

Influence of immediate dentin sealing and temporary restoration on the bonding of CAD/CAM ceramic crown restoration

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This study examined the influences of clinical application of immediate dentin sealing (IDS) and temporary restoration (TR) on prepared abutment surfaces on the bonding of computer-aided design/computer-aided manufacturing (CAD/CAM) ceramic crown restorations after cyclic loading. Standardized abutments were prepared in 60 human mandibular premolars. Dentin surfaces of half of the specimens were sealed with adhesive and flowable composite, while those of the other half were not sealed. A half of both sealed and non-sealed specimens were restored using a temporary cement and temporary crown. Each individual CAD/CAM ceramic crown was fabricated and cemented to an individual abutment. The restored specimens were subjected to cyclic loading, and the micro tensile bond strengths (μ -TBS) were measured. IDS contributed to an increase in the bond strength, whereas TR did not affect the bond strength. IDS restoration without TR yielded the maximum bond reliability in achieve specific μ -TBS values for the restoration and ensuring durability against debonding.

Keywords: CAD/CAM restoration, Immediate dentin sealing, Temporary restoration, Microtensile bond strength, Weibull analysis

INTRODUCTION

Computer-aided design/computer-aided manufacturing (CAD/CAM) technology has recently begun to be employed in dental clinical practice. Conventional indirect restorations, such as cast gold restorations, require complex procedures. However, CAD/CAM restorations created using digital data taken from optical impressions can simplify these procedures. The latest CAD/CAM systems are especially capable of fabricating high-quality and uniform inlay/onlay/crown efficiently. Nevertheless, metal-free CAD/CAM restorations require robust adhesion between the tooth substance and the fabricated inlay/onlay/crown to obtain an excellent prognosis¹⁾. Immediate dentin sealing contributes to improved adhesion²⁾, enhanced adaptation³⁾, and the protection of the dentin pulp complex⁴⁾ in inlay/onlay restorations. However, the efficacy of immediate dentin sealing with adhesive systems and flowable resin composites on metal-free CAD/CAM crown restorations has not been examined. Metal-free crown restorations for vital teeth may cause pulp damage, *i.e.*, inflammation and necrosis, because of the substantial reduction in tooth substance as a result of the abutment preparation process⁵⁾. Therefore, establishment of an application method for immediate dentin sealing of metal-free crown restorations should provide benefits in clinical practice.

Chair-side CAD/CAM systems allow one-day treatment^{6,7)}. In contrast, laboratory CAD/CAM restorations that are fabricated in the laboratory using digital data obtained with an intraoral scanner at the clinical office are worldwide⁸⁾. However, the laboratory service requires multiple patient visits, similar to the conventional indirect restoration. The use of temporary restorations using temporary crowns and cement

is necessary for the abutment tooth during crown restoration over multiple visits. Thus, determination of the influences of one-day treatment without temporary restoration and laboratory CAD/CAM restoration with temporary restorations on the bonding of CAD/CAM restorations is significant for the clinical application of these two restoration approaches. In this context, immediate dentin sealing has also been reported to ameliorate the reduction in bond strength caused by the application of temporary cement^{9,10)}. However, there is no report that evaluate the influence of the immediate dentin sealing and temporary cement on bonding under condition which mimicked intraoral environment.

Measurement of bond strength is a method for evaluating adhesive restorations. The microtensile bond strength (μ -TBS) test introduced by Sano *et al.*¹¹⁾ is a useful method for investigating internal bond strength that is influenced by various intraoral stresses, such as thermal and cyclic load stress¹²⁾. In this regard, the International Organization for Standardization (ISO) technical specification 11405 guidelines state¹³⁾ that calculations of the probability of failure using the Weibull distribution function are a suitable approach for comparing many materials¹⁴⁾.

This study aimed to examine the differences in bonding behavior among CAD/CAM ceramic restorations with and without immediate dentin sealing and temporary restorations after cyclic loading, simulating the intraoral condition, by measurement of μ -TBS values, investigation of the bond reliability and durability, and observation of the failure mode. The null hypotheses of this study were as follows: 1) immediate dentin sealing did not improve the bonding of CAD/CAM ceramic crown restorations; 2) temporary restorations did not have a negative influence on the bonding of CAD/

CAM ceramic crown restorations.

MATERIALS AND METHODS

Experimental materials

The product name, composition, lot number, and manufacturer details of each material used in this study

are shown in Table 1. For immediate dentin sealing, a all-in-one adhesive system (Clearfil Universal Bond Quick, Kuraray Noritake Dental, Tokyo, Japan) and a low-viscosity resin composite (Clearfil Majesty ES Flow, Kuraray Noritake Dental) were used. For temporary restorations, a bis-acrylic composite (Protemp4 Temporization Material, 3M, Seefeld, Germany) and

Table 1 Materials used in this study

Composition		Lot no.	Manufacturer
Immediate Dentin Sealing Materials			
Clearfil Universal Bond Quick	HEMA, Bis-GMA, MDP, Hydrophilic amide monomers, Colloidal silica, Silane, Sodium fluoride, Ethanol, Water	AR0010	Kuraray Noritake Dental
Clearfil Majesty ES Flow (Shade : A3)	Barium grass filler, Silica filler, TEGDMA, Hydrophobic-aromatic dimethacrylate, DI-Camphorquinone, Photo initiator	9T0203	
Temporary Restoration Materials			
Protemp4 Temporization Material	Dimethacrylate polymer, Bis-GMA, Zirconia Silica, Fumed Silica, Silane, Pigments	B 632665 C 631021	3M
TempBond NE	Base: Zinc oxide, Carnauba wax Accelerator: Rosin, Ortho-ethoxybenzoic acid, Octanoic acid.	5859290	Kerr
Chair-side CAD/CAM System			
CEREC AC Omnicam CEREC MC XL	CEREC operating system software version 4.3	—	Dentsply Sirona
Dental CAD/CAM Restorative Block			
VITABLOCS MarkII (Shade: A3C)	Silicon dioxide, Aluminum oxide, Sodium oxide, Potassium oxide, Calcium oxide, Titanium dioxide	44910	VITA
Pretreatment Materials for Cementation			
Porcelain Etchant (9.5%HF)	Polyacrylamidomethylpropane sulfonic acid, Hydrofluoric acid	17000000304	BISCO
Clearfil Ceramic Primer Plus	3-trimethoxysilylpropyl methacrylate, MDP, Ethanol	CA0011	Kuraray Noritake Dental
PANAVIA V5 Tooth Primer	MDP, HEMA, Hydrophilic aliphatic dimethacrylate, Accelerators, Water	2S0015	
Adhesive Resin Cement			
PANAVIA V5 (Universal Shade)	Paste A: Bis-GMA, TEGDMA, Silanated barium glass filler, Silanated fluoroalminosilicate glass filler, Hydrophobic aromatic dimethacrylate, Hydrophilic aliphatic dimethacrylate, Colloidal silica, Initiators, Accelerators Paste B: Bis-GMA, Silanated barium glass filler, Silanated alminium oxide filler, Hydrophobic aromatic dimethacrylate, Hydrophilic aliphatic dimethacrylate, Accelerators, DI-Camphorquinone, Pigments	7M0008	Kuraray Noritake Dental

HEMA, 2-hydroxyethyl methacrylate; Bis-GMA, bisphenol-A-glycidyl methacrylate; MDP, 10-methacryloyloxydecyl dihydrogen phosphate; TEGDMA, triethyleneglycol dimethacrylate.

non-eugenol zinc-oxide cement (TempBond NE, Kerr, Orange, CA, USA) were used. A chair-side CAD/CAM system (CEREC AC Omnicam SW v4.3 and CEREC MC XL, Dentsply Sirona, York, PA, USA) was used for scanning, designing, and milling of the ceramic crown. For the CAD/CAM block, the most feldspathic ceramic block (VITABLOCS Mark II, VITA Zahnfabrik, Bad Säckingen, Germany) was used. For pretreatment before cementation, 9.5% hydrofluoric acid (Porcelain Etchant, BISCO, Schaumburg, IL, USA) and a silane coupling agent (Clearfil Ceramic Primer Plus, Kuraray Noritake Dental) were applied to the inner surfaces of the fabricated crowns. Next, a self-etching primer (PANAVIA V5 Tooth Primer, Kuraray Noritake Dental) was applied to the abutment surface according to the manufacturer's instructions. For cementation, a dual-cure adhesive resin cement (PANAVIA V5, Kuraray Noritake Dental) was used. For all-light irradiation, a light-emitting diode (LED) curing unit (G-Light Prima II, GC, Tokyo, Japan) in the "normal" mode with an output of 900 mW/cm² using a 13/8 mm diameter turbo tip light guide was used. Before and after each light

irradiation, the light intensity was measured by a radiometer (Demetron L.E.D. Radiometer, Kerr).

Tooth selection and experimental procedures

The use of human teeth in this study was approved by the ethics committee of the Nippon Dental University School of Life Dentistry, Tokyo (approval number: NDU-T2016-06). Sixty human caries-free extracted lower premolars that had similar size and color within one year of storage in 0.1% thymol solution at 24°C after extraction were selected and used. A schematic flow chart of the experimental procedure is shown in Fig. 1. Each tooth was set into a standardized cylindrical mold such that the line connecting the top points of the mesiodistal cervical line and the line connecting the lowest points of buccolingual cervical line were parallel to the base plane of the mold [Fig. 1-(a)].

Each tooth was embedded with an acrylic resin (PROVINICE, Shofu, Kyoto, Japan) to 1 mm below from lowest point of the cervical line. The intact coronal form of each embedded tooth was scanned with a CEREC AC Omnicam to reproduce the original form onto each

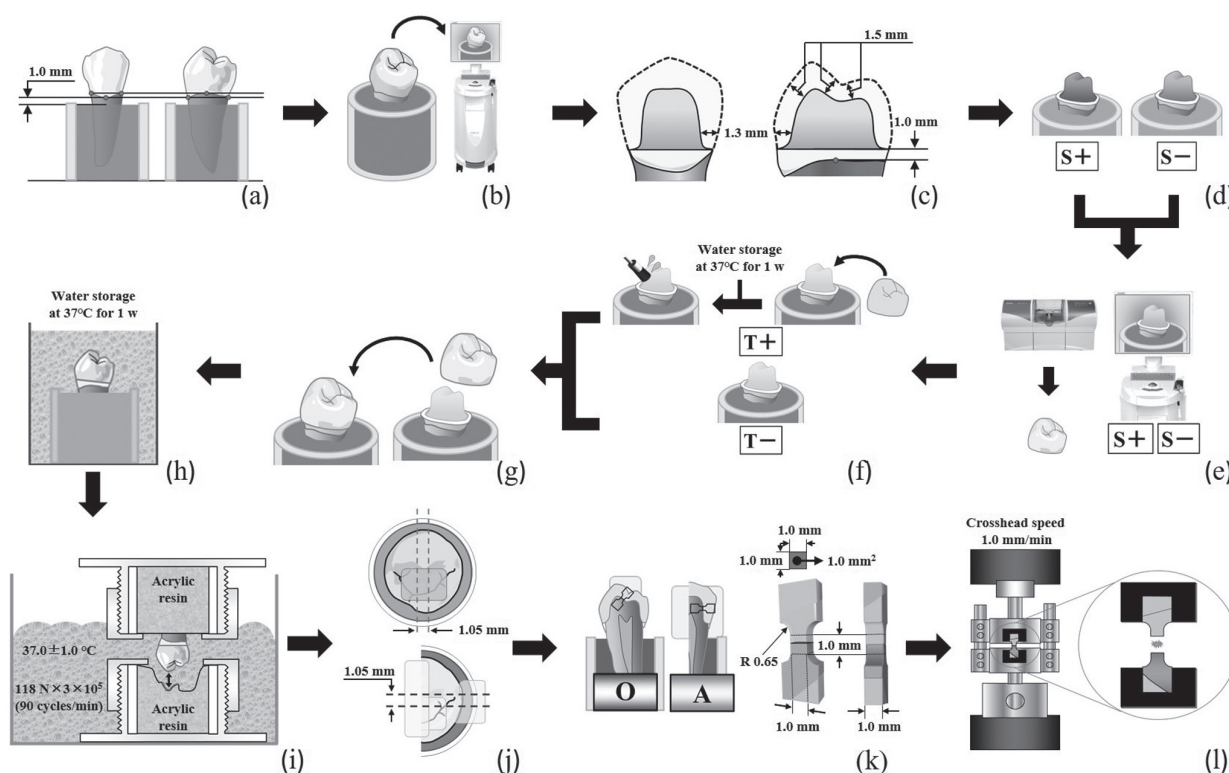


Fig. 1 Schematic flow chart of the experimental procedure.

Standardized CAD/CAM ceramic crown abutments were prepared and divided into two groups: an immediate dentin sealing group (S+) and a non-sealing group (S-). A half of both S+ and S- specimens were temporarily restored (T+) using a bisacrylic composite crown and a non-eugenol zinc-oxide cement, regardless of sealing mode. The other specimens were not temporarily treated (T-). Each CAD/CAM crown was designed and fabricated by a chair-side CAD/CAM system, and then cemented for each individual abutment. All restored specimens were subjected to cyclic loading stress and then sectioned. A 1.0-mm-thick slab was obtained from each specimen, and was trimmed into a standardized dumbbell-form specimen bonded to the occlusal dentin wall. The μ -TBS was measured at a crosshead speed of 1.0 mm/min.

crown [Fig. 1-(b)]. Impressions of the tooth coronal form were taken with a silicone impression material (Exaflex Putty, GC) for confirmation of the tooth volume reduction by the abutment preparation and for fabrication of temporary crowns. The parallel-sided bur of diameter 1.4 mm (FG211; ISO #: 110 070 014, mean grit size: 100 μ m; Shofu) was selected for preparation of the occlusal surface, and the round-end diamond bur of maximum diameter 2.1 mm designed for CAD/CAM crown restoration (FG106RD, ISO #: 198 090 021, mean grit size: 100 μ m; Shofu) was selected for preparation of the axial wall and margin. Standardized abutment specimens were prepared using a custom-made abutment and cavity duplicator (Tokyo Giken, Tokyo, Japan, Fig. 2) equipped with two types of diamond burs.

The abutment specimens were prepared according to general method of CAD/CAM crown restoration¹⁵⁾. First, the tooth structure of the occlusal surface was removed with FG211 to a depth of 1.5 mm [Fig. 1-(c)]. Then, the axial wall with a rounded shoulder of 1.3-mm width was prepared using FG 106RD. Diamond burs were replaced every three abutment preparations. Subsequently, all abutment specimens were divided into two groups; an immediate dentin sealing restoration group (S+) and a non-immediate dentin sealing restoration group (S-) [Fig. 1-(d)]. The prepared dentin surfaces in the S+ group were treated with a Clearfil Universal Bond Quick and light cured for 10 s. Then, Clearfil Majesty ES Flow (average: 17 mg) was applied to the pretreated dentin surface with a standardized thickness using a small brush, followed by light-curing for 20 s. The unpolymerized superficial layer in the immediate dentin sealing group was removed by a cotton pellet soaked in 70% ethanol. All abutment specimens were scanned using the CEREC AC Omnicam according to

the manufacturer instructions. Each ceramic crown was designed using the duplicate function of CEREC AC Omnicam and the data for the intact coronal form, and milled with the CEREC MC XL [Fig. 1-(e)].

Next, half of the samples in both S+ and S- groups were selected to form the temporary restoration group (T+) [Fig. 1-(f)]. The other specimens were assigned to the non-temporary restoration group (T-). For the T+ group, temporary crowns were fabricated individually with an impression of a pre-prepared coronal form and Protemp4 Temporization Material. The fabricated temporary crowns were cemented to each specimen of the T+ group using TempBond NE, and the samples of the T+ restoration group were stored in water at 37°C for 1 week. After removal of temporary crowns, the abutment surface of the T+ restoration group was cleaned with a polishing brush (Merssage brush CA No.1, Shofu) under water¹⁶⁾. Individual ceramic crowns of the T- group were cemented to the abutment without the temporary restoration step.

Before cementation, each inner surface of the fabricated ceramic crown was etched with Porcelain Etchant for 90 s, rinsed, and air-dried. The etched surfaces were treated with Clearfil Ceramic Primer Plus. Every surface of all abutment specimens was treated with the PANA VIA V5 Tooth Primer for 20 s, and dried under a gentle flow of air. PANA VIA V5 resin cement was applied to the inner surface of the ceramic crowns, and the crown was pressed onto the abutment under a certain force of 900 g for 1 min [Fig. 1-(g)]. After removal of excess cement, each restored specimen was light-irradiated from the occlusal, mesial, distal, buccal, and lingual directions with G-Light Prima II for 10 s, for a total irradiation period of 50 s. Then, each restored specimen was polished with a series of polishing disk (Sof-Lex XT, 3M), from coarse disk (#400 grit, 12.7 mm diameter, 5,000 rpm) up to super fine disk (#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 incline of the functional cusps of the ceramic crown. All restored specimens were subjected to a cyclic load of 118 N over 90 cycles/min for a total of 3×10^5 cycles [Fig. 1-(i)]. This process was performed in water at 37°C using a custom-made multi-function apparatus (Tokyo Giken). Using a precision sectioning machine (IsoMet 1000, Buehler, Lake Bluff, IL, USA), every restored specimen was sectioned along the buccolingual dimension into a slab specimen of 1.05-mm thickness including the bonded interface at the inner incline of the functional cusps (O) [Fig. 1-(j)]. Then, each remaining distal part of the restored specimen was sectioned along the mesiodistal dimension into a slab specimen of 1.05-mm thickness including the bonded interface of the axial wall (A). The obtained slab specimens were polished with a series of silicone carbide papers up to #2000, and adjusted to a

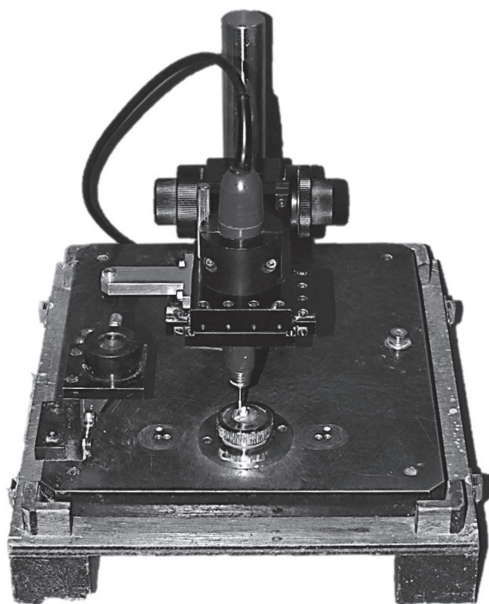


Fig. 2 Custom-made abutment and cavity duplicator.

thickness of 1.0 mm. Each polished slab was trimmed to a standardized dumbbell-formed specimen¹⁷⁾ with a cross-sectional area of 1.0×1.0 mm using a custom-made test piece duplicator (Tokyo Giken) [Fig. 1-(k)]. Next, the μ -TBS values of each specimen ($n=15$) were measured at a crosshead speed of 1.0 mm/min using a universal testing machine (Autograph AG-1, Shimadzu, Kyoto, Japan) [Fig. 1-(l)].

Statistical analysis

The data distribution between two groups were examined with F test and the distribution among three groups were determined with Bartlett's test. Then the μ -TBS data were analyzed with Welch's *t*-test, two-way ANOVA, and Tukey's HSD test 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, namely, the Weibull modulus and the Weibull stress values at 10 and 90% probability of failure (PF10 and PF90), were analyzed using the same spreadsheet software to examine the bond reliability and durability.

Fracture mode observation

After μ -TBS measurements, the fracture mode of each dumbbell-shaped specimen was observed using a light microscope (Measurescope MM-11, Nikon, Tokyo, Japan) at a magnification of 200×. Fracture mode was classified to Ri: interfacial fracture occurring at the interface between fabricated crown and resin cement; Cc: cohesive fracture occurring within the resin cement; Ai: interfacial fracture occurring at the interface between

abutment and resin cement.

RESULTS

Microtensile bond strength

Pre-testing failure was not recognized in this study. The differences in the μ -TBS values between the CAD/CAM restoration groups with and without immediate dentin sealing or temporary restorations and between the occlusal and axial abutment surfaces are shown in Fig. 3. The μ -TBS values in the restoration group with immediate dentin sealing (S+) were significantly greater than those without immediate dentin sealing (S−). Thus, immediate dentin sealing contributed to an increase in the bond strength. On the other hand, no significant difference was noted in the μ -TBS between the restoration groups with and without temporary restoration and between the occlusal (O) and axial abutment surfaces (A). Thus, the application of temporary restorations did not affect the bond strength, and the bond strengths to the occlusal and axial abutment surfaces were equivalent.

Figure 4 shows the differences in the μ -TBS values for the occlusal and axial abutment surfaces among the four CAD/CAM restoration groups with and without immediate dentin sealing and temporary restoration. Temporary restoration did not affect the μ -TBS value for the occlusal abutment surface, but immediate dentin sealing significantly influenced the value. However, the effect of immediate dentin sealing on the μ -TBS to the occlusal abutment surface varied depending on the use of temporary restorations. In the μ -TBS assessments for the occlusal abutment surface in the T− group, the value

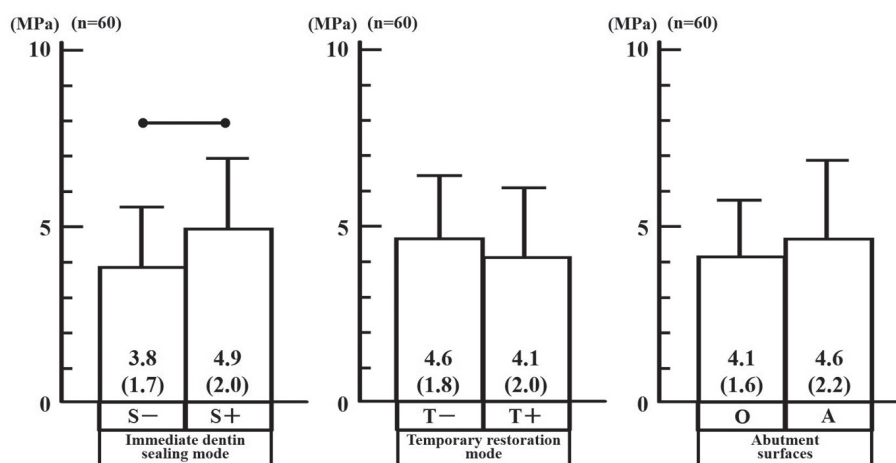


Fig. 3 Differences in μ -TBS between the CAD/CAM restoration groups with and without immediate dentin sealing or temporary restoration and between occlusal and axial abutment surfaces.

μ -TBS, micro-tensile bond strength; (), standard deviation; Two groups connected with a straight line indicate a significant difference at $p < 0.05$; S−: a non-immediate dentin sealing restoration group; S+: an immediate dentin sealing restoration group; T−: the non-temporary restoration group; T+: the temporary restoration group; O: the inner incline of the functional cusps; A: including the bonded interface of the axial wall.

in the S+ group was significantly greater than that in the S- group. In contrast, the modes of immediate dentin sealing and temporary restoration did not affect the

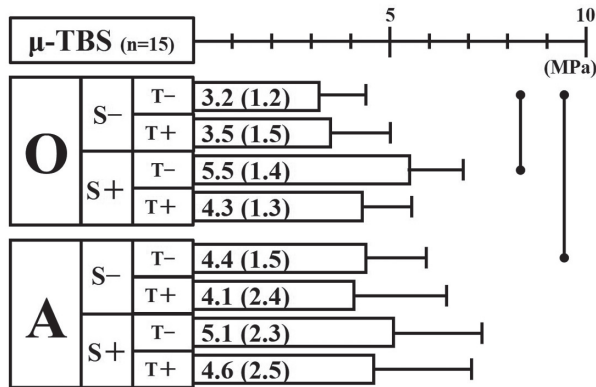


Fig. 4 Differences in μ -TBS values for occlusal and axial abutment surfaces among the four CAD/CAM restoration groups with and without immediate dentin sealing and temporary restoration. μ -TBS, micro-tensile bond strength; (), standard deviation; Two groups connected with a straight line indicate a significant difference at $p < 0.05$; S-: a non-immediate dentin sealing restoration group; S+: an immediate dentin sealing restoration group; T-: the non-temporary restoration group; T+: the temporary restoration group; O: the inner incline of the functional cusps; A: including the bonded interface of the axial wall.

μ -TBS. Consequently, for the axial abutment surface, no significant differences were recognized among the μ -TBS values of the four restoration groups. There was no significant difference in the μ -TBS values between the occlusal and axial abutment surfaces, except in the S-T- restoration group.

Bonding reliability and durability

Figure 5 presents the differences in the Weibull parameters, *i.e.*, the Weibull modulus and the PF10 and PF90, between the CAD/CAM restoration groups with and without immediate dentin sealing or temporary restoration and between the occlusal and axial abutment surfaces. The Weibull modulus, PF10, and PF90 values in the S+ restoration group were significantly greater than those in the S- restoration group. The Weibull modulus and PF10 values in the T- restoration group were significantly greater than those in the T+ restoration group, although no significant difference was noted in the PF90 values of these two restoration groups. In contrast, the values of the Weibull parameters did differ between occlusal and axial abutment surfaces.

Figure 6 shows the differences in Weibull modulus, PF10, and PF90 (95% confidence intervals, lower-upper limit values), for the occlusal abutment surface among the CAD/CAM restoration groups with and without immediate dentin sealing and temporary restorations. Weibull modulus and PF10 values decreased in the following order: S+T->S+T+>S-T->S-T+, and the values in the S+T- group were significantly greater than those in the other restoration groups. Significant differences were noted in the Weibull modulus values

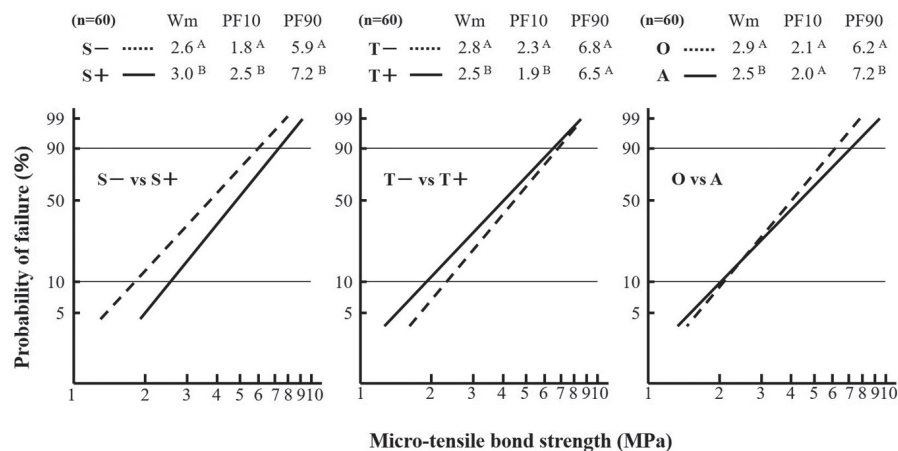


Fig. 5 Differences in Weibull parameters between the CAD/CAM restoration groups with and without immediate dentin sealing or temporary restoration and between occlusal and axial abutment surfaces. Values with different letters in the same column indicate a statistically significant difference at $p < 0.05$. Wm, Weibull modulus; PF10, PF90, the Weibull stress value in MPa for 10 and 90% probability of failure level; S-: a non-immediate dentin sealing restoration group; S+: an immediate dentin sealing restoration group; T-: the non-temporary restoration group; T+: the temporary restoration group; O: the inner incline of the functional cusps; A: including the bonded interface of the axial wall.

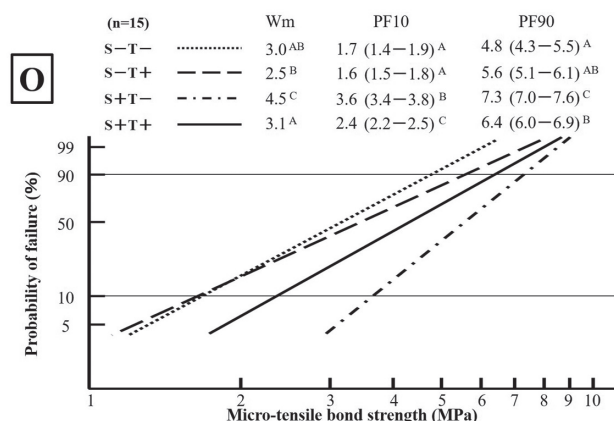


Fig. 6 Differences in Weibull parameters for occlusal abutment surfaces among CAD/CAM restoration groups with and without immediate dentin sealing and temporary restoration.

Values with different letters in the same column indicate a statistically significant difference at $p < 0.05$. Wm, Weibull modulus; PF10, PF90, the Weibull stress value in MPa for 10 and 90% probability of failure (95% confidence interval); S-: a non-immediate dentin sealing restoration group; S+: an immediate dentin sealing restoration group; T-: the non-temporary restoration group; T+: the temporary restoration group; O: the inner incline of the functional cusps.

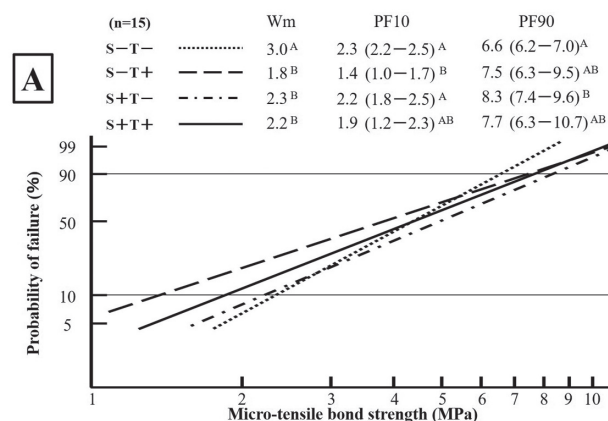


Fig. 7 Differences in Weibull parameters for axial abutment surfaces among four CAD/CAM restoration groups with and without immediate dentin sealing and temporary restoration.

Values with different letters in the same column indicate a statistically significant difference at $p < 0.05$. Wm, Weibull modulus; PF10, PF90, the Weibull stress value in MPa for 10 and 90% probability of failure (95% confidence interval); S-: a non-immediate dentin sealing restoration group; S+: an immediate dentin sealing restoration group; T-: the non-temporary restoration group; T+: the temporary restoration group; A: including the bonded interface of the axial wall.

Table 2 Fracture mode distribution observed using light microscopy

Immediate dentin sealing mode		S-		S+	
Temporary Restoration mode		T-	T+	T-	T+
Number of specimen		Amount (Occlusal / Axial wall)			
Mixed	Ri	1 (0/1)	2 (0/2)	1 (0/1)	0 (0/0)
	Ri + Cc	26 (13/13)	21 (11/10)	21 (9/12)	25 (11/14)
	Ri + Cc + Ai	0 (0/0)	0 (0/0)	2 (1/1)	2 (1/1)
	Cc + Ai	2 (1/1)	6 (4/2)	6 (5/1)	1 (1/0)
	Cc	1 (1/0)	1 (0/1)	0 (0/0)	2 (2/0)

Ri: interfacial fracture occurring at the interface between fabricated crown and resin cement; Cc: cohesive fracture occurring within the resin cement; Ai: interfacial fracture occurring at the interface between abutment and resin cement; S-: a non-immediate dentin sealing restoration group; S+: an immediate dentin sealing restoration group; T-: the non-temporary restoration group; T+: the temporary restoration group.

of the S+T+ and S-T+ restoration groups. On the other hand, the PF90 values decreased in the following order: S+T->S+T->S-T->S-T-, and the PF90 value of the S+T- restoration group was significantly greater than the values in the other restoration groups. Therefore, for the occlusal abutment surface, the S+T- restoration group showed maximal bond reliability in achieving a specific μ -TBS value for a restoration and durability against debonding.

Figure 7 shows the differences in Weibull modulus,

PF10, and PF90 (95% confidence intervals, lower-upper limit values) for the axial abutment surfaces among the four CAD/CAM restoration groups with and without immediate dentin sealing and temporary restoration. The values for the Weibull parameters decreased in the following order: S-T->S+T->S+T->S-T+ for Weibull modulus, S-T->S+T->S+T->S-T+ for PF10, and S+T->S+T->S-T->S-T- for PF90.

The fracture mode distribution of the specimens

The distribution of the failure modes observed under a light microscope are presented in Table 2. Cohesive fracture within immediate dentin sealing layer was not recognized. Regardless of the restoration, most of the post-test specimens exhibited mixed fractures consisting of interfacial fracture occurring at the interface between fabricated crown and resin cement and cohesive fracture occurring within the resin cement. The number of mixed fractures consisting of interfacial fracture occurring at the interface between fabricated crown and resin cement and interfacial fracture occurring at the interface between fabricated crown and resin cement was 26 (87%) for the S–T– group; 25 (83%) for the S+T+ group, 21 (70%) for the S–T+ group, and 21 (70%) for the S+T– group.

DISCUSSION

This study clarified that 1) immediate dentin sealing improved the bonding of CAD/CAM ceramic crown restorations; 2) temporary restorations did not have a negative influence on the μ -TBS values, whereas it decreased bonding of CAD/CAM ceramic crown restorations in the qualitative evaluation.

Efficacy of immediate dentin sealing on the bonding of CAD/CAM ceramic crown restorations

Metal-free restorations require robust and reliable adhesion for excellent prognosis. Immediate dentin sealing contributed to achieving robust μ -TBS values for the bonding interface in this study (Fig. 3). Murata *et al.*¹⁸⁾ reported that the immediate dentin sealing layer between the resin cement and dentin acts as a stress breaker for external forces, such as those generated by mastication, and contributes to an improvement in μ -TBS by functioning as a stress breaker in CAD/CAM ceramic onlay restorations.

The cyclic loading in this study was set at 118 N at 90 cycles/min for a total of 3×10^5 cycles. Previous studies have reported that the human chewing motion generates stress equivalent to 70–150 N^{19,20)}, which is repeated 60–90 times per minute^{21,22)}. In addition, Sakaguchi *et al.*²³⁾ reported that the average cycle of human chewing motion per year was approximately 2.5×10^5 times. Therefore, the setting of cyclic loading used in this study corresponds to clinical loading or more severe loading in the oral environment over 14 months without sleeping or resting.

Large differences in the elastic modulus values among the fabricated crown elements, cement, and the tooth substrate produce substantial stress at both interfaces and the stress decreases the μ -TBS under the cyclic load condition. Dong *et al.*²⁴⁾ concluded that approximation of the elastic modulus between the cement and bonded material reduces the risk of bonding failure. The elastic modulus values of the restorative materials and tooth substrate used in this study are as follows; feldspathic ceramic block, 45 GPa²⁵⁾; adhesive resin cement, 6.3 GPa²⁶⁾; flowable resin composite used for immediate dentin sealing, 7.4 GPa¹²⁾; and dentin,

16–18 GPa^{27,28)}. The elastic modulus of the flowable resin composite is smaller than that of dentin and is slightly larger than that of the adhesive resin cement. Consequently, the reduction in the difference between the elastic modulus values of the between dentin and adhesive resin cement mediated by the use of flowable resin composite for immediate dentin sealing helped achieve a robust μ -TBS.

The laboratory environment represents an ideal set of conditions in comparison with the oral environment of the patient. Previous studies^{2,9,10,16)} have examined adhesion using the mean values of bond strength as a representative parameter, regardless of stress loading. Assessments using mean values represent a quantitative evaluation of the adhesion. However, for evaluation of adhesion, in addition to quantitative determination, qualitative investigations, *e.g.*, reliability analysis, are important. The Weibull analysis is especially helpful in evaluating reliability¹⁴⁾. It is characterized by two principal parameters: the Weibull modulus, which can predict the reliability of a bond, and the Weibull stress values required to cause a failure, which evaluate the performance of a bond at certain percentage level *e.g.*, 10% level, 63.2% level, 90% level. A high Weibull modulus value is desirable for all materials because it indicates greater homogeneity in defect distribution and greater predictability of failure behavior²⁹⁾. Inokosi *et al.*³⁰⁾ reported that higher Weibull modulus values indicate better bond reliability. In addition, the ISO/TS 11405¹³⁾ suggested that stress values calculated at the 10 and 90% failure levels (PF10 and PF90) in data evaluations using Weibull analysis are useful for characterizing the strength of the bond. The application of immediate dentin sealing helped improve Weibull modulus, PF10, and PF90 (Fig. 5). Therefore, immediate dentin sealing should be effective in improving both quantitative and qualitative states of adhesion in CAD/CAM crown restorations.

In comparison with metal crown restorations, ceramic crown restorations require a large amount of tooth reduction to ensure mechanical strength and esthetics of the restoration. Ceramic crown restorations show excellent esthetics when applied on vital teeth in 25–72% of the clinical cases^{31–35)}. The large amount of tooth reduction for vital teeth exposes the deep dentin, and may cause injury to the dentin pulp complex because of external stimulations such as thermal and mechanical irritations, rarely leading to pulp necrosis. The deep dentin surface coating provided by immediate dentin sealing helps prevent postoperative sensitivity. Thus, immediate dentin sealing for CAD/CAM ceramic crown restorations allows both preservation of the adhesion and protection of the dentin pulp complex.

Influence of temporary restorations on the bonding of CAD/CAM ceramic crown restorations

For conventional indirect restorations, temporary restoration is usually applied to the abutment after the impression until the next chair-time visit^{36,37)}. Although digital dental treatment enables one-day treatment

and completion of the restoration in a single visit, laboratory CAD/CAM restorations⁸⁾ based on digital data obtained chair-side with an intraoral scanner are currently. However, methods based on laboratory CAD/CAM restorations require multiple visits, similar to a conventional indirect restoration. Thus, the abutment needs to be protected by a temporary restoration until the next visit. The aims of temporary restorations include pulpal protection, preservation of tooth substrate, restoration of occlusal function, and maintenance of esthetics^{36,37)}. Although temporary cement has been reported to decrease the bond strength of resin cement for the final restoration^{38,39)}, these results were based on measurements obtained after storage of specimens in water without any stress loading. This study evaluated the influence of temporary restoration by assessing the μ -TBS values for specimens restored with fabricated crowns after cyclic loading. The mode of temporary restoration did not significantly affect the mean μ -TBS value (Fig. 3). In theory, contamination with temporary cement increases the number of fractures including the abutment surface. However, the number of fractures including the abutment surface was almost equivalent between the non-temporary restoration group (10 specimens) and temporary restoration group (9 specimens) in this study (Table 2). Accordingly, the cleaning method employed in this study, *i.e.*, cleaning with a polishing brush under water¹⁶⁾ was effective in removing the harmful effect of the temporary cement.

However, in the qualitative evaluations, the temporary restoration decreased the Weibull modulus and PF10 values (Fig. 5), indicating that while contamination with temporary cement did not affect the μ -TBS, it had a negative effect on the bond reliability and the bond durability at a low probability level of failure. Therefore, thorough removal of the temporary cement and sufficient follow-up will be required to determine the final prognosis of CAD/CAM restorations with temporary restoration.

Influence of difference between occlusal and axial walls on the bonding of CAD/CAM ceramic crown restorations

Difference between occlusal and axial walls did not affect the mean μ -TBS values (Fig. 3). In any restoration of the four groups, the μ -TBS for the axial surface tended to be larger than the value for the occlusal surface (Fig. 4). However, bond reliability, based on the Weibull modulus value, of occlusal surfaces was significantly superior to that of axial surfaces, and the PF10 values showed no significant differences between the occlusal and axial surfaces. The PF90 value of the occlusal surface was significantly smaller than that of the axial surface (Fig. 5). Thus, severe cyclic loading set at 118 N had different influences on the bond reliability and durability of the two types of abutment surfaces. In the occlusal surface, where the cyclic load exerted a vertical force, the bonding was damaged uniformly; the bond reliability, including the negative factor, increased with a homogeneous degradation; and the bond durability at a high probability level of failure decreased simultaneously. In contrast, in

the axial surface, where the cyclic load stress exerted a horizontal force, the damage to bonding due to the shear stress caused by cyclic loading was small because the CAD/CAM crown material had a largish elastic modulus (45 GPa²⁵⁾). Consequently, the bond reliability, including the positive factor, decreased with a slight degradation, and the bond durability at a high probability level of failure increased.

Influence of CAD/CAM restoration with and without immediate dentin sealing and temporary restoration in the occlusal abutment surface on bonding

The non-temporary restoration group in this study can be considered to be representative of one-day treatment^{6,7)} with a chair-side CAD/CAM system. The immediate dentin sealing improved the μ -TBS, Weibull modulus, PF10, and PF90 values in this group (Figs. 4, 6). One-day treatment may serve as a more gentle restoration method for patients because of the impression-material-free treatment, single-visit protocol, and high-quality esthetics⁷⁾.

The temporary restoration group in this study can be considered to be representative of laboratory CAD/CAM restorations⁸⁾, which require multiple visits. Immediate dentin sealing did not affect the μ -TBS in the temporary restoration group (Fig. 4). In contrast, the Weibull modulus and PF10 values increased with immediate dentin sealing (Fig. 6). Thus, the efficacy of immediate dentin sealing in temporary restorations was inapparent in quantitative evaluations but was revealed by a qualitative assessment. Immediate dentin sealing also ameliorated the bond strength reduction caused by the application of temporary cement^{9,10)}. This may be attributable to the ability of immediate dentin sealing to prevent the invasion of temporary cement into the dentinal tubules. Thus, immediate dentin sealing might decrease the inapparent influence of temporary cement, which was undetectable in quantitative evaluations.

Although there was no significant difference in the μ -TBS values between the non-temporary (one-day treatment) and temporary restoration (laboratory CAD/CAM restoration) groups under the immediate dentin sealing condition (Fig. 4), the non-temporary restoration group showed superior Weibull modulus, PF10, and PF90 values (Fig. 6). Thus, a single application of immediate dentin sealing may not be sufficient to completely prevent the qualitative degradation caused by the temporary cement. However, the prepared dentin surface coated by immediate dentin sealing was protected against external stimulation by the layer of flowable resin composite. Therefore, the coated surface can be cleaned with a chemical method using phosphoric acid or other material.

Influence of CAD/CAM restoration with and without immediate dentin sealing and temporary restoration in the axial abutment surface on bonding

The magnitude relationships of Weibull modulus, PF10, PF90 values among the four restorations revealed different behaviors (Fig. 7) in occlusal and axial surfaces.

For the occlusal surface, the cyclic loading exerts its effects vertically, with the effects occurring directly on the luting zone, which consists of an interface between the surface and resin cement, the inner side of the resin cement, the interface between the resin cement and abutment surface or the immediate dentin sealing material, and the interface between the immediate dentin sealing material and the dentin surface via the restoration. Homaei *et al.*⁴⁰⁾ examined the stress distribution of metal-free crown restorations in premolars by using finite-element analysis and reported that the occlusal surface was most influenced by loading. For the axial surface, the stress behavior would be different because the loading stress is dispersed circumferentially over a broad margin.

The fracture mode distribution of the measured specimens

Mixed fractures consisting of Ri and Cc were observed on 97 sample surfaces (81%, Table 2). Therefore, the weakest part where bonding failure occurred might be the surface or the inner side of the resin cement. This study employed pretreatment with hydrofluoric acid and a silane coupling agent to the internal surface of feldspathic ceramic crowns, which is the global standard method^{36,37)}. Accordingly, some novel materials and a technique based on a new concept may be necessary to improve bonding. In addition, reinforcement of the mechanical properties of resin cement may help decrease the occurrence of Cc. This might be a useful strategy to improve quantitative and qualitative bonding.

CONCLUSION

Immediate dentin sealing contributed to an increase in the bond strength. The application of temporary restorations did not affect the bond strength, and the bond strengths for the occlusal and axial abutment surfaces were equivalent. The mode of temporary restoration did not affect the μ -TBS values for the occlusal abutment surface, whereas the mode of immediate dentin sealing significantly affected the values. The effect of immediate dentin sealing on the μ -TBS for the occlusal abutment surface did vary with the mode of temporary restoration. For axial abutment surfaces, the mode of both immediate dentin sealing and temporary restoration did not affect the μ -TBS values. Consequently, no significant difference was recognized among the μ -TBS values of the four restoration groups. The Weibull modulus, PF10, and PF90 values of the S+ restoration group were significantly greater than the corresponding values in the S- restoration group. For occlusal abutment surfaces, the S+T- restoration group showed the most superior bond reliability for achieving specific μ -TBS values of the restoration and bond durability against debonding.

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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