each polished and adjusted slab was trimmed to a standardized dumbbell-shaped specimen with a cross-sectional area of 1.0×1.0 mm using a custom-made test piece duplicator (Tokyo Giken). For the inlay group, the center of the cross-sectional area of the dumbbell-shaped specimen was adjusted to be consistent with the center of the bonded pulpal wall directly under the central fossa. On the other hand, for the onlay and crown groups, the center of the cross-sectional area of the dumbbell-shaped specimen was adjusted to be consistent with the center of the inner inclined surface of the functional cusps. The µ-TBS value of each specimen (n=16) was measured at a crosshead speed of 1.0 mm/min with a universal testing machine (Autograph AG-1, Shimadzu, Kyoto, Japan) [Fig. 1(l)]. If any test specimen failed during trimming before the µ-TBS test [pre-testing failure (ptf)], the value of the specimen was replaced by a random value from zero to the lowest µ-TBS value measured in the respective group.

Statistical analysis
The effects of the two factors (i.e., the type of restoration and adhesive resin cement system) on the µ-TBS were examined by two-way analysis of variance (ANOVA) using spreadsheet software (Excel 2010 for Windows, Microsoft, Redmond, WA, USA), with the level of significance set at 0.05%. Furthermore, the Weibull parameters based on µ-TBS values —the Weibull modulus (Wm) and Weibull stress at 10% and 90% failure probabilities (PF10 and PF90)— were analyzed with the same spreadsheet software to examine the bonding reliability.

RESULTS
Table 2 presents the mean µ-TBS (MPa), standard deviation (SD), and number of ptf s for the three type of restorations and three adhesive resin cement systems. The differences for the type of restoration and adhesive resin cement system did not significantly influence the µ-TBS. No interaction between the type of restoration and adhesive resin cement system was recognized for the µ-TBS. ptf was confirmed to occur under every experimental condition.

Bonding reliability
Figure 2 shows the differences in the Weibull parameters (i.e., Wm, PF10, and PF90) among the three type of restorations and three adhesive resin cement systems. There were significant differences in Wm, which indicates the bonding reliability, and PF10 and PF90. Inlay restoration showed similar or significantly smaller values for the Weibull parameters compared to the onlay and crown restorations. There were significant differences in the values of both Wm and PF10 among the three systems. The adhesive resin composite cement applied with a self-etching primer (PV) demonstrated

Table 2  Differences in the mean µ-TBS (MPa) among the three type of restorations cemented with three adhesive resin cement systems

| Adhesive resin cement system | Type of restoration | Mean µ-TBS | SD  | ptf | (n=16) |
|-----------------------------|---------------------|------------|-----|-----|--------|
| SB                          | Inlay               | 5.4        | 3.2 | 3   |        |
|                             | Onlay               | 5.8        | 2.4 | 1   |        |
|                             | Crown               | 6.1        | 3.5 | 2   |        |
| CC                          | Inlay               | 4.9        | 2.9 | 3   |        |
|                             | Onlay               | 5.1        | 4.1 | 3   |        |
|                             | Crown               | 6.4        | 4.0 | 2   |        |
| PV                          | Inlay               | 5.2        | 2.7 | 2   |        |
|                             | Onlay               | 5.9        | 2.6 | 1   |        |
|                             | Crown               | 7.3        | 2.5 | 1   |        |

µ-TBS: micro-tensile bond strength, SD: standard deviation, ptf: pre-testing failure
There were no significant differences among the mean µ-TBS of the three type of restorations cemented with the three adhesive resin cement systems.
Fig. 2 Differences in Weibull parameters among the three type of restorations and three adhesive resin cement systems.
Wm: Weibull modulus, PF10: Weibull stress (MPa) for a 10% failure probability, PF90: Weibull stress (MPa) for a 90% failure probability

Fig. 3 Differences in Weibull parameters among the three type of restorations cemented with the three adhesive resin cement systems.
Wm: Weibull modulus, PF10: Weibull stress (MPa) for a 10% failure probability PF90: Weibull stress (MPa) for a 90% failure probability

highly reliable CAD/CAM ceramic restoration compared to the non-filler-containing 4-META/MMA-TBB cement (SB) and adhesive resin composite cement applied with a designated all-in-one adhesive agent (CC). Figure 3 shows the differences in the Weibull parameters (i.e., Wm, PF10, and PF90) among the three type of restorations with the three adhesive resin cement systems. With SB, onlay restoration had significantly higher Wm and PF10 values than the other type of restorations. With CC, the three types of restorations showed no significant differences in Wm, PF10, and PF90. With PV, the crown restoration had the highest Wm and PF10 values, followed by the onlay restoration and then the inlay restoration; significant differences were recognized between any pair of the three type of restorations. Figure 4 shows the differences in the Weibull parameters (i.e., Wm, PF10, and PF90) among the three adhesive resin cement systems applied to the three types of restoration. With inlay restoration, the three adhesive cement systems showed no significant differences. With onlay restoration, SB had the highest Wm and PF10 values, which were similar to or significantly greater than those of the two other cement systems. With crown restoration, PV had significantly greater Wm and PF10 values than the other two cement systems. The above results regarding the differences in bonding reliability indicate that the three adhesive resin cements had no qualitative difference for inlay restoration. In contrast, onlay restoration with SB and crown restoration with PV demonstrated excellent performances.

Fracture mode distribution of the specimens
Table 3 presents the distribution of the fracture modes analyzed under a light microscope. Regardless of the restoration and cement system, every post-test specimen exhibited mixed fracture consisting of three.
Fig. 4 Differences in Weibull parameters among the three adhesive resin cement systems applied to three types of restoration.

Wm: Weibull modulus, PF10: Weibull stress (MPa) for a failure probability of 10%, PF90: Weibull stress (MPa) for a failure probability of 90%

Table 3 Distribution of fracture modes

| Adhesive resin cement system | SB | CC | PV |
|-----------------------------|----|----|----|
| Type of restoration         | Inlay | Onlay | Crown | Inlay | Onlay | Crown | Inlay | Onlay | Crown |
| Ir+Cr                       | 7   | 3   | 10  | 6    | 7    | 4    | 6    | 5    | 8    |
| Ir+Cr+Is                    | 1   | 4   | —   | —    | —    | 3    | —    | 1    | 2    |
| Cr+Is                       | 8   | 9   | 6   | 10   | 9    | 9    | 10   | 10   | 6    |
| ptf                         | 3   | 1   | 2   | 3    | 3    | 2    | 2    | 1    | 1    |

Ir: Interfacial fracture at the interface between the restorative and resin cement
Cr: Cohesive fracture within the resin cement and within the integrated layer of cement and adhesive agent
Is: Interfacial fracture at the sealing surface/resin cement
ptf: Pre-testing failure during the trimming procedure

fracture modes: a restorative-resin cement interface (Ir), a cohesive fracture within the resin cement and within the integrated layer of cement and adhesive agent (Cr), and a resin cement-sealing interface (Is). In addition, every mixed fracture always included Cr. Mixed fracture consisting of Cr and Is accounted for 53% of all post-test specimens. Ptf occurred in eight, five, and five specimens of the inlay, onlay, and crown restoration groups, respectively.

Figure 5 shows representative SEM images (×50 magnifications) of dentin-side surface of the post-test three restoration specimens luted with the three cement systems. Figures 5-1 and 5-2 (a test specimen of inlay and onlay with SB) showed the mixed fracture mode consisting of cohesive fracture within the resin cement and within the integrated layer of cement and adhesive agent (Cr) and interfacial fracture at interface between the sealing surface/resin cement (Is). The slightly coarse surface of Cr and smooth and wavy surface of Is were observed. Figure 5-3 (a test specimen of crown with SB) indicated the mixed fracture mode consisting of interfacial fracture at interface between the restorative/resin cement (Ir) and Cr. The smooth surface of Ir and slightly coarse surface of Cr were observed. Figures 5-4, 5-5 and 5-6 (a test specimen of inlay, onlay and crown with CC) presented the mixed fracture mode consisting of Cr and Is. The Cr surface was observed as coarse. The Is surfaces of Figs. 5-4 and 5-5 were smooth, and the surface of Fig. 5-6 was wavy. Figures 5-7 and 5-8 (a test specimen of inlay and onlay with PV) showed the mixed fracture mode consisting of Cr and Is. The slightly rough surface of Cr and smooth surface of Is were observed.
DISCUSSION

Differences in the type of restoration did not significantly influence the mean values of the µ-TBS in this study (Table 2). Cyclic loading was employed at 157 N and 90 cycles/min for a total of $3 \times 10^5$ cycles. These conditions were set based on previous reports that the human mastication motion generates stress equivalent to 70–150 N\(^{11,12}\), which is repeated 60–90 times per minute\(^{13,14}\). In addition, the total number of loading cycles was based on a study indicating that the average cycle of human mastication motion per year is approximately $2.5 \times 10^6$ times\(^{15}\), which would match clinical loading in the oral environment for approximately 14 months without sleeping or resting. The CAD/CAM ceramic restorations with the adhesive resin cements used in this study successfully achieved a clinical level of bonding based on the quantitative indicator (i.e., mean value of µ-TBS) regardless of the type of restoration.
The number of specimens with ptf indicate that onlay and crown restorations may provide better bonding certainty (five ptf specimens) than inlay restoration (eight ptf specimens). Consequently, careful operation is necessary if inlay restoration is selected in clinical practice. No previous studies have examined the effect of different types of restoration (i.e., inlay, onlay, and crown) on the $\mu$-TBS, especially the $\mu$-TBS obtained from the intra-cavity wall after a dynamic load. Evaluations of the bond strength mainly focused on the mean value of the $\mu$-TBS[4,5,10,16,17]. This is a quantitative evaluation that is easy to understand, because the magnitude of the obtained data can be simply related to the bond strength. The quantitative evaluation of the $\mu$-TBS in this study confirmed that the $\mu$-TBS on the IDS pulp wall after a cyclic load simulating the oral environment did not vary with the restoration type. In addition to a quantitative evaluation of bonding, a qualitative evaluation is very useful for understanding the bonding characteristics. The Weibull analysis[8] is a qualitative evaluation advocated by ISO to characterize the bond strength[7] and is characterized by two principal parameters; Weibull modulus (Wm) and Weibull stress values at the 10% and 90% failure probabilities (PF10 and PF90). De Munck et al.[18] reported that PF10 may be a more important indicator than the mean value because a low value may reflect early failure in clinical scenarios. Thus, Wm and PF10 may be more important indicators than PF90. For the qualitative evaluation for Weibull parameters, inlay restoration with the three adhesive resin cements tended to have inferior bonding reliability compared to onlay and crown restorations (Fig. 2). Therefore, inlay restoration with the three adhesive resin cement systems tended to have inferior bonding reliability compared to the onlay and crown restorations. Feitosa et al.[19] analyzed the stress distribution for inlay restorations after mechanical loading and reported a higher stress concentration in the area close to the marginal crest near the restoration margin. The occlusal margin, which is exposed to a harsh cyclic load, was less for the onlay restoration than for the inlay restoration. This is one reason why the inlay restoration would have inferior bonding reliability compared to the onlay restoration. The inlay restoration has a smaller total area of the band-like gingival wall that resists the cyclic load (crown restoration has the largest area, while onlay restoration has the second-largest), which may be another reason for the low qualitative results.

The different adhesive resin cements did not affect the mean values of the $\mu$-TBS (Table 2). However, there were significant differences in the qualitative evaluation among the three adhesive resin cements (Fig. 2). The adhesive resin cement system with the best performance was PV, followed by SB and then CC. The cement systems used in this study required different pretreatments according to the manufacturer’s instructions. Before the resin cement mixtures were applied to the prepared surfaces, SB and PV specified the application of a self-etching primer that would not generate any layered structure. In contrast, CC applied a designated all-in-

one adhesive agent that would produce a thin layered structure. Therefore, SB, CC, and PV had two, three, and two interfaces, respectively, in the space between the restorative and prepared surface. Interfaces are vulnerable parts that can cause debonding. Therefore, increasing the number of interfaces makes it difficult to achieve robust adhesion. Although the application of an adhesive agent prior to cementation provides some advantages such as improved wettability, the existence of a layered adhesive resin structure negatively influenced both the bonding reliability. The main ingredients of the adhesive resin cement can have a great influence on its physical properties. The elastic moduli of the adhesive resin cements were 1.7 GPa for SB[20], 7.1 GPa for CC[21], and 6.3 GPa for PV[22]. The elastic moduli of the restorative materials and tooth substrate were 45 GPa for the feldspathic ceramic block[23, 24], 7.4 GPa for the flowable resin composite used for IDS[24, 25], and 16–18 GPa for dentin[24, 25]. Murata et al.[17] reported that the IDS layer between the resin cement and dentin improves the $\mu$-TBS by functioning as a stress breaker against external forces in CAD/CAM ceramic onlay restorations. In this study, IDS was employed for all prepared dentin surfaces, and the sealing layer may have contributed to the robust adhesion as a stress breaker. Therefore, SB and PV, which had lower elastic moduli than the flowable resin composite, had better bonding reliability because of the absorption or dispersion of stress[26]. Meanwhile, CC had low bonding reliability because it had a lower elastic modulus than the IDS layer. The results for the fracture modes showed that mixed fracture consisting of cohesive fracture in the cement (Cr) and interfacial fracture between the cement and sealing layer (Is) accounted for 53% of all post-test specimens. This tendency was particularly notable for CC (Table 3). Therefore, the fracture mode of CC, which consisted mainly of Cr and Is, differed from those of SB and PV. This may have caused the differences in the bonding reliability of CC compared to SB and PV.

With SB, the onlay restoration showed significantly greater Wm and PF10 values than the other type of restorations (Fig. 3). A study using finite element analysis reported that MODB onlay restoration covering the functional cusps is more effective at absorbing the load and transferring the stress to the cavity walls compared to MOD inlay restoration[27]. In addition,SB has an elastic modulus of 1.7 GPa[20], which is significantly smaller than those of the restorative materials used in this study and the tooth substrate (45 GPa for the feldspathic ceramic block[23], 7.4 GPa for the flowable resin composite used for IDS[24, 25] and 16–18 GPa for dentin[24, 25]). Therefore, the onlay restoration had superior bonding reliability to the inlay restoration. In contrast, the crown restoration received the cyclic load stress on the occlusal surface of restorative, whereas the onlay restoration was subjected to stress on both the tooth substance and ceramic restorative material. Specifically, for the crown restoration, the cyclic load was caught by the outer and inner inclined surfaces of the restored functional cusps and the inner inclined surfaces
of the restored non-functional cusps. Meanwhile, for the onlay restoration, the dynamic load was caught by the outer and inner inclined surfaces of the restored functional cusps and the inner inclined surfaces of the non-functional cusps consisting of the restorative and tooth substance. The difference in where the cyclic load was applied on the onlay and crown restorations may have influenced the bonding reliability of the CAD/CAM ceramic restorations with SB. In addition, the bonding characteristics with SB seemed to be influenced by the small elastic modulus of the cement. With CC, the three type of restorations showed no significant differences in Wm, PF10, and PF90 (Fig. 3). CC applies a designated all-in-one adhesive agent prior to cementation, and the layered resin adhesive structure may help absorb the cyclic stress and transfer the stress to the prepared surface. However, CC had small values for every Weibull parameter compared to SB and PV. Therefore, although the bonding reliability is not influenced by the type of restoration with CC, the clinical use of this cement for CAD/CAM ceramic restoration requires careful follow-up. With PV, significant differences were recognized between any pair of the three type of restorations (Fig. 3). Furthermore, the Wm and PF10 values were higher with PV than with the other cements. These bonding characteristic may be due to the relatively large elastic modulus (6.3 GPa) of PV, which would not influence the bonding characteristics, in contrast to SB, and improve the endurance against cyclic loads based on the total area of the band-like gingival wall.

The inlay restoration showed no significant differences in Wm, PF10, and PF90 among the three cement systems (Fig. 4). The inlay restoration had a smaller total area of the gingival wall than the other type of restorations. Therefore, the cyclic load stress was not decreased by the restorative support against the gingival wall area, and the stress was transferred through the inlay restoration to the pulpal wall where the bond strength was measured. Thus, the Weibull parameters of the inlay group were homogenized regardless of the cement system. For the onlay restoration, SB had the highest Wm and PF10 values compared to the other cement systems (Fig. 4). The low elastic modulus of SB (1.7 GPa) may have effectively eased the stress for onlay restoration. In the actual oral environment, the restorative surface is exposed to the chewed food and also experiences wear. SB has inferior wear resistance to the other cements because it does not contain inorganic filler. Therefore, the interfacial gap formation that occurs between the restorative and tooth substance should be considered, especially for restoration cemented with SB having an interfacial margin consisting of the tooth substance and restorative material. For crown restoration, PV had significantly greater Wm and PF10 values than the other two cement systems (Fig. 4). The elastic modulus of PV (6.3 GPa) was similar to that of the sealing layer (7.4 GPa), while SB (1.7 GPa) had a much smaller value. Dong et al. concluded that approximately equal elastic moduli for the cement and bonded material reduces the risk of bonding failure. Therefore, the stress that occurs at the interface between the cement and sealing layer may be small for restorations with PV. The elastic modulus of CC (7.1 GPa) is similar to those of PV (6.3 GPa) and the sealing layer (7.4 GPa). This may be one reason why the Wm and PF10 values of CC were smaller than those of PV. Restoration with CC should require the application of a designated resin adhesive system.

Every mixed fracture always included the Cr mode. Mixed fracture consisting of Cr and Is accounted for 53% of all ptf specimens. However, no obvious tendency related to differences in either the type of restoration or adhesive resin cement was recognized for the failure mode. On the other hand, ptf occurred in eight, five, and five specimens of the inlay, onlay, and crown restoration groups, respectively. The type of restorations employed in this study had different areas of the gingival wall that received the cyclic load stress with the pulpal wall. All restorations in this study used not only the pulpal wall but also the gingival wall to receive the cyclic load stress. However, the total area of the gingival wall did vary with the type of restoration.

CONCLUSION

Differences in the type of restoration and adhesive resin cement system did not significantly influence the μ-TBS. However, there were significant differences in Wm, which indicated the bonding reliability, and PF10 and PF90, among the three restoration types and three adhesive resin cement systems. Inlay restoration tended to have inferior bonding reliability compared to onlay and crown restoration with the same cements. An adhesive resin composite cement applied with a self-etching primer (PV) demonstrated excellent performance with highly reliable CAD/CAM ceramic restoration compared to a non-filler-containing 4-META/MMA-TBB cement (SB) and an adhesive resin composite cement applied with a designated all-in-one adhesive agent (CC). No qualitative difference was recognized among the three cements for the inlay restoration. Onlay restoration cemented with SB and crown restoration cemented with PV demonstrated excellent performances.

ACKNOWLEDGMENTS

This study was partially supported by the Japan Society for the Promotion of Science (KAKENHI Grant Number 17K11719).

CONFLICTS OF INTEREST

The authors do not have any financial interest in the companies whose materials are mentioned in the article.

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