The effect of space setting values and restorative block materials on the bonding of metal-free CAD/CAM onlay restorations

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The effects of space setting values and restorative materials on the bonding of metal-free CAD/CAM onlay restoration were examined quantitatively and qualitatively. Seventy-two standardized MODB onlay cavities, prepared using human molars were restored under nine conditions, based on three space setting values, Increased (IC), Standard (SC, control), Decreased (DC), and three restorative block materials, resin-composites (RC), lithium disilicate glass-ceramics (LD), Feldspar ceramics (FC, control). All the restored specimens were subjected to cyclic loading and thereafter the microtensile bond strength (µ-TBS) was measured and analyzed statistically. The effect of space setting value on the µ-TBS varied with the restorative material. The bonding reliability of RC and the bonding durability of LD were significantly superior to FC. The bonding characteristics of RC under IC and DC were similar to those under SC. LD under DC and FC under IC were effective in obtaining an excellent bonding reliability relative to their SC.

Keywords: CAD/CAM restoration, Space setting value, Restorative block material, Microtensile bond strength, Weibull analysis

INTRODUCTION

Metal-free indirect restorations are preferred in clinical practice; recently, computer-aided design/computer-aided manufacturing (CAD/CAM) systems are widely used because it improves the efficiency of restorative production process and is less time-intensive and low cost. In the treatment process of metal-free indirect restoration, an adhesive resin cement is required for the cementation of the restorative to the cavity/abutment. The internal and marginal adaptation of the metal-free restorative is very important for the success of both temporary and permanent inlay/onlay-crown restorations, on human teeth as well as implants. The cement space (i.e., the adaptation of restorative to cavity/abutment) is one important factor contributing to the longevity of the restoration. It was reported that the actual cement spaces of metal-free inlay/onlay restorations are 23 to 243 μm. Gressler et al. found that the large-valued space setting of the CAD/CAM system causes decrease in the bond strength. In addition, some reports indicated that the marginal misfit of crown restorative may lead to microleakage and cement dissolution and then cause secondary caries, endodontic inflammation, and periodontal disease. From the above, the internal and marginal cement thickness may influence the bonding of metal-free CAD/CAM restorations. Further, previous studies showed that the thicker space setting provides an excellent crown adaptation to abutment. Therefore, there is no clear consensus regarding the optimum space setting for the CAD/CAM systems in the fabrication of the indirect restoratives. The CAD/CAM system can configure to any space setting value required for various cases of system software operation. There were several papers that examined the adaptation of CAD/CAM restorations conducted with different space setting values. However, there is no study that investigates the effect of space setting values on the bond strength of CAD/CAM restoration. Adding the clinical restorative process, including the recovering of anatomical coronal form to the experimental procedures, facilitates the estimation of clinical prognosis through the examination of the actual bonding state after the dynamic cyclic loading simulation in the intra-oral environment.

The demands for dental esthetics, biocompatibility, and long-termed restorations have led to the evolution of CAD/CAM systems and its various restorative block materials. Particularly, glass-ceramic type and resin-composite type blocks are typical CAD/CAM metal-free materials having superior esthetics and good mechanical properties. Feldspar ceramics have the longest history as the popular material for CAD/CAM restorations. Until now, feldspar ceramic block material has been employed for clinical application since the introduction of CAD/CAM restorations, and the material has demonstrated excellent clinical success rates. Accordingly, the feldspathic block can be one of the representative materials for CAD/CAM restoration. But this material has several disadvantages, such as low flexural strength and fracture toughness, compared with recent CAD/CAM block materials. Recently, lithium disilicate glass-ceramic, a glass-ceramic block material, is widely used in clinical practice. The mechanical properties of the material have been greatly improved, while retaining the advantages of glass-ceramics. Thus, lithium disilicate glass-ceramics is globally popular due to the superior esthetics and excellent mechanical properties. On the other hand, the material caused the highest human enamel antagonist wear compared with the wear caused by feldspar and resin-composite blocks owing to the hardness of the material. Resin-composite blocks
consist of inorganic ceramics, glass-ceramics, glasses, and organic resin. This material demonstrated excellent marginal chipping durability because it has low elastic modulus compared with the glass-ceramic block materials. Three types of metal-free block material are applied to CAD/CAM restoration in the recent years. However, there is no study that examined the actual bonding state of the CAD/CAM restoration using the aforementioned blocks after dynamic cyclic loading.

The aim of this study is to clarify the relationship between space setting for the chair-side CAD/CAM system and the actual cement thickness. The effect of differences in space setting value and restorative block material on the bonding behavior of metal-free CAD/CAM onlay restorations, after dynamic cyclic loading is investigated based on the values of microtensile bond strength (µ-TBS).

The null hypotheses of this study are as follows: 1) there is no relationship between the space setting for the chair-side CAD/CAM system and the actual cement thickness; 2) the differences in space setting values and restorative block materials do not influence the µ-TBS of metal-free CAD/CAM onlay restoration; 3) the aforementioned two factors do not affect the bonding reliability of the restorations.

MATERIALS AND METHODS

Experimental material

The product name, composition, lot number, and manufacturer name for all materials used in this study are presented in Table 1. The experimental codes assigned to the products are also provided. For the dental CAD/CAM restorative block materials, a polymer-infiltrated ceramic network (PICN) material as one of resin-composite block (VITA ENAMIC, VITA, Bad Säckingen, Germany; RC), two glass-ceramic blocks, a lithium disilicate glass-ceramic (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein; LD), and a feldspar ceramic block (VITALOCS Mark II, VITA; FC) were selected. A typical chair-side CAD/CAM system (CEREC AC Omnicam and CEREC MC XL) were operated based on the software version 4.5, Dentsply Sirona, Charlotte, NC, USA) was employed for scanning, designing, and fabricating the ceramic onlay. For immediate dentin sealing, an all-in-one adhesive system (Clearfil Universal Bond Quick, Kuraray Noritake Dental, Tokyo, Japan) was employed for scanning, designing, and fabricating the ceramic onlay. For immediate dentin sealing, an all-in-one adhesive system (Clearfil Universal Bond Quick, Kuraray Noritake Dental, Tokyo, Japan) was employed for pretreatment to prepared dentin surface, and a flowable resin composite (Clearfil Majesty ES Flow, Kuraray Noritake Dental) was used to seal the pretreated dentin surface. For etching pretreatment to the inner surfaces of lithium disilicate glass-ceramic and feldspar ceramic onlays prior to cementation, 9.5% hydrofluoric acid (Porcelain Etchant, BISCO, Schaumburg, IL, USA) was used. For cementation, a dual-cure type adhesive resin cement kit (PANAVIA V5, Universal, Kuraray Noritake Dental) were chosen. For light irradiation, a light-emitting diode (LED) light curing unit (G-Light Prima II, GC, Tokyo, Japan) and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer's default cement space setting group (Decreased condition; DC), and manufacturer’s default cement space setting group (Standard condition; SC, as control). The ethics committee of the Nippon Dental University School of Life Dentistry at Tokyo approved the use of extracted human teeth in this study (approved number: NDU-T2019-32). Seventy-two intact human mandibular molars of similar size and color were selected, which had been stored in 0.1% thymol solution at 23±2ºC for less than one year. The 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) that was set up as a plane set with three apexes of the mesiobuccal, distobuccal, and mesiolingual cusps, parallel to the base plane of the mold [Fig. 1(a)]. The intact coronal form of each embedded tooth was scanned with the scanner of the CAD/CAM system in order to reproduce the original form onto each fabricated onlay restorative [Fig. 1(b)].

A straight cylinder diamond bur (FG211, ISO #: 110 070 014, mean grit size: 100 µm, Shofu) and a round-end diamond bur (FG107RD, ISO #: 198 090 023, mean grit size: 100 µm, Shofu) for CAD/CAM restoration were equipped in a custom-made cavity duplicator (Tokyo Giken, Tokyo, Japan) and used for the standardized cavity preparation. The two types of diamond bur were changed every five tooth-preparations.

The inner and outer inclined surfaces of the buccal cusp were prepared with a FG211 at a depth of 1.7 mm. Then, the lingual wall was prepared with a FG107RD at a distance of 0.8 mm from the central fossa. The gingival wall with 1.5 mm width and the axial wall with a height of 2.0 mm or higher was prepared from the mesial side to distal side, through the buccal side. Accordingly, the standardized MODB onlay cavity preparation was completed [Fig. 1(c)]. For immediate dentin sealing, the prepared dentin surfaces were treated with an all-in-one adhesive system. Then, 30 mg of a flowable resin composite was applied to the treated dentin surfaces with a small brush to control the thickness. Both the materials were separately polymerized with a light curing unit for 20 s. The unpolymerized superficial layer of the immediate dentin sealing was removed with a cotton pellet soaked in 70% ethanol and the sealed MODB onlay cavity specimen was scanned with the scanner [Fig. 1(d)]. Thereafter, all specimens were randomly divided into three groups: increased cement space setting group (Increased condition; IC), decreased cement space setting group (Decreased condition; DC), and manufacturer’s default cement space setting group (Standard condition; SC, as control). Both the intra-cavity space setting values of the IC (180 µm) and DC (60 µm) were provided by a 60 µm increase or
Table 1 Materials used in this study

| Materials | Composition                                                                 | Lot no. | Manufacturer |
|-----------|-----------------------------------------------------------------------------|---------|--------------|
| **Dental CAD/CAM restorative blocks** | | | |
| VITA ENAMIC (2M2-T) [Code: RC] | Silicon dioxide, Aluminum oxide, Sodium oxide, Potassium oxide, Boron trioxide, Zirconia, Calcium oxide, UDMA, TEGDMA | 75410 | VITA |
| IPS e.max CAD (MT A3) [Code: LD] | Silicon dioxide, Lithium oxide, Potassium oxide, Phosphorus pentoxide, Zirconium oxide, Zinc oxide, Aluminum oxide, Magnesium oxide, Coloring oxides | X48573 | Ivoclar Vivadent |
| VITABLOCS Mark II (A3C) [Code: FC] | Silicon dioxide, Aluminum oxide, Sodium oxide, Potassium oxide, Calcium oxide, Titanium dioxide | 82620 | VITA |
| **Chair-side CAD/CAM system** | | | |
| CEREC AC Omnicam CEREC MC XL | CEREC operating system software version 4.5 | — | Dentsply Sirona |
| **Immediate dentin sealing materials** | | | |
| Clearfil Universal Bond Quick | HEMA, Bis-GMA, MDP, Hydrophilic amide monomers, Colloidal silica, Silane, Sodium fluoride, Ethanol, Water | 8A0018 | Kuraray Noritake Dental |
| Clearfil Majesty ES Flow (A3) | Barium grass filler, Silica filler, TEGDMA, Hydrophobic-aromatic dimethacrylate, Di-camphorquinone, Photo initiator | 6D0238 | |
| **Pretreatment material for glass ceramics** | | | |
| Porcelain Etchant | Polyacrylamidomethylpropane sulfonic acid, Hydrofluoric acid | 1800005815 | Bisco |
| **Adhesive resin cement system** | | | |
| Clearfil Ceramic Primer Plus | 3-trimethoxysilylpropyl methacrylate, MDP, Ethanol | 6J0036 | |
| PANAVIA V5 Tooth Primer | MDP, HEMA, Hydrophilic aliphatic dimethacrylate, Water | 8L0055 | Kuraray Noritake Dental |
| Past A: Bis-GMA, TEGDMA, Silanated barium glass filler, Silanated fluororasilicate glass filler, Initiators, Hydrophobic aromatic dimethacrylate, Hydrophilic aliphatic dimethacrylate, Colloidal silica, Accelerators | | | |
| PANAVIA V5 (Universal) | Paste B: Bis-GMA, Silanated barium glass filler, Hydrophilic aliphatic dimethacrylate, Dicamphorquinone, Pigments, Hydrophobic aromatic dimethacrylate, Silanated aluminum oxide filler, Accelerators | 6N0081 | |

UDMA, urethane dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; HEMA, hydroxyethyl methacrylate; Bis-GMA, bisphenol A glycidyl methacrylate; MDP, 10-methacryloyloxydecyl dihydrogen phosphate.

decrease according to the SC (120 µm) [Fig. 1(e)]. The space setting values of both the occlusal and gingival margins in all the specimens were set based on the manufacturer's default setting value (60 µm). Thereafter, a third of each group specimen was randomly divided into three groups: resin-composite block restoration (RC), lithium disilicate glass-ceramic block restoration (LD), and feldspar ceramic block restoration (FC, as control) [Fig. 1(f)]. Each restorative was designed by
54 MPa air pressure using a sandblaster (HI-BLASTER II, Shofu). All inner surfaces of LD and FC restoratives were etched with 9.5% hydrofluoric acid for 90 s, rinsed with sprayed water, and air-dried [Fig. 1(g)]. Thereafter, the prepared surface of each restorative was treated by the silane coupling agent and air-dried. Further, all the MODB onlay cavity surfaces were treated by the one-bottle self-etching primer for 20 s and dried with gentle air. The adhesive resin cement paste was applied to the inner surface of the restoratives, and the restoratives were pressed onto the cavity under a force of 8.8 N for 1 min; then the cement paste was tuck-cured for 3 s and the excess cement was removed. Each specimen was light-irradiated from the occlusal, mesial, distal, and buccal directions by the LED light curing unit for 10 s each, for a total irradiation period of 40 s [Fig.1(h)]. All restored specimens were finished with a flame-type diamond bur (DP-04, Kuraray Noritake Dental) and polished with a flame-type silicone point (1F, J Morita, Tokyo, Japan), according to the manufacturer’s instructions and finally stored in 37°C distilled water for 1 h [Fig.1(i)].

Cyclic loading and μ-TBS test
For every restored specimen, an opposing object of acrylic resin (PROVINICE, Shofu) was fabricated for the cyclic loading masticatory simulation 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 the cyclic loading condition of 157 N at 90 cycles/min for a total of 3×10^5 cycles. The cyclic loading was performed in circulated water at 37°C in a custom-made multifunction apparatus (Tokyo Giken) [Fig.1(j)]. Thereafter, all loaded specimens were sectioned three times along the bucco-lingual dimension to obtain two slab specimens of 1.05 mm thickness using a precision sectioning machine (IsoMet 1000, Buehler, Lake Bluff, IL, USA) [Fig.1(k)]. The slab specimens were polished with a series of silicone carbide papers up to #2000 and adjusted to a thickness of 1.0 mm. Then, the polished central side surface of each slab specimen was subjected to the measurement of the actual cement thickness. The thickness at three positions of each polished surface, the center of the inner inclined surface of the functional cusp, where was the place for the μ-TBS measurement, and the thickness of occlusal and gingival margin were measured using a light microscope with a measurement accuracy of 1 μm scale (Measurescope MM-11, Nikon, Tokyo, Japan) at ×200 magnification [Fig.1(l)]. Every slab specimen 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) so that the center coincided with the bonding interface at the center of the inner inclined surface of the functional cusp [Fig.1(m)]. Then, the μ-TBS values of the nine conditioned specimens (n=16) were measured at a crosshead speed of 1.0 mm/min using a universal testing machine (Autograph AG-1, Shimazu, Kyoto, Japan) [Fig.1(n)]. If the specimens failed before actual testing [pre-testing failure (ptf)], the value of the specimen was replaced by a random value in the range of zero and the lowest μ-TBS value measured for the respective group19).

Statistical analysis
The actual cement thicknesses obtained and the μ-TBS
values were analyzed through a two-way analysis of variance and the Tukey's HSD test using a spreadsheet software (Excel 2016 Windows, Microsoft, Redmond, WA, USA) at a 0.05% level of significance. Furthermore, as a qualitative evaluation, three typical Weibull parameters based on the µ-TBS values, the Weibull modulus (Wm) and the Weibull stress values at 10% and 90% probability of failure (PF10 and PF90), were examined using a spreadsheet software (Excel 2016 Windows, Microsoft) at a 0.05% level of significance.

Fracture mode observation
Following the µ-TBS test, the fracture mode of each specimen was observed with a light microscope (Measurescope MM-11, Nikon) at ×200 magnification. In addition, typical post-test specimens were selected from all specimens using three restorative block materials set with the three space setting values. The dentin-side surface of every post-test specimen was osmium-coated and observed by a scanning electron microscope (SEM; S-4000, Hitachi, Tokyo, Japan) under ×50 magnification with an accelerating voltage of 5.0 kV, to confirm the fracture mode components. Prior to the SEM observation, fracture surfaces of the beam-shaped specimens made of the immediate dentin sealing material (Clearfil Majesty ES Flow) and the resin cement (PANAVIA V5) were prepared. Fabricated surfaces of the three CAD/CAM restorative blocks were also prepared. Two types of “cohesive fracture” occurred within the immediate dentin sealing material and the resin cement and the intact fabricated surfaces of the CAD/CAM blocks were observed by SEM as an observation index.

RESULTS

Effect of differences in actual cement thickness among three space setting values
The differences in actual cement thickness among the three space setting values are shown in Table 2. From the results of the two-way analysis of variance, it can be observed that the space setting value significantly affects the actual cement thickness, regardless of the measured position, intra-cavity space, occlusal and gingival margin spaces, and the restorative block material. Particularly, in case of the gingival margin space, the restorative block material significantly affected the actual cement thickness. There were statistical differences in the actual cement thickness among the three space setting values, i.e., under the IC, SC and DC, regardless of the measured position, i.e., intra-cavity space, occlusal, and gingival margin spaces. For the intra-cavity space, the numerical difference of the actual cement thickness compared to the space setting values, i.e., 180 µm/IC, 120 µm/SC, and 60 µm/DC, were −32/+5/+58. Consequently, the standard space setting value (120 µm) was superior with respect to reproducibility, compared with the other setting values. In addition, for the occlusal and gingival margin spaces, the difference compared to the stable space setting values, i.e., 60 µm/IC, 60 µm/SC, and 60 µm/DC, ranged from +57 to +123 µm. Accordingly, the reproducibility values at the occlusal and gingival margins were inferior to that of the intra-cavity space.

Mean µ-TBS and Weibull parameters of three space setting values and three restorative block materials
The µ-TBS of the three space setting values are shown in the figure.

![Fig. 2 The micro-tensile bond strength of three space setting values.](image-url)

### Table 2 Differences in actual cement thickness among three space setting values (µm)

| Space setting value         | IC   | SC   | DC  |
|-----------------------------|------|------|-----|
| Intra-cavity space          | 180  | 120* | 60  |
| Occlusal margin space       | 60*  | 60*  | 60* |
| Gingival margin space       | 60*  | 60*  | 60* |
| Intra-cavity space (Qi=±15) | 148A | 125A | 118C|
| Occlusal margin space (Qi=±28)| 183A| 158B | 147C|
| Gingival margin space (Qi=±12)| 150A| 127B | 117C|

*: Default setting value

Values with different capital letters in same row among three space setting values indicate a statistically significant difference at p<0.05
Fig. 2. The mean values of μ-TBS (SD) under the IC, SC, and DC were 5.1 (3.0), 4.5 (2.9), and 5.3 (3.6); the space setting values did not affect the μ-TBS significantly. The μ-TBS of the three restorative block materials are shown in Fig. 3. The mean values of μ-TBS (SD) in RC, LD, and FC were 5.1 (3.1), 5.4 (3.7), and 4.4 (2.8), and the effect of restorative block materials on the μ-TBS was not recognized. The differences in Weibull parameters (i.e., Wm, PF10, and PF90) calculated from the μ-TBS values corresponding to the three space setting values and the three restorative block materials are shown in Fig. 4. Based on the space setting values, the Wm and PF10 values of the IC were significantly greater than those of the SC. From the above, the bonding reliability of the IC was superior to both the SC and DC. Further, the values under the DC no significant difference compared with the values of the SC, and thus, the bonding reliability of the DC was similar to that of the SC. For PF90, there was no statistical difference between the SC and IC, but there was a significant difference between the SC and DC. From the above, the DC demonstrated better bonding reliability under a high failure probability condition than the SC. From the above results, it was understood that the bonding reliability of the IC and the bonding durability of the IC and DC were similar or superior to those of the SC. Further, for the restorative block materials, the Wm and PF10 values of RC were significantly greater than the values of FC (control); thus RC demonstrated superior bonding reliability compared with FC. No difference in the Wm value was observed between LD and FC (control), and the PF10 and PF90 values of LD were significantly greater than the values of FC. Therefore, the bonding durability of LD was superior in comparison with FC (control). Based on the above, it was revealed that the bonding reliability of

![Fig. 3 Micro-tensile bond strength of three restorative block materials.](image)

![Fig. 4 Differences in Weibull parameters among three space setting values and three restorative block materials.](image)

![Fig. 5 Differences in micro-tensile bond strength among three space setting values and three restorative block materials.](image)
RC and the bonding durability of LD were significantly superior to FC (control).

**Differences in µ-TBS and Weibull parameters among three space setting values and three restorative block materials**

The differences in µ-TBS among three space setting values and three restorative block materials are shown in Fig. 5. Individually, the space setting value or the restorative block material did not affect the µ-TBS significantly, but the effect of the space setting value on the µ-TBS did vary with the restorative block material. The differences in Weibull parameters for each restorative block material among the three space setting values are shown in Fig. 6. With respect to the differences in cement space setting values, the Wm, PF10, and PF90 values of RC, obtained from the IC and DC did not indicate any significant difference compared with the values of the SC. In the case of LD, there was not any significant difference in the Wm value among the IC, DC, and SC; however, the PF10 and PF90 values of the DC were significantly greater than the values of the SC. In the case of FC, the Wm and PF10 values of the IC were statistically greater than those of the SC; however, the PF90 value of the IC was significantly smaller than the SC. In addition, no significant difference in the values of the Weibull parameters was observed between the DC and SC. In case of the differences in restorative

![Fig. 6 Differences in Weibull parameters of each restorative block material among three space setting values.](image)

Values with different capital letters in same row indicate a statistically significant difference at $p<0.05$. Values with different small letters in same column indicate a statistically significant difference at $p<0.05$. Wm: Weibull modulus; PF10: Weibull stress (MPa) for a 10% failure probability; PF90: Weibull stress (MPa) for a 90% failure probability.

**Table 3 Distribution of fracture mode**

| Restorative block materials | RC | | | LD | | | FC | | |
|-----------------------------|----|--|----|----|---|---|----|---|---|
| Space setting values        | IC | SC | DC | IC | SC | DC | IC | SC | DC |
| Ri+Cc                       | 2  | 3  | 2  | 2  | 1  | 3  | 6  | 10 | 10 |
| Ri+Cc+Si                    | 9  | 10 | 6  | 9  | 14 | 10 | 9  | 2  | 6  |
| Cc+Si                       | 5  | 3  | 8  | 3  | 1  | 3  | 1  | 4  | 0  |
| ptf                         | 0  | 1  | 0  | 5  | 3  | 2  | 0  | 0  | 2  |

Ri: Interfacial fracture occurred at the interface between restorative and resin cement
Cc: Cohesive fracture occurred within the resin cement
Si: Interfacial fracture occurred at the interface between sealing material and resin cement
ptf: Pre-testing failure occurred during trimming procedures
block materials, the Wm values of the IC, obtained from RC and LD were significantly smaller than the value of FC (control). There was no significant difference in the PF10 value of RC and FC (control) obtained from the IC, but the PF90 value of RC was statistically greater than the value of FC. The PF10 value of LD obtained from the same condition was statistically smaller than the value of FC (control), and no difference in the PF90 value was confirmed relative to FC. In case of the SC, the Wm value of RC was significantly greater than that of FC (control), although no significant difference in the Wm value was recognized between LD and FC. There was no significant difference in the PF10 and PF90 values among the three restorative block materials. In case of the DC, the Wm and PF10 values of RC and LD were significantly greater than those of FC (control). Moreover, the PF90 value of LD was significantly greater than that of FC (control).

From the above results, it was clarified that the bonding reliability and durability of RC restoration under the IC and DC were similar to those of the SC. In case of the LD and FC restorations, the DC and IC were effective in obtaining an excellent bonding reliability of the CAD/CAM restoration, with respect to the SC.

The fracture mode distribution of the measured specimens
The distribution of fracture modes observed is shown in Table 3. Regardless of the space setting values and restorative block materials, the surfaces of all the post-bond test specimens exhibited mixed-fracture consisting of three fracture surfaces: interfacial fracture at the interface between restorative and resin cement (Ri), cohesive fracture within the resin cement (Cc), and interfacial fracture at the interface between the sealing material and resin cement (Si). Moreover, Cc was observed across all the fracture surfaces of the specimens, regardless of the space setting values and restorative block materials. For 48 specimens of RC with the three space settings, 67% of all specimens indicated two types of mixed-fracture containing Ri; Si was observed in 85% of the specimens. For the LD specimens, mixed-fracture mode consisting of Ri, Cc, and Si were found in more than half of the specimens, regardless of the three space setting values. For the 48 FC specimens, 46% of all the specimens indicated mixed-fracture containing Si, and 90% of the specimens contained Ri. PtF occurred in one, ten, and two specimens of the RC, LD, and FC, respectively. In addition, the numbers of ptF specimens under the IC, SC, and DC were five, four, and four respectively, and all ptF specimens exhibited mixed-fracture containing Cc. The representative SEM images (×50 magnification) of dentin-side surfaces of the post-test specimens using three restorative block materials set with the three space setting values are shown in Fig. 7. The moderate roughen surface of Ri, the slightly coarse surface of Cc and the flat and smooth surface of Si were observed, regardless of restorative block materials. For RC restoration, high rates of the post-test specimens set with IC (56%) and SC (63%) indicated the mixed-fracture mode consisting of Ri, Cc and Si shown in Fig. 7-1 and Fig. 7-2. On the other hand, 50% of the post-test specimens set with DC exhibited the mixed-fracture mode consisting of Cc and Si shown in Fig. 7-3. For LD restoration, high rates of the post-test specimens set with IC (56%), SC (88%) and DC (63%) displayed the mixed-fracture mode consisting of Ri, Cc and Si shown in Fig. 7-4, 7-5 and 7-6. For FC restoration, 56% of the post-test specimens set with IC produced the mixed-fracture mode consisting of Ri, Cc and Si. For FC restoration, 56% of IC specimens produced the mixed-fracture mode consisting of Ri, Cc and Si. For LD restoration, high rates of IC (56%), SC (88%) and DC (63%) specimens displayed the mixed-fracture mode consisting of Ri, Cc and Si. For FC restoration, 56% of IC specimens produced the mixed-fracture mode consisting of Ri, Cc and Si. For LD and FC restorations, the DC and IC were effective in obtaining an excellent bonding reliability of the CAD/CAM restoration, with respect to the SC.
DISCUSSION

Effect of differences in actual cement thickness among three space setting values

The actual cement thickness on the intra-cavity was significantly affected by the difference in space setting value. The actual cement thickness under the SC as a control was similar to the setting value, although the actual value under the IC tended to be smaller and that under the DC tended to be larger than the setting values (Table 2). The actual cement thickness under the SC (125 µm) was similar to the space setting value (120 µm). Therefore, it was concluded that the manufacturer’s default space setting value that was considered as the SC in this study, produced relatively accurate actual cement thickness. Under the IC, the sinking-down slippage of the onlay restorative resulting from the press-in pressure onto the cavity might produce thinner cement thickness (148 µm) relative to the space setting value (180 µm). Nakamura et al. reported that the actual cement thickness in the occlusal wall was in the range of 112–144 µm, although it was set to be 70 µm through the CAD/CAM software. Maeno et al. measured the internal cement thickness of ceramic crown restoration for canine/premolar/molar using CEREC system that the default cement space setting value programed at 120 µm for all teeth. The mean values of actual internal cement thickness were 270/270/230 µm respectively.

Furthermore, another study reported that MOD (VITA ENAMIC/VITABLOCS MarkII) inlay restorations were 124/211 µm on pupal intra-cavity wall. The values were obtained by the cement space setting value programed at 80 µm for all groups, according to CEREC manufacturer. For the DC, the lift-up slippage of the onlay restorative resulting from the increase of the restorative/cavity-wall contact due to the thin space setting might cause thicker actual cement thickness (118 µm) relative to the space setting value (60 µm).

Furthermore, the actual cement thicknesses at both the occlusal and gingival margins were always greater than the space setting value (60 µm), regardless of the space setting value and restorative block material. The current chair-side CAD/CAM system fabricated restoratives mainly use the milling system. Goujat et al. described that the type of milling bur used, and its particle size may affect the restoration accuracy. Chavali et al. revealed that the chipping of the fabricated restorative varied with the type of the restorative block material. In addition, it may be considered that the marginal part of the fabricated restorative demonstrates the highest risk in chipping due to vulnerable structure at the end of restorative. The thicker actual cement thickness in both the occlusal and gingival margins, compared with the manufacturer’s default space setting value (60 µm), might be due to marginal chipping. The increase of cement thickness in the marginal area enhances the risk of bacterial infiltration, secondary caries, pulp inflammation, and periodontal disease. The quality of the marginal and internal adaptation affects the longevity of an indirect restoration, including CAD/CAM restoration. An appropriate CAD/CAM block material choice, accurate cavity/abutment design, and adequate space setting are necessary for attaining excellent long-term prognosis. The mean µ-TBS values were not influenced by the space setting value, but the actual cement thickness at the intra-cavity was significantly affected by the difference in space setting value (Table 2, Fig. 2). For the distribution of fracture modes shown in Table 3, every post-bond test specimen exhibited mixed fracture and most of specimens showed Ri+Cc or Ri+Cc+Si modes. The percentage of the two modes for all fracture modes in IC/SC/DC were 77%/83%/77% respectively. Based on the above, the vulnerable parts where debonding occurred might exist at the intra-surface of restorative (Ri) and/or the inner side of the resin cement (Cc), and the mean µ-TBS values did not vary with the space setting value because of the fracture modes.

Mean µ-TBS and Weibull parameters of three space setting values and three restorative block materials

The differences in space setting value and restorative block material did not significantly affect µ-TBS, and there was no significant difference among the three space setting values (Fig. 2) and the three restorative block materials (Fig. 3). The dynamic cyclic loading condition in this study (157 N and 90 times/min) was set based on the fact that the stress of human mastication is approximately 70–150 N, and the frequency of mastication per minute is approximately 60–90 times. The number of cyclic loading in this study (3×10^5 times) corresponds to 14 months according to a report conveying that the average number of human mastication per year is approximately 2.5×10^6 times. However, the loading was carried out continuously; one example of cyclic stress is chewing all day long without sleep or rest. Metal-free CAD/CAM restoration may encounter clinical issues such as debonding and fracture. Particularly, it was revealed that the CAD/CAM posterior restoration using resin composite blocks caused clinical failures at a certain rate (14.3%) after two years. A severe cyclic loading condition conducted in this study affected the interfacial zone, consisting of restorative bonded surface, resin cement, sealing material and dentin surface, and as a result, generated equivalent mean µ-TBS regardless of the space setting value and restorative block material. All post-test specimens, including the ptf specimens, showed the mixed-fractures consisting of Cc and Ri and/or Si. Cc, one of fracture mode components, was observed on every fracture surface, regardless of restorative block materials and space setting values (Table 3, Fig. 7). Any material should break starting from the weakest portion of the material. In addition, the higher modulus of elasticity of the restorative block material, the more cyclic load stress directly propagates to the cement. The mechanical strength (flexural strength) of the adhesive resin cement (127 MPa) used in this study is weaker than those of the immediate dentin sealing material (151 MPa) and CAD/CAM restorative block materials (RC:150–160MPa,
LD: 360 MPa, FC: 154 MPa). From the above, the cement layer might be greatly damaged by a severe cyclic load stress carried out in this study and as a results, there were no significant differences in the μ-TBS, regardless of the restorative block materials and the space setting values. Therefore, the mechanical strength improvement of adhesive resin cement may increase the bonding state of CAD/CAM restoration after the dynamic cyclic loading simulation in the intra-oral environment. For bonding evaluation, both quantitative evaluation of the mean value of μ-TBS as well as qualitative evaluation, such as reliability investigation that helps to understand the bonding characteristic, is important. It is well known that Weibull analysis is a very useful method to evaluate reliability. The use of Weibull analysis is recommended to evaluate the quality of a bond, according to the International Organization for Standardization (ISO) 11405 guidelines. In particular, the guidelines state that the Weibull stress values for 10% and 90% failure probability level (PF10 and PF90) are useful means of characterizing the strength of a bond. For all materials, a high Wm is desirable because it facilitates in obtaining homogeneity in the flaw distribution and in predicting the failure behavior. In addition, a large Wm implies a high bonding reliability.

In case of the Weibull parameters under the space setting values, the IC indicated superior bonding reliability relative to the SC, based on the values of Wm and PF10 (Left on Fig. 4). It was reported that the thick immediate dentin sealing that acts as a stress breaker against dynamic cyclic loading owing to mechanical properties, as typified by elastic modulus, contributes to achieving the desirable intra-cavity bonding compared to thin sealing. The elastic modulus (6.3 GPa) of adhesive resin cement used in this study is approximate to the value of the flowable resin composite (7.4 GPa), applied as an immediate dentin sealing material. Thus, the thick layer consists of resin cement and the immediate dentin sealing material acts as a stress breaker and facilitates well-bonding reliability. In contrast, the DC indicated superior bonding reliability with respect to the SC based on the values of PF90. The flexural strengths of the CAD/CAM restorative block materials used in this study were: RC: 150–160 MPa, LD: 360 MPa, FC: 154 MPa, the value of the adhesive resin cement was 127 MPa, the flowable resin composite used for immediate dentin sealing was 151 MPa and that for dentin was 213 MPa. PF90 is the stress corresponding to 90% probability of bonding failure that may occur under serious external force in the oral environment. When the bonding failure occurs owing to serious external force, the cement layer that has lower mechanical properties compared with the other restorative block materials and bonded substrates, may act as the starting point of debonding. Thus, the DC might demonstrate excellent bonding reliability due to the existence of thin cement layer that reduces the probability of debonding.

For the Weibull parameters of the restorative block materials, RC restoration indicated superior bonding reliability relative to the FC restoration (control) based on the values of Wm and PF10 (Right on Fig. 4). RC material consists of 86 wt% porous glass and 14 wt% polymer material and has both the aesthetic properties of ceramics as well as the flexibility of the polymer. The elastic modulus of RC material is 30 GPa, and it is smaller than the value of FC material (45 GPa), control. Ishii et al. reported that resin-composite block is preferable to a glass-ceramic block in obtaining higher bond strength in metal-free CAD/CAM restoration based on the difference in elastic modulus. Therefore, it was considered that RC material with low elastic modulus, efficiently absorbs cyclic load stress and as a result, obtains excellent bonding reliability. On the contrary, LD restoration indicated superior bonding durability relative to FC restoration (control) based on the greater values of PF10 and PF90. Based on the greater Weibull stress values, it can be seen that the restoration demonstrates robust bonding durability in qualitative evaluation. LD material (95 GPa) exhibited more than twice and thrice the elastic modulus of FC material (45 GPa) and RC material (30 GPa), respectively, due to the presence of lithium disilicate. As a result, it is considered that the elastic deformation of LD material that occurs by the application of cyclic loading is extremely small relative to the other restorative block materials. Ausiello et al. reported that the cyclic loading stress can almost totally be transferred to the cavity walls in the case of restoration using a high elastic modulus material (90 GPa). The stress propagation behavior of restoration using a high elastic modulus material differs from the behavior of RC restoration using a low elastic modulus material (30 GPa) that absorbs cyclic loading through the restorative itself. For LD restoration with a high elastic modulus (95 GPa) in this study, the cyclic loading is homogeneously distributed to the cavity walls, including the belt-like gingival wall and pulpal wall. Considering the aforementioned observations, the superior bonding durability based on PF10 and PF90 values of LD restoration might have resulted from the cyclic loading that is homogeneously spread to all the cavity walls without local stress concentration, relative to the FC restoration (control).

Differences in μ-TBS and Weibull parameters among three space setting values and three restorative block materials

Individually, neither the space setting value nor the restorative block material affected the μ-TBS significantly; however, the effect of the space setting value on the μ-TBS varied with the restorative block material (Fig. 5). Therefore, it was clarified that the interaction between the space setting value and restorative block material specifically influences the μ-TBS. The bonding reliability was significantly affected by the differences in the space setting values and restorative block materials (Fig. 6).

In case of the differences in the space setting values, all RC restoration Weibull parameters under the IC and DC were similar to those parameters under the SC.
Thus, it was confirmed that the RC restoration is able to provide some level of bonding reliability regardless of the space setting values. For LD restoration, there were no significant differences among the Wm values under the IC, DC, and SC; however, the PF10 and PF90 values under the DC were significantly greater than the values under the SC. LD material has a higher elastic modulus value compared with the other restorative block materials; the cyclic load stress is therefore almost totally transferred to the intra-cavity walls\(^{40}\). Considering this, in the case of LD restoration, the stress is not absorbed by the restorative block material itself and is directly transferred to the cement layer and the intra-cavity surface. The mechanical strength of the cement layer is lower than the values of the other materials used in this study and dentin. It may be assumed that the bonding damage occurs at the cement layer zone. Accordingly, it is considered that the DC of LD restoration having a thin cement layer that plays an important role as the starting point of debonding demonstrates excellent bonding reliability. In case of the FC restoration (control), the IC indicated superior bonding reliability relative to the SC, based on the values of Wm and PF10. Lithium disilicate glass ceramic is the most popular CAD/CAM restorative block used in recent clinical practice\(^{45}\). Moreover, fine-structure feldspar ceramics, used in FC block material, has the longest history as a CAD/CAM block and is still supplied smoothly around the world\(^{11,12}\). Consequently, there are still many opportunities for the clinical application of feldspar ceramic blocks. In the case of feldspar ceramic block restoration, a high bonding reliability could be achieved by increasing the cement space setting from the default setting value.

Considering the differences in restorative block materials, RC and LD restorations under IC indicated inferior bonding reliability compared with FC restorations (control), based on the values of Wm and PF10. Therefore, feldspar ceramic block selection and careful prognostic observation are required for the clinical metal-free CAD/CAM restorations that require large cement setting value. Moreover, the PF90 value of RC restoration was significantly greater than the value of FC restoration (control). It was reported that the approximation in the elastic modulus between the bonded material and resin cement reduces the risk of failure\(^{46}\). The risk of bonding failure in the RC material (30 GPa\(^{33}\)) restoration with a resin cement (6.3 GPa\(^{23}\)) should be lower than the risk in the FC material (45 GPa\(^{35}\), control) restoration with the same cement because of the approximation in the elastic modulus between the bonded material and resin cement. In the SC, the RC restoration performed superior bonding reliability with respect to FC restoration (control), based on the Wm value. There are reports that the polymer chains in the RC block material can improve the crack resistance under cyclic loading due to the spreading of plasticity\(^{47}\), resulting in higher Wm\(^{40}\). The plasticity of RC material reduced the effect of cyclic loading on the bonding of the restoration and facilitated an excellent bonding reliability in this study. Further, there were no significant differences in the PF10 and PF90 values among the three restorative block materials. It was clarified that the manufacturer's default space setting promotes no difference in the bonding reliability and durability of the three CAD/CAM block materials used in this study. In the DC, the Wm and PF10 values of RC and all the Weibull parameters of LD restorations were superior to those of the FC restoration (control). It was considered that the stress absorption characteristics of the RC material that indicates a lower elastic modulus (30 GPa\(^{33}\)) compared with the FC material (45 GPa\(^{35}\), control) contributes to the reduction in damage of the RC restoration bonding. The excellent bonding reliability of LD restoration, compared with the FC restoration, might be caused by the homogeneous stress to all the cavity walls owing to the well-transferability of stress\(^{44}\), based on the higher elastic modulus (95 GPa\(^{48}\)).

### The fracture mode distribution of the measured specimens

This study was performed with a typical composite resin-type cement demonstrating superior physical properties compared with the 4-META/MMA-TBB type resin cement\(^{49}\). However, all the post-bond test specimens showed a mixed-fracture consisting of Cc (Table 3). Therefore, the improvement of resin cement to ensure high mechanical strength facilitates robust bonding.

In addition, for 48 specimens of RC restoration with three space settings, 67% of the specimens exhibited mixed-fracture containing Ri and 85% of all specimens presented mixed-fracture containing Si. In this study, sandblasting was applied to the intra-surface of RC restorative prior to the silane coupling pretreatment in order to form the microscopic convexo-concave structure that improves mechanical bonding. Further, the bonded surface of cavity, where the dentin cavity walls were covered with an immediate dentin sealing material, was pretreated with a primer to improve the chemical bond between the dentin sealing material and the resin cement, according to the manufacturer's instruction. The difference of pretreatment with and without sandblasting might be one of the causes for the difference in percentage between two mixed-fracture conditions containing Ri or Si. For the 48 specimens of FC restoration with three space settings, 46% of the specimens exhibited mixed-fracture containing Ri and 90% of all the specimens presented mixed-fracture containing Ri. From the above, for the feldspar ceramic CAD/CAM restoration, it was considered that the intra-surface of the restorative would act as the starting point of fracture compared with the surface of the immediate dentin searing material covering the dentin cavity walls. For FC restoration in this study, the pretreatment with a silane coupling agent was employed to the inner surface of restorative, following hydrofluoric acid etching, a global standard pretreatment for feldspar ceramics. Based on this, a novel material or technique replacing hydrofluoric acid or etching is desirable to facilitate an optimum feldspar ceramic bonding. The number of ptf specimens in LD restoration (ten) was obviously greater than the
number of FC restoration (two specimens, control). Table 3 shows that a larger space setting value resulted in a larger number of ptf specimens, in the following order: IC, five specimens > SC, three specimens > DC, two specimens. Furthermore, all ptf specimens exhibited mixed-fracture containing Cc. From these results, it was confirmed that the greater the elastic modulus of CAD/CAM restorative block and the thicker the cement space, the greater the potential for easy debonding owing to the damage caused by the transferred cyclic loading stress of the CAD/CAM restorative block material.

CONCLUSION

For the intra-cavity space, the standard 120 µm space setting created accurate actual cement thickness compared with the other setting values of 180 µm and 60µm. The reproducibility at the occlusal and gingival margins was inferior to that of the intra-cavity space. The effect of space setting value on the µ-TBS did vary with the restorative material. The bonding reliability of RC restoration and the bonding durability of LD restoration were significantly superior to those of FC restoration (control). The bonding reliability and durability of RC restoration under the IC and DC were similar to those under the SC. The LD and FC restorations under the DC and IC, respectively, were effective in obtaining an excellent bonding reliability of CAD/CAM restoration, in comparison with the SC.

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CONFLICTS OF INTERESTS

The authors do not have any financial interest in the companies from where the materials mentioned in the article have been sourced.

REFERENCES

1) Alghazzawi TF. Advancements in CAD/CAM technology: Options for practical implementation. J Prosthodont Res 2016; 60: 72-84.
2) Özcelik TB, Yılmaz B, Şeker E, Shah K. Marginal adaptation of provisional CAD/CAM restorations fabricated using various simulated digital cement space settings. Int J Oral Maxillofac Implants 2018; 33: 1064-1069.
3) Goujat A, Abouelleih H, Colon P, Jeannin C, Pradelle N, Seux D, et al. Marginal and internal fit of CAD/CAM inlay/onlay restorations: A systematic review of in vitro studies. J Prosthodont Dent 2019; 121: 590-597.
4) Boitelle P, Mawusi B, Tapie L, Fromentin O. A systematic review of CAD/CAM fit restoration evaluations. J Oral Rehabil 2014; 41: 853-874.
5) Gressler May L, Kelly JR, Bottino MA, Hill T. Influence of the resin cement thickness on the fatigue failure loads of CAD/CAM feldspathic crowns. Dent Mater 2015; 31: 895-900.
6) Riccitiello F, Amato M, Leone R, Spagnuolo G, Sorrentino R. In vitro evaluation of the marginal fit and internal adaptation of zirconia and lithium disilicate single crowns: Micro-CT comparison between different manufacturing procedures. Open Dent J 2018; 12: 160-172.
7) Suárez MJ, González deVillambrosia P, Pradés G, Lozano JF. Comparison of the marginal fit of procera allceram crowns with two finish lines. Int J Prosthodont 2003; 16: 229-232.
8) Kale E, Seker E, Yılmaz B, Özcelik TB. Effect of cement space on the marginal fit of CAD-CAM-fabricated monolithic zirconia crowns. J Prostheth Dent 2016; 116: 890-895.
9) Huang Z, Zhang L, Zhu J, Zhao Y, Zhang X. Clinical marginal and internal fit of crowns fabricated using different CAD/CAM technologies. J Prosthodont 2015; 24: 291-295.
10) Nakamura T, Tanaka H, Kinuta S, Akao T, Okamoto K, Wakabayashi K, et al. In vitro study on marginal and internal fit of CAD/CAM all-ceramic crowns. Dent Mater J 2005; 24: 456-459.
11) Spitznagel FA, Boldt J, Gierthmuellen PC. CAD/CAM ceramic restorative materials for natural teeth. J Dent Res 2018; 97: 1092-1091.
12) Datzmann G. In: Mörmann WH, editor. CEREC Vitablocs Mark II Machinable ceramic. CAD/CIM in Aesthetic Dentistry, Berlin: Quintessence Publishing Co; 1996. p. 205-215.
13) Bindl A, Richter B, Mörmann WH. Survival of ceramic computer-aided design/manufacturing crowns bonded to preparations with reduced macroretention geometry. Int J Prosthodont 2005; 18: 219-224.
14) Martin N, Jedynakiewicz NM. Clinical performance of CEREC ceramic inlays: a systematic review. Dent Mater 1999; 15: 54-61.
15) Willard A, Gabriel Chu TM. The science and application of IPS e.Max dental ceramic. Kaohsiung J Med Sci 2018; 34: 236-242.
16) Mörmann WH, Stawarczyk B, Ender A, Sener B, Attin T, Mehla A. Wear characteristics of current aesthetic dental restorative CAD/CAM materials: Two-body wear, gloss retention, roughness and Martens hardness. J Mech Behav Biomater Mater 2013; 20: 113-125.
17) Ruse ND, Sadoun MJ. Resin-composite blocks for dental CAD/CAM applications. J Dent Res 2014; 93: 1232-1234.
18) Awada A, Nathanson D. Mechanical properties of resin-ceramic CAD/CAM restorative materials. J Prostheth Dent 2015; 114: 587-593.
19) Souza EM, De Munck J, Pongprueksa P, Van Ende A, Van Meerbeeck B. Correlative analysis of cement–dentin interfaces using an interfacial fracture toughness and micro-tensile bond strength approach. Dent Mater 2016; 32: 1575-1585.
20) Nakamura K, Mouhat M, Nergård JM, Lægreid SJ, Kanno T, Milleding P, et al. Effect of cements on fracture resistance of monolithic zirconia crowns. Acta Biomater Odontol Scand 2016; 2: 12-19.
21) Maeno M, Tokita C, Komoto M, Koshibe S, Nagas S, Dogon L, et al. Effect of Immediate-dentin-sealing on Adaptation of CAD/CAM-ceramic-crown-restoration. Proceedings of the 96th General Session & Exhibition of the IADR; 2018 July 25-28; London, England. https://iadr.abstractarchives.com/abstract/18iags-2958891/influence-of-clinical-treatments-to-abutment-surface-on-bond-strength-of-cadcam-ceramic-crown-restoration
22) Bottino MA, Campos F, Ramos NC, Rippe MP, Valandro LF, Melo RM. Inlays made from a hybrid material: adaptation and bond strengths. Oper Dent 2015; 40: E83-E91.
23) Goujat A, Abouelleih H, Colon P, Jeannin C, Pradelle N, Seux D, et al. Mechanical properties and internal fit of 4 CAD/CAM block materials. J Prostheth Dent 2018; 119: 384-389.
24) Chavali R, Nejat AH, Lawson NC. Machinability of CAD/CAM materials. J Prostheth Dent 2017; 118: 194-199.
25) Anderson DJ. Measurement of stress in mastication. II. J Dent Res 1956; 35: 671-673.
26) Lavelle C, Relova-Quinterio JL. Mastication: Scully C, editors. Oxford Handbook of Applied Dental Science. New York: Oxford University Press. Inc. 2002. p. 149-156.

27) Neill DJ. Studies of tooth contact in complete dentures. Br Dent J 1967; 123: 369-378.

28) Shepherd RW. A further report on mandibular movement. Aust Dent J 1960; 5: 337-342.

29) Sakaguchi RL, Douglas WH, DeLong R, Pintado MR. The wear of a posterior composite in an artificial mouth: a clinical correlation. Dent Mater 1986; 2: 235-240.

30) Zimmermann M, Koller C, Reymus M, Mehl A, Hickel R. Clinical evaluation of indirect particle-filled composite resin CAD/CAM partial crowns after 24 months. J Prosthodont 2018; 27: 694-699.

31) Kuraray. Simply create the PANAVIA™ smile. https://www.kuraraynoritake.eu/en/files/index/index/id/6440/ (accessed 20.08.03).

32) CLEARFIL MAJESTY™ ES Flow. https://www.kuraraynoritake.eu/en/files/index/index/id/4907 (accessed 20.08.03).

33) VITA. VITA ENAMIC Technical and scientific documentation. https://cdn.vivarep.com/contrib/vivarep/media/pdf/4_4642_ENAMIC_TechnicalAndScientific_20170830205744578.pdf#search='vita+enamic+technical+and+scientific (accessed 20.08.03).

34) IPS e.max CAD Scientific Documentation. https://www.ivoclarvivadent.com/zoolu-website/media/document/9793/IPS e-max CAD (accessed 20.08.03).

35) VITA. VITA BLOCS Working Instructions. https://www.kuraraynoritake.eu/pub/media/pdfs/Panavia_V5_brochure_ENG.pdf (accessed 20.08.03).

36) Weibull W. A statistical distribution function of wide applicability. J Appl Mech 1951; 18: 293-297.

37) ISO/TS 11405: 2015. Dentistry: Testing of adhesion to tooth structure. 3rd ed, International Organization for Standardization, Geneva, 2015.

38) Robin C, Scherrer SS, Wiskott HW, de Rijk WG, Belser UC. Weibull parameters of composite resin bond strengths to porcelain and noble alloy using the Rocatec system. Dent Mater 2002; 18: 389-395.

39) Inokoshi M, Kameyama A, De Munck J, Minakuchi S, Van Meerbeck B. Durable bonding to mechanically and/or chemically pre-treated dental zirconia. J Dent 2013; 41: 170-179.

40) Murata T, Maseki T, Nara Y. Effect of immediate dentin sealing applications on bonding of CAD/CAM ceramic onlay restoration. Dent Mater J 2018; 37: 928-939.

41) Kawai T, Maseki T, Nara Y. Bonding of flowable resin composite restorations to class I occlusal cavities with and without cyclic load stress. Dent Mater J 2016; 35: 408-417. ISO/TS 11405: 2015. Dentistry: Testing of adhesion to tooth structure. 3rd ed, International Organization for Standardization, Geneva, 2015.

42) Plotino G, Grande NM, Bedini R, Pameijer CH, Somma F. Flexural properties of endodontic posts and human root dentin. Dent Mater 2007; 23: 1129-1135.

43) Ishii N, Maseki T, Nara Y. Bonding state of metal-free CAD/CAM onlay restoration after cyclic loading with and without immediate dentin sealing. Dent Mater J 2017; 36: 357-367.

44) Ausiello P, Rengo S, Davidson CL, Watts DC. Stress distributions in adhesively cemented ceramic and resin composite Class II inlay restorations: a 3D-FEA study. Dent Mater 2004; 20: 862-872.

45) Makaji SA, Lawson NC, Gilbert GH, Litaker MS, McClelland JA, Louis DR, et al. Dentist material selection for single-unit crowns: Findings from the National Dental Practice-Based Research Network. J Dent 2016; 55: 40-47.

46) Dong XD, Wang HR, Darvell BW, Lo SH. Effect of stiffness of cement on stress distribution in ceramic crowns. Chin J Dent Res 2018; 19: 217-223.

47) Leung BT, Tsui JK, Matlinlin JA, Pow EH. Comparison of mechanical properties of three machinable ceramics with an experimental fluorophlogopite glass ceramic. J Prosthodont Dent 2015; 114: 440-446.

48) Kendall K, Alford NM, Tan SR, Birchall JD. Influence of toughness on Weibull modulus of ceramic bending strength. Journal of Materials Research 1986; 1: 120-123.

49) Li J. Effect of flexural strength of orthodontic resin cement on bond strength of metal brackets to enamel surfaces. Eur J Orthod 2011; 33: 167-173.