Effect of Thermomechanical Loading on the Cementation Interface of Implant-Supported CAD/CAM Crowns Luted to Titanium Abutments

Alexis Ioannidis, Dr Med Dent
Alfonso Gil, DDS, PhD
Christoph H. F. Hämmerle, Prof Dr Med Dent
Ronald E. Jung, Prof Dr Med Dent, PhD
Clinic of Reconstructive Dentistry, Center of Dental Medicine, University of Zurich, Zurich, Switzerland.
Spiros Zinelis, PhD
George Eliades, DDS, Dr Dent
Department of Biomaterials, School of Dentistry, National and Kapodistrian University of Athens, Athens, Greece.

**Purpose:** To investigate the effect of aging on the morphology of the interface between monolithic implant crowns and standardized titanium base abutments. **Materials and Methods:** Four groups of hybrid abutment crowns differing in restorative material (lithium disilicate [LD] or polymer-infiltrated ceramic network [PICN]) and in fabrication procedure of the interfacial zone for luting to a titanium abutment (milled during CAD/CAM procedure [M] or prefabricated [P]) were formed: LDS-M, LDS-P, PICN-M, and PICN-P (n = 10 each). The morphology of the crown-abutment interface was examined before and after artificial aging using scanning electron microscopy. The total gap length per specimen was measured at both time points, and intergroup (Kruskal-Wallis [KW]) plus pairwise (Wilcoxon Mann-Whitney [WMW]) comparisons were performed (α = .05).

**Results:** Before aging, statistically significant differences in gap length were identified among groups (KW: P = .0369) for PICN-P > LDS-P (WMW: P = .0496) and LDS-M > LDS-P (WMW: P = .0060). The effect of aging among the groups, expressed as an increment of total gap length, was 50% in LDS-M, 30% in LDS-P, 20% in PICN-M, and 30% in PICN-P. After aging, the statistically significant differences in gap length identified among groups (KW: P = .0048) were for PICN-P > LDS-P (WMW: P = .0134); LDS-M > PICN-M (WMW: P = .0204); PICN-P > PICN-M (WMW: P = .0486); and LDS-M > LDS-P (P = .0022). However, comparison of the difference in gap length from before to after aging among the groups was not statistically significant (KW: P = .3549).

**Conclusion:** The cementation interfaces of CAD/CAM crowns on standardized titanium base abutments demonstrated a high percentage of gaps before and after thermomechanical loading. The composition of the restorative material and the nature of the interface influenced the interfacial gap dimension.
crowns are complex structures of titanium, luting cement, and restorative material. Titanium and ceramic materials are known to show high biocompatibility. However, the interface area sets additional biologic challenges, since any excess cement or interfacial gap may result in soft tissue inflammation, which affects the long-term stability of such restorations. The gap size at the implant-abutment interface has been estimated to be from 20 to 1,680 μm, with acceptable discrepancies being less than 120 μm. Other authors have reported success with misfit of up to 200 μm. With hybrid abutment crowns, the interface is occupied by the luting cement, which is vulnerable to intraoral aging and may develop defects at the interface prone to bacterial colonization.

The aim of the present study was to investigate the interfacial morphology of CAD/CAM–fabricated monolithic LD and PICN hybrid abutment crowns before and after thermomechanical loading. The null hypothesis was twofold: (1) there are no statistically significant differences between the two materials in reference to their interfacial morphology before and after aging; (2) and there are no differences in the interfacial gap change as a result of the aging process.

MATERIALS AND METHODS

Case Selection and Groups
For fabrication of the implant crowns, one standard clinical case was selected in which a molar was replaced by a one-piece dental implant (Standard Plus Regular Neck SLA 4.1 mm, Straumann). Two abutment types were selected, one for CAD/CAM milling (M) and one that was prefabricated (P), and were combined with crowns made of two restorative materials: LDS or PICN. This resulted in four specimen groups for testing (LDS-M, LDS-P, PICN-M, and PICN-P; n = 10 each, Table 1).

Scanning Procedures and Fabrication of the Hybrid Abutment Crowns
The master cast of the clinical case was digitized by 3D scanners (M groups: Ceramill Map 400, Amann Girrbach; P groups: CEREC Omnicam, Dentsply Sirona), and an implant-supported molar crown was designed (M groups: Ceramill Mind, Amann Girrbach; P groups: CEREC inLab 16.0, Dentsply Sirona). Within the given digital workflow, the crowns and interfaces for cementation in the M groups were milled by means of a five-axis milling unit (Ceramill Motion 2, Amann Girrbach). The spacer settings for the milled crowns were set at 50 μm. The crowns in the P groups were milled by means of a four-axis milling unit (CEREC MC XL, Dentsply Sirona) in which the interface and access hole were preexisting and not part of the milling process. According to the manufacturers, the spacer settings for the interface were 20 to 40 μm for PICN-P (VITA Zahnfabrik). No information was given by the manufacturer for LDS-P.

Crown Finalization and Luting
After the milling procedures, the LDS-M and LDS-P crowns were sintered (Programat 500, Ivoclar Vivadent) to full density, and a glaze paste (e.max CAD Crystall Glaze Paste and Liquid, Ivoclar Vivadent) was simultaneously applied. The inner surfaces of all groups and the outer surfaces of the PICN groups were etched with 5% hydrofluoric acid gel (IPS Ceramic Etching Gel, Ivoclar Vivadent; 20 seconds for LD and 60 seconds for PICN) and then silanized (Monobond Plus, Ivoclar Vivadent) as instructed. In the PICN groups, the outer surfaces were treated with a glaze (VITA ENAMIC Glaze, VITA Zahnfabrik) and then light cured three times for 180 seconds each time with a bench-top light-curing unit (HiLite power 3D, Kulzer; xenon stroboscope lamp, 20-Hz flash frequency, 390–540 nm wavelength).

Subsequently, all crowns were cemented to the titanium base abutments (LDS-M and PICN-M: Variobase, Straumann; LDS-P and PICN-P: Variobase C, Straumann) with a self-curing luting composite (Multilink Hybrid Abutment, Ivoclar Vivadent). A glycerin gel (Liquid Strip, Ivoclar Vivadent) was applied on the cementation joint, left intact for 7 minutes, and then rinsed off with water. The interface area was carefully polished (LDS: OptraFine, Ivoclar Vivadent; PICN: VITA ENAMIC Polishing Set technical, VITA Zahnfabrik).

In Vitro Thermomechanical Loading
For the artificial aging procedures, one implant (4.1 x 12 mm) per specimen was embedded in an acrylic hollow cylinder using acrylic resin (SCANDIOUICK, Scan Dia). The vertical distance from the top of the acrylic resin to the implant shoulder was set at 3 mm. The hybrid abutment crowns were fixed on the implant with a torque of 35 Ncm. All specimens were aged by means of thermocycling (5°C to 50°C, dwelling time 120 seconds) and chewing simulation (1,200,000 cycles, 49-N force, 1.67-Hz loading frequency, 90-degree loading angle to the occlusal surface) in a custom-made chewing simulator. A stainless steel indenter (V4A) with a rounded tip (diameter = 8 mm) was used as an antagonist. After the aging procedures, external contaminants were removed by rinsing with water.

Scanning Electron Microscopy
The interfacial morphology between the crown and titanium base abutment before and after aging was studied by means of low-vacuum scanning electron microscopy (SEM) imaging. A specimen holder (Fig 1) was designed for precise rotation and reproducible acquisition of interfacial images at the buccal, lingual, and interproximal locations, thus covering the entire...
specimen periphery. The images around the specimen interface were acquired with an SEM unit (JSM-6010, JEOL) operated at 1.5 kV and 22x magnification. The acquired pictures were imported into the Image J 1.43 open-source software (National Institutes of Health), and the total length of the interfacial gap was calculated for each specimen before and after aging.

### Statistical Analyses
Descriptive statistics included mean, SD, minimum, maximum, median, and quartile (Q1 and Q3) values for the interface gap in each material and treatment. Kruskal-Wallis (KW) test was used for intergroup comparisons and Wilcoxon Mann-Whitney U test (WMW) was performed for pairwise comparisons, employing a 95% confidence level (alpha = .05), both before and after aging. Statistical analysis was performed with SAS 9.4 software.

### RESULTS
Representative SEM images of the luted interfaces before and after aging are presented in Fig 2. Interfacial gaps appeared in all materials and conditions. Before aging, the main location of the gap was at the luting agent–crown interface, whereas after aging, the gap in many cases extended into the main body of the luting agent. Descriptive statistics for the interfacial gap length per material and time point are presented in Table 2 and summarized in Fig 3.

Before aging, 50% of the specimens (20 out of 40) exhibited interfacial gaps: 80% of LDS-M specimens, 20% of LDS-P specimens, 40% of PICN-M specimens, and 60% of PICN-P specimens. The median (quartile) lengths of the total interfacial gaps were estimated to be 950 μm (Q1: 500 μm, Q3: 1,300 μm) for LDS-M; 0 μm (Q1: 0 μm, Q3: 0 μm) for LDS-P; 0 μm (Q1: 0 μm, Q3: 500 μm) for PICN-M; and 600 μm (Q1: 0 μm, Q3: 2,400 μm) for PICN-P. Statistically significant differences identified (KW: P = .0369) were attributed to the significantly higher values of PICN-P compared to LDS-P (WMW: P = .0496) and LDS-M compared to LDS-P (WMW: P = .0060).

After aging, no crown fractures or decementation were observed, and interfacial gaps were registered in 65% of the specimens (26 out of 40): 90% of the LDS-M specimens, 50% of the LDS-P specimens, 40% of the PICN-M specimens, and 80% of the PICN-P specimens. The corresponding median (quartile) lengths of the total interfacial gaps were estimated to be 1,450 μm (Q1: 1,100 μm, Q3: 2,200 μm) for LDS-M; 150 μm (Q1: 0 μm, Q3: 0 μm) for LDS-P; 0 μm (Q1: 0 μm, Q3: 500 μm) for PICN-M; and 1,750 μm (Q1: 500 μm, Q3: 2,600 μm) for PICN-P. Statistically significant differences were identified (KW: P = .0048) and attributed to the significantly higher values of PICN-P compared to LDS-P (WMW: P = .00496) and LDS-M compared to LDS-P (WMW: P = .006).

The effect of aging among the groups, expressed as an increment of the total gap length before and after aging.

### Table 1 Distribution of Groups According to Type of Material and Interface Tested

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Composition Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDS</td>
<td>Milled</td>
<td>Lithium disilicate ceramic (IPS e.max CAD, Ivoclar Vivadent)</td>
</tr>
<tr>
<td>LDS</td>
<td>Prefab</td>
<td>Silicon dioxide (SiO₂) 57%–80%, Lithium oxide (Li₂O) 11%–19%, Potassium oxide (K₂O) up to 13%, Phosphorus pentoxide (P₂O₅) up to 11%, Zirconium dioxide (ZrO₂) up to 8%, Zinc oxide (ZnO) up to 8%, other oxides and ceramic pigments (up to 10%)</td>
</tr>
<tr>
<td>PICN</td>
<td>Milled</td>
<td>Polymer-infiltrated ceramic network (VITA ENAMIC, VITA Zahnfabrik)</td>
</tr>
<tr>
<td>PICN</td>
<td>Prefab</td>
<td>Polymer part (14%): UDMA, TEGDMA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ceramic part (86%): SiO₂ (58%–63%), Al₂O₃ (20%–23%), Na₂O (9%–11%), K₂O (4%–6%), B₂O₃ (0.05%–2%), ZrO₂ (&lt; 1), CaO (&lt; 1)</td>
</tr>
</tbody>
</table>

**SiO₂ = silicon dioxide; Li₂O = lithium oxide; K₂O = potassium oxide; P₂O₅ = phosphorus pentoxide; ZrO₂ = zirconium dioxide; ZnO = zinc oxide; UDMA = urethane dimethacrylate; TEGDMA = triethylene glycol dimethacrylate; Al₂O₃ = aluminum oxide; Na₂O = sodium oxide; B₂O₃ = boron oxide; CaO = calcium oxide.**

![Fig 1 Specimen holder used for the SEM investigation.](image)
aging, occurred in 50% of the LDS-M specimens, 30% of the LDS-P specimens, 20% of the PICN-M specimens, and 30% of the PICN-P specimens. The interfacial gap increased in 32.5% of the specimens (13 out of 40) because of the aging effect. Comparison of the difference in gap length from before to after aging among the groups showed no statistical significance (KW: $P = .3549$).

**DISCUSSION**

The present study investigated the morphology of the interface between CAD/CAM–fabricated monolithic LDS or PICN crowns and prefabricated titanium base abutments before and after artificial aging. The results showed significant differences in interfacial gap length among the groups tested both before and after aging. Therefore, the first part of the null hypothesis should be rejected. An increase in interfacial gap due to aging occurred in one-third of the specimens; however, the intragroup comparison of the difference in gap dimension from before to after aging was not significant. Therefore, the second part of the null hypothesis should be accepted.

The majority of studies investigating misfit of implant components have focused on the vertical gap formed between the abutment and the implant interface. The acceptable marginal misfit has been estimated to be 120 $\mu$m, even though greater values do not necessarily always correlate with the development of biologic complications. There is controversy in the literature

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**Fig 2** Representative SEM images of the resin-bonded interface (white arrows) between the crown and the titanium base abutment in all groups before and after artificial aging. Dashed lines show the presence of gaps (22x magnification, bar = 500 $\mu$m). (a) Before and (b) after aging in LDS-M; (c, d) LDS-P; (e, f) PICN-M; and (g, h) PICN-P.
regarding the effect of loading simulation on the misfit of implant components. In some studies, it has been shown that artificial aging did not influence the vertical misfit between different components of an implant restoration,8,18 whereas in other studies, a negative effect was demonstrated on the vertical misfit of implants with an internal or external connection.19

In the present study, it was observed that thermo-mechanical aging in terms of thermal and load cycling affected one-third of the crowns by increasing the horizontal interfacial gap. It is important to point out that this was a horizontal gap along the interface between the crown and the abutment without taking into account any vertical misfit. Vertical misfit was considered

<table>
<thead>
<tr>
<th>Group</th>
<th>Condition</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Minimum</th>
<th>Q1</th>
<th>Q3</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDS-M</td>
<td>Before aging</td>
<td>910</td>
<td>677</td>
<td>950</td>
<td>0</td>
<td>500</td>
<td>1,300</td>
<td>2,200</td>
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<tr>
<td></td>
<td>After aging</td>
<td>1,500</td>
<td>883</td>
<td>1,145</td>
<td>0</td>
<td>1,100</td>
<td>2,200</td>
<td>3,000</td>
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<tr>
<td></td>
<td>Difference</td>
<td>590</td>
<td>748</td>
<td>250</td>
<td>0</td>
<td>0</td>
<td>1,100</td>
<td>20</td>
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<tr>
<td>LDS-P</td>
<td>Before aging</td>
<td>130</td>
<td>275</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td></td>
<td>After aging</td>
<td>230</td>
<td>271</td>
<td>150</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>100</td>
<td>163</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>PICN-M</td>
<td>Before aging</td>
<td>450</td>
<td>800</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>2,400</td>
</tr>
<tr>
<td></td>
<td>After aging</td>
<td>570</td>
<td>972</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>900</td>
<td>3,000</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>120</td>
<td>253</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>PICN-P</td>
<td>Before aging</td>
<td>1,320</td>
<td>1,550</td>
<td>600</td>
<td>0</td>
<td>0</td>
<td>2,400</td>
<td>4,200</td>
</tr>
<tr>
<td></td>
<td>After aging</td>
<td>1,700</td>
<td>1,409</td>
<td>1,750</td>
<td>0</td>
<td>500</td>
<td>2,600</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>380</td>
<td>738</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>300</td>
<td>2,000</td>
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</table>

![Box plots of the total gap length (μm) in all groups before and after aging and their corresponding differences showing mean (rhomboid), median (horizontal line), interquartile range (box), and range (vertical line).](image-url)
negligible since there was no crown decementation, so the vertical gap component was apparently stable.

SEM was used for gap assessment, as it offers increased depth of field to allow for better resolution on curved specimens. SEM was operated without conductive coating under low-vacuum and low-voltage conditions to avoid interfacial artifacts, since the same specimens were imaged before and after aging. A low magnification was selected to match that of conventional stereomicroscopes used in dental laboratories, but with a lower depth of field so that the results were relevant to the laboratory processes used.

For LDS, the employment of P surfaces for bonding seemed to be favorable regarding the total gap length both before and after aging when compared to the M counterpart. However, when PICN was used for the fabrication of hybrid abutment crowns, this seemed to not be an issue. It can be assumed that this difference is attributable to the greater hardness of LDS, which might affect the milling procedure, whereas for the softer, stress-absorbing PICN, factory production of the interface is not beneficial. Although no information was given for the factory methods used to prepare the surfaces, it can be concluded that such fabrication offers a significant advantage for LDS but shows greater variance for PICN as far as interfacial integrity is concerned. Another factor that might contribute to the gaps measured at baseline is the polishing procedure performed. Although these were indicated by the individual manufacturers, differences in the number of steps, bur shape, and particle size of the abrasion media may affect the morphology of the interface. Since interfacial gaps were present in each group before the aging process, further research should be performed on this issue to validate gap-free luting procedures.

The effect of aging seemed to be more pronounced in LDS than in PICN, as it resulted in greater gaps in 50% of the M specimens and 30% of the P specimens in the former group, but in only 20% of the M and 30% of the P specimens in the latter group. As the aging process included mechanical loading of the specimens, the physical properties of the restorative material could have an effect on gap formation. As a much harder and high-modulus material than PICN, LD demonstrates less stress absorption capacity and therefore transfers most of the occlusal loading to the luting layer. Under these conditions and assisted by thermally induced stresses, weak luting cement may debond from the margins. A magnification of the defective interface region clearly demonstrated that in all cases and materials, the gap was associated with the luting agent–metal interface. This was expected, since the luting agent used achieved a strong micromechanical bonding with the topography of the acid-etched and silanized ceramics, whereas with the titanium surface, there was simply adaptation and secondary bonding. Therefore, the use of primers with bonding capacity to titanium could improve the interfacial integrity. Nevertheless, such treatments may not be useful in cases of regional disintegration of the luting agent, which is mainly attributed to the load cycling of the chewing simulator. The luting agent used is composed of hydrophobic dimethacrylates (bisphenol glycidyl methacrylate [bis-GMA], ethoxylated bisphenol glycidyl methacrylate [bis-EMA], urethane dimethacrylate [UDMA]), hydroxethyl methacrylate (HEMA), and 36 vol% inorganic filler particles of an average size of 0.9 μm. An increase in filler loading and replacement of the hydrophilic HEMA with a more hydrophobic monomer could improve strength and hydrolytic stability of the luting agent without affecting film thickness.

The clinical consequence of the development of these horizontal gaps is unknown. It has been postulated that gap formation may lead to bacterial colonization and contamination with endotoxins and acidic compounds. Consequently, gap formation may enhance microbial invasion at the cervical restoration region and may therefore contribute to the development of peri-implant disease. Moreover, microbial degradation of the composite resin cement—as well as microbial corrosion of the exposed implant and abutment surfaces facing the gap—due to the challenging acidic conditions formed in such crevices may release metallic particles associated with peri-implant disease. These issues raise important questions as to the long-term performance of hybrid abutment crowns in vivo, which will require further laboratory and clinical documentation to be fully answered.

CONCLUSIONS

The cementation interfaces of CAD/CAM crowns on standardized titanium base abutments showed a high percentage of gaps before and after thermomechanical loading. The composition of the restorative material, as well as the nature of the interface, influenced the dimension of the interfacial gap.

ACKNOWLEDGMENTS

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There is a long-held assumption that teeth are superior to implants because the periodontal ligament (PDL) confers a preeminent defense against biologic and mechanical challenges. However, adequate analysis of the literature is lacking. As a result, differential treatment planning of tooth- and implant-supported restorations has been compromised. Given the abundance and diversity of research, the purpose of this mapping review was to identify basic scientific gaps in the knowledge of how teeth and implants respond to biologic and mechanical loads. These findings will enhance evidence-based clinical decision-making when considering replacement of periodontally compromised teeth and the design of implant prostheses. The online databases PubMed, Science Direct, and Web of Science were searched. Published work from 1965 to 2020 was collected and independently analyzed by both authors for inclusion in this review. A total of 108 articles met the inclusion criteria of clinical, in vivo, and in vitro studies in the English language on the periradicular and peri-implant bone response to biologic and mechanical loads. These findings will enhance evidence-based clinical decision-making when considering replacement of periodontally compromised teeth and the design of implant prostheses. The online databases PubMed, Science Direct, and Web of Science were searched. Published work from 1965 to 2020 was collected and independently analyzed by both authors for inclusion in this review. A total of 108 articles met the inclusion criteria of clinical, in vivo, and in vitro studies in the English language on the periradicular and peri-implant bone response to biologic and mechanical loads. These findings will enhance evidence-based clinical decision-making when considering replacement of periodontally compromised teeth and the design of implant prostheses. 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