Porcelain Veneers: Dentin Bonding Optimization and Biomimetic Recovery of the Crown

Pascal Magne, Dr Med Dent[a]
William H. Douglas, BDS, MS, PhD[b]

Purpose: The purpose of this study was to investigate the biomimetic principle in porcelain veneer reconstruction, or in other words, to assess the extent to which the restoration can mimic the biomechanics and structural integrity of the original tooth. Using an optimized luting procedure, porcelain veneers are expected to present such features even when bonded to an extensive dentin surface. **Methods and Materials:** Dentin-bonded porcelain veneers were assessed using functional and cyclic thermal loads with respect to two parameters: coronal stiffness (investigated using experimental strain gauges and finite element analysis) and morphology of the tooth-restoration interface (scanning electron microscope evaluation). Two different application modes of the same dentin-bonding agent, Optibond FL, were evaluated: a traditional method (dentin adhesive applied when proceeding to luting the veneer) and an alternative method (dentin adhesive applied to dentin and cured before taking the impression for the veneer). **Results:** In the finite element model, the crown compliance increased by a factor of 2.16 after facial enamel removal and returned to 96% of its original value after the placement of the veneer. The finite element values showed a good correlation with strain gauge experimental results (one-sample *t* test, $P > 0.35$ after facial enamel removal and $P > 0.19$ after veneer placement). The dentin adhesive application mode was not critical to the recovery of tooth stiffness (analysis of variance, $P = 0.10$). However, qualitative scanning electron microscope observations demonstrated that the traditional dentin adhesive application was associated with bonding failures between the hybrid layer and the overlying resin, whereas unbroken and continuous interfaces were obtained with the new method using the same dentin adhesive. **Conclusion:** The results of this study definitely favor the biomimetic behavior of porcelain veneers bonded to teeth using an optimized application mode of dentin adhesives, because this treatment modality proved to restore both the mechanical behavior and microstructure of the intact tooth. *Int J Prosthodont 1999;12:111–121.*

Modern concepts in medical research involve the investigation of both structures and physical functions of biologic "composites" and the designing of new and improved substitutes.[1] This newly emerging interdisciplinary material science is called "biomimetics." The primary meaning refers to material processing in a manner similar to the oral cavity, such as the calcification of a soft tissue precursor. The secondary meaning of biomimetics refers to the mimicking or recovery of the biomechanics of the original tooth by the restorative material. This of course is the goal of restorative dentistry.

It is assumed that the hardness of enamel protects the soft underlying dentin. On the other hand, the crack-arresting effect of dentin and of the thick collagen fibers at the dentinoenamel junction[2] compensate for the inherently brittle nature of enamel. This structural and physical interrelationship

[a]*Visiting Associate Professor, Minnesota Dental Research Center for Biomaterials and Biomechanics, Department of Oral Science, School of Dentistry, University of Minnesota, Minneapolis; and Lecturer, Department of Prosthodontics and Department of Prevention and Therapeutics, School of Dental Medicine, University of Geneva, Switzerland.*
[b]*Professor and Academic Director, Minnesota Dental Research Center for Biomaterials and Biomechanics, Department of Oral Science, School of Dentistry, University of Minnesota, Minneapolis.*

Reprint requests: *Dr Pascal Magne, University of Minnesota, Minnesota Dental Research Center for Biomaterials and Biomechanics, Department of Oral Science, School of Dentistry, 16-212 Moos Tower, 515 Delaware Street SE, Minneapolis, Minnesota 55455-0329. Fax: 612-626-1484. e-mail: pascal@web.dent.umn.edu*

Fig 1 *(Left)* Typical situation of dentin exposure as a result of tooth position. Initial situation favors the indication of porcelain veneers: large Class IV composite resin restorations are worn down and need to be replaced, and an increase in central incisor predominance is requested by the patient. *(Center)* Maxillary right central incisor, left lateral incisor, and left canine have a favorable position and the preparations remain confined to enamel. However, because of its buccal position and thin enamel, the left central incisor shows extensive dentin exposure after preparation. The use of a dentin bonding agent is indicated. *(Right)* Postoperative view. Mandibular right central and lateral incisors were also treated with porcelain veneers.

between an extremely hard tissue and a more pliable, softer tissue provides the natural tooth with its unique ability to withstand masticatory and thermal loads during a lifetime. Because of the improvement of adhesive procedures, it is expected that the biomechanical and structural integrity of the enamel-dentin complex could be partially mimicked using porcelain veneers. The success of bonding to teeth relies on adequate preparation and conditioning of the surfaces involved, ie, the ceramics and the mineralized dental tissues. For both enamel and ceramic surfaces, etching procedures combined with the use of a liquid resin have demonstrated their efficiency and ability to surmount extreme conditions.[3,4] If a substantial accessible area of dentin has been exposed by the preparation (Fig 1), application of a dentin-bonding agent (DBA) is recommended. In spite of encouraging results, the absolute reliability and clinical performance of the dentin bond is still impaired by the composite polymerization shrinkage and stresses resulting from thermal dimensional changes.[5,6] The choice of the restorative method will have a critical impact on the behavior of the dentin-resin interface.[7] In addition to the aforementioned variables, dentin is a heterogeneous substrate and it is difficult to predict the overall behavior of the dentin-resin interface. Multiple parameters may be involved within the same tooth, such as the preparation depth, previous pathologies, and contamination by dental products applied to the tooth.[8,9]

Clinically, 2 methods may be applied to promote dentin adhesion when placing indirect bonded restorations. The first and conventional approach consists of delaying the application of the DBA (eg, acid etching followed by the application of the primer liquid and the bonding resin) until the last treatment stage, when proceeding to luting the veneer. To avoid incomplete seating of the restoration, it is usually recommended to keep the adhesive resin uncured when placing the veneer. It is assumed that the pressure of the luting composite during the seating of the veneer may create a collapse of demineralized collagen fibers and subsequently affect the adhesive interface cohesiveness.[10] More recently, another approach was proposed to optimize the DBA application.[11,12] Because the DBA appears to have a superior potential for adhesion when applied to freshly prepared dentin, its application is recommended immediately after the completion of tooth preparation, before the final impression itself. A substantial clinical advantage is that this measure protects the pulpodentinal organ and prevents sensitivity and bacterial leakage during the provisional phase.

Dentin-bonding agents have been widely evaluated using standard shear bond and microtensile tests combined with scanning electron microscope (SEM) observations. However, it is assumed that the structural performances of brittle dental materials cannot be directly correlated to their nominal strength values.[13] Consequently, the simulation of the tooth-restoration complex should be included during mechanical testing because it may significantly influence the behavior of the adhesive. Among other factors, stress and strain measurements open new perspectives in this matter.[14] This study, which used both experimental strain gauges and numeric analysis, proposed the application of the criteria of biomimetics to incisors subjected to extensive preparation (total facial enamel removal) and restored with dentin-bonded porcelain veneers. The efficiency of the 2 different application methods of the DBA was evaluated. Qualitative and quantitative microscope evaluations of the interface were used to access essential information about the thickness of the luting materials and the possible failure modes of the dentin bond.

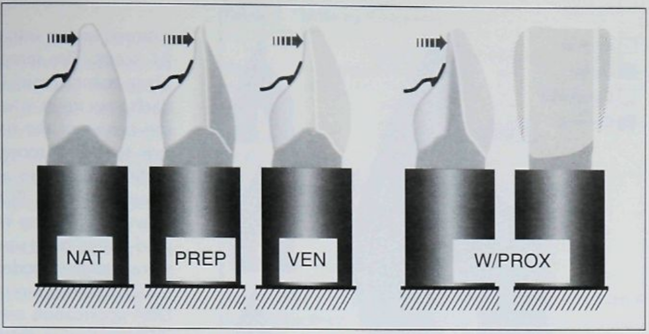


Fig 2 Experimental conditions. The *arrows* show the force application point, about 3 mm above the center of the strain gauge. Condition 1000× is not illustrated because it corresponds to condition W/PROX after thermocycling. NAT = intact natural tooth; PREP = prepared tooth with facial enamel completely removed; VEN = tooth restored with a porcelain veneer; W/PROX = elimination of proximal enamel and proximal surfaces.

Methods and Materials

Experimental Strain Gauge Model

Extracted maxillary incisors were collected, scaled, and stored in saline solution and azide 0.2%. The teeth were mounted in a special positioning device with an orthodontic resin (Ortho Resin Caulk, Dentsply) embedding the root up to 2 mm below the cementoenamel junction. A small depression was created 1 mm from the incisal edge and centered mesiodistally on the palatal surface. This allowed the standardized positioning of the load tip of a servohydraulic universal testing machine[15] (MTS Systems). A strain gauge (type CEA-06-032UW-120, Measurements Group) was bonded in the palatal concavity of each anatomic crown following the longitudinal axis of the tooth. Each test specimen was wired in a Wheatstone bridge circuit with an intact reference tooth to allow the use of the common rejection mode. Loading was applied perpendicular to the long axis of the tooth, in the direction of the facial surface. The force was controlled with a digital function generator to allow a ramp loading from 2 to 42 N in 5 seconds. The measurement was repeated 5 times for each specimen and each experimental phase. The recorded force/strain curves were linear, and were reproducible during the repeated runs. This allowed the calculation of the relative local compliance at the 5 different experimental steps: *(1)* intact natural tooth (NAT); *(2)* prepared tooth with facial enamel completely removed (PREP); *(3)* tooth restored with a porcelain veneer (VEN); *(4)* elimination of proximal enamel and proximal surfaces (W/PROX); and *(5)* thermocycling of the restored tooth (W/PROX) at 1000× between 5 and 55°C with 30 seconds of dwell time (Fig 2). The last experimental condition (1000×, thermocycling) was included to simulate clinical aging. Cyclic mechanical loading combined with thermocycling definitely represents the best experimental design to simulate clinical aging. Such a situation was indirectly reproduced in the simple design of the present experiment; it seems reasonable to assume that thermal variations generated the cyclic mechanical load resulting from differential thermal expansion of the luting composite[16] (in the range of $30/°C \times 10^{-6}$) when compared to the traditional feldspathic porcelain ($13.5/°C \times 10^{-6}$) and the tooth[17] ($11/°C \times 10^{-6}$).

The teeth were maintained in a wet environment during all of the preparation and restorative steps. Two experimental groups (I-DBA and D-DBA, with Optibond FL as the dentin-bonding agent) and a control group (NO-DBA) were investigated, each group comprising 6 specimens. For the traditional approach, I-DBA (indirect curing of the DBA), the dentin-bonding procedures were realized just prior to the placement of the veneer. The adhesive resin was therefore not cured immediately, but only indirectly through the veneer after the seating of the restoration. The alternative approach was also investigated in D-DBA (direct curing of the DBA), in which the dentin-bonding procedures were carried out immediately after the completion of the tooth preparation, before taking the final impression. This allowed the immediate and direct curing of the adhesive resin. In this case, the surface of the adhesive was later roughened (using a coarse diamond bur at low speed) and dried with alcohol just before luting procedures.

After the preparations were completed (the DBA being applied at this stage for group D-DBA), impressions were made with addition silicon material (Express, 3M) and poured in a vacuum-mixed

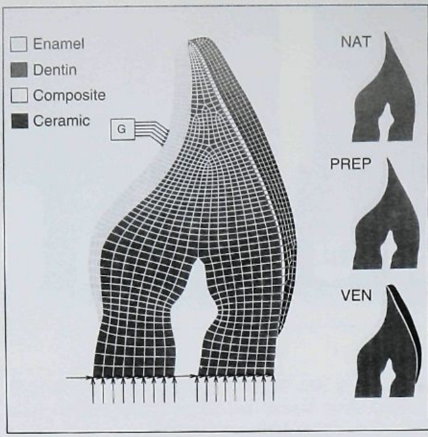


Fig 3 Numeric model. Original single mesh that was used for the 3 numeric conditions (NAT, PREP, and VEN) by deleting or changing the properties of the sets "ceramic" and "composite." *G* represents the nodes corresponding the strain gauge location in the experiment.

improved stone (Vel Mix Stone, Kerr). The ceramic laminates were fabricated using a refractory die technique (Ducera-Lay Superfit refractory die material, Duceram) and a feldspathic porcelain (Creation, Klema). For each specimen, the volume of the original tooth was used as a reference for the definition of the ceramic thickness. However, because the enamel was initially thin for some teeth, a slight overcontour was eventually created. The veneers were tried on the teeth and traditional luting procedures were performed, including etching of porcelain for 90 seconds using 10% ammonium bifluoride gel (Biodent Retentionsgel, Dentsply/DeTrey). The same primer and filled-dentin adhesive (Optibond, Kerr) was used for both experimental groups, with a photopolymerizing composite (Herculite Incisal LT, Kerr). The restorations were seated with finger pressure. After the removal of excess luting material, the margins were covered with a glycerin jelly and the polymerization tip was applied for 120 seconds on each side of the tooth (palatal first, then facial). The margins were then finished with a scalpel to remove excess resin and with carbide finishing burs.

Qualitative and Quantitative Microscope Evaluation

At the end of the experiment, the teeth were subjected to a dye infiltration test by immersion of the restored crown into a 0.5% cresyl blue solution for 24 hours. The samples were then embedded in a clear epoxy resin (PL-1, Measurements Group). Each specimen was sectioned incisogingivally in the center of the tooth and mesiodistally, with a low-speed diamond saw (Isomet, Buehler). The sectioned surfaces were immediately etched for 2 minutes with H_3PO_4 37% and replicated with a polyvinylsiloxane material for the fabrication of gold-plated resin samples. The gold-plated replicas were analyzed under an SEM for a qualitative evaluation of the dentin-resin interface. Since the 2 DBA application methods were assumed to create different luting thicknesses, quantitative evaluations of the luting agent thickness and related layers (composite, bonding resin) were performed directly on the sample sections at the middle third of the tooth using a charge-coupled device camera (Sony DXC-151A) attached to a stereomicroscope (Olympus SZH10) and an image-analysis software program (Optimas 5.22, Optimas).

Finite Element Model and Analysis Definitions

An extracted maxillary central incisor was selected, embedded in a clear epoxy resin (Ortho Resin Caulk), and sectioned longitudinally in the buccolingual plane. The sectioned surface was digitized with a computer scanner device (UMAX, Umax Data System). The contour of enamel, dentin, and pulp chamber were manually traced using graphic software (Freelance Graphics, Lotus). Additional lines were included to simulate the restorative design, namely a facial preparation without incisal overlap. The luting composite thickness varied along the interface between 100 and 200 µm, whereas 50-µm thicknesses were produced for both buccal and incisal margins. The lines were then transferred to a Silicon Graphics workstation and a single mesh was developed (Fig 3). The 3 experimental conditions NAT, PREP, and VEN were simulated. For VEN, a perfect adhesive interface was modeled because all nodes corresponding to the interface were shared by elements of both the luting composite and the dentin. The root was only partially modeled, as it may be assumed that the overall stress distribution is restricted to the coronal restoration. Fixed zero-displacement in both horizontal and vertical directions was therefore applied at the cut-plane of the root. The stress distribution was solved using the MARC Analysis solver (MARK K7.2, MARC Analysis Research). The simulation was performed with plane strain elements (linear, 4-node, isoparametric, and arbitrary quadrilateral).

Three mechanical material properties were required for this finite element simulation: the coefficient of linear shrinkage, the Poisson's ratio, and the modulus of elasticity (Table 1). The surface tangential strain was calculated for the 5 nodes corresponding to the location of the strain gauge in the experimental setup (Fig 3), using the values of strain in the x and y directions and the xy-shear strain, integrated in a transformation equation.[18] Similarly, the surface tangential stress for each node located on the palatal surface of the tooth was calculated from the values of stress in the x and y directions and the xy-shear stress.

Analysis of Strain Gauge Measurements

The natural variations of teeth strongly affect the absolute strain gauge measurements. Accordingly, normalized results were used for comparisons between the different specimens. The absolute measurements supplied by the strain gauges were converted to a relative value given by the following equation:

$$\text{Relative compliance} = \frac{\text{Compliance given at selected test condition}}{\text{Compliance given by the unaltered tooth}}$$

$$= \frac{\text{Maximum strain given at selected test condition/Maximum load}}{\text{Maximum strain given by the unaltered tooth/Maximum load}}$$

$$= \frac{\text{Maximum strain at selected test condition}}{\text{Maximum strain given by the unaltered tooth}}$$

Note that the compliance was here defined as strain/load. The differences in the relative compliance were compared using an analysis of variance (ANOVA), specifically, a between- and within-subjects design where:

- The between-tooth factor was the DBA application mode (NO-DBA vs I-DBA vs D-DBA).
- The within-tooth factor was the experimental step (NAT vs PREP vs VEN, etc).

The common logarithm of the relative compliance was analyzed to homogenize the variance and to make the analyzed measurements more normally distributed. After using the ANOVA to determine the significance of DBA application mode, experimental step, and the interaction of DBA application mode and experimental step, the experimental steps and the interaction were examined to see why each effect was significant. The latter was done using standard errors from the ANOVA and by applying Bonferroni's method separately within the experimental step effect and the interaction. In comparing the 4 experimental steps, 6 comparisons were made, each with a type I error rate of $\alpha = 0.05/6 = 0.0083$, ie, a comparison was declared significant if $P < 0.0083$. Similarly, in examining the interaction, $\alpha = 0.05/18 = 0.0028$ was used, allowing for all 18 possible interactions between a pair of experimental steps and a pair of DBA application modes. Measured relative compliances were also compared to compliances from the finite element analysis using one-sample *t* tests.

Table 1 Material Properties

Material	Elastic modulus (GPa)	Poisson's ratio	Linear shrinkage
Composite	20[19]	0.24[17]	0.0022[20]
Ceramic	69*	0.28[21]	
Enamel	50	0.30[17]	
Dentin	12	0.23[22]	

*Data from Klema (manufacturer of Creation Dental Porcelain).

Results

The mean local compliance was at least doubled after enamel removal (Fig 4). For all groups, the parameter was back to normal (87% to 97% of the initial value) after the placement of the veneers. No major changes were observed after the removal of proximal surfaces for any experimental group or after thermocycling for the experimental groups I-DBA and D-DBA, although thermocycling caused increased compliance for the experimental group NO-DBA.

In the ANOVA, the main effect for DBA application modes was not significant across experimental steps ($P = 0.10$). The main effect for experimental steps was highly significant ($P < 10^{-5}$), as was the interaction between DBA application mode and experimental step ($P < 10^{-5}$), ie, the 3 DBA application modes did not have the same pattern across the experimental steps. Post-hoc tests showed that when averaged across DBA application modes, PREP had the highest relative compliance (2.3 to 2.7) and 1000× was next highest; VEN and W/PROX, while lower than 1000×, did not differ from each other. Further post-hoc tests showed that the interaction between DBA application mode and experimental step arises entirely because NO-DBA was radically affected by thermocycling, while I-DBA and D-DBA were not (Fig 4).

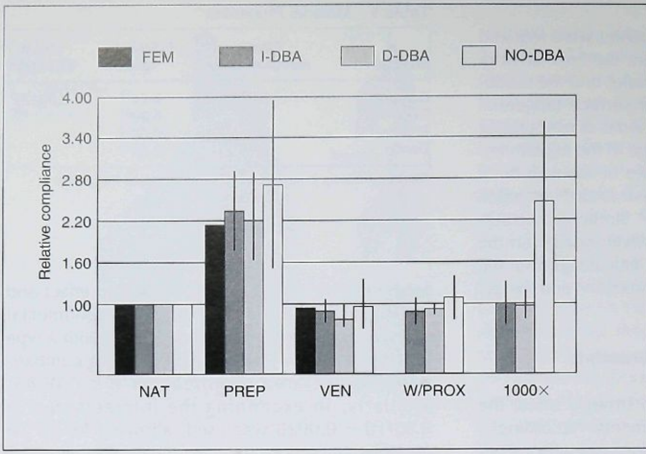
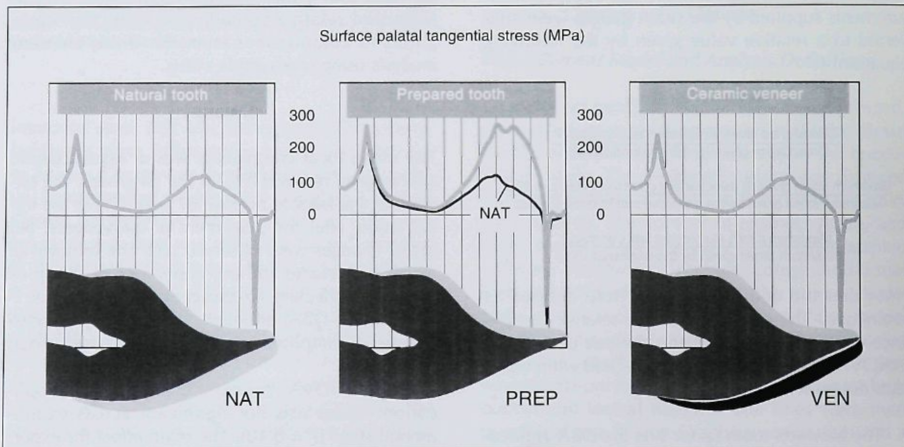


Fig 4 *(Left)* Relative compliance results (± SD). Finite element analysis (FEM) results are represented only for conditions NAT, PREP, and VEN. 1000×= thermocycling of the restored tooth (W/PROX) 1000× between 5 and 55°C with 30 seconds of dwell time.

Fig 5 *(Below)* Graphic representation of the palatal surface tangential stress for the 3 numeric conditions. The plot of tangential stresses *(gray line)* proceeds for each tooth along the palatal surface from the cervical area (left) to the incisal edge (right).



Finite Element Analysis Simulation

The results of relative compliance calculations for the finite element model are represented in Fig 4. In the finite element model, the relative compliance increased by a factor of 2.16 after preparation, and returned to 96% of its original value after the placement of the veneer. The finite element values showed a good correlation with experimental results for the conditions PREP ($P > 0.35$) and VEN ($P > 0.19$).

Figure 5 displays the tangential stresses of the palatal surface and shows the dramatic effect of facial enamel removal on the stress distribution throughout the remaining palatal enamel, especially at the level of the fossa, where maximum tensile stress of 274 MPa was encountered for condition PREP. The tooth showed a complete recovery after the placement of the veneer because both tangential and principal stresses are similar for conditions NAT and VEN. Both conditions exhibited a maximum tensile stress of 115 MPa at the level of the fossa.

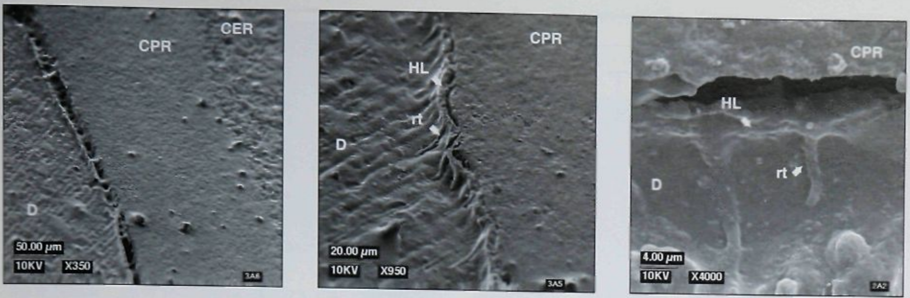


Fig 6 Typical SEM views of demineralized sample section replica for group I-DBA. *(Left)* Luting composite *(CPR)* is well connected to the ceramic *(CER)*, but a gap is detectable between the composite and the dentin *(D)*. *(Center)* Higher magnification reveals the acid-resistant composite and hybrid layer *(HL)*. Some resin tags *(rt)* are protruding because of the dentin demineralization. *(Right)* Very high magnification shows the continuity between the hybrid layer *(HL)* and dentin *(D)*, and the gap at the top of the hybrid layer.

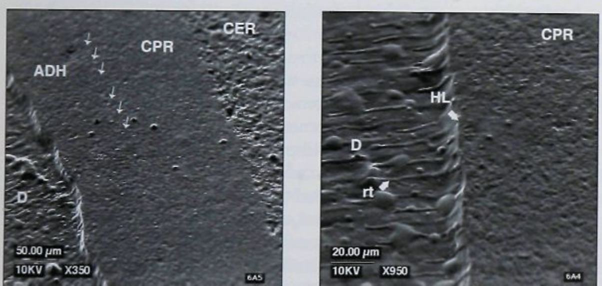


Fig 7 Typical SEM view of demineralized sample section replica for group D-DBA. CER = ceramic; HL = hybrid layer. *(Left)* Junction between the luting composite *(CPR)* and the precured adhesive *(ADH)* is barely visible *(arrows)* and no gap can be detected between the adhesive and the dentin *(D)*. *(Right)* Higher magnification shows the acid-resistant adhesive and hybrid layers tightly related to each other and reveals the presence of long resin tags *(rt)* in dentin.

Microscope Evaluation

No measurable microleakage could be detected in the interface of either I-DBA or D-DBA samples. However, the dentin-resin interface showed notable differences when observed under an SEM (Figs 6 and 7). Both DBA application modes generated a well-organized hybrid layer of 3 to 4 µm thickness and resin tags. This "interdiffusion zone" was always in continuity with the dentin underneath. However, for I-DBA specimens the hybrid layer systematically presented a partial disruption with the overlying resin (Fig 6). In contrast, D-DBA specimens exhibited longer resin tags and did not show any discontinuity either in the dentin-resin interface or between the precured adhesive and the luting composite (Fig 7). Only the cervical marginal area sometimes exhibited a disrupted interface. The specific morphologic aspects described above were very consistent for all samples within the same experimental group.

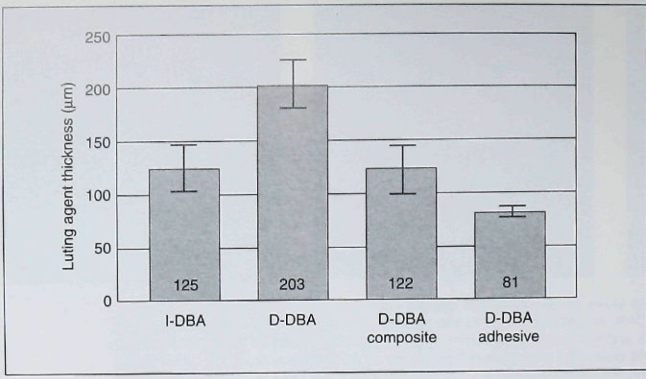


Fig 8 Total luting thickness for D-DBA samples is constituted of the precured adhesive thickness *(D-DBA adhesive)* and the luting composite thickness *(D-DBA composite).*

The luting agent thicknesses are presented in Fig 8. Significant differences (t test, $P = 0.0001$) could be detected between I-DBA (125 ± 22 µm) and D-DBA specimens (203 ± 23 µm). However, in the latter the luting space was composed of 2 distinct layers: the precured adhesive and the luting composite itself. On average, the precured adhesive was thin (81 ± 5 µm) compared to the luting composite (122 ± 22 µm). The thickness of the luting composite alone was similar for D-DBA and I-DBA samples (t test, $P = 0.82$).

Discussion

The design of this study allowed us to explore both the mechanical behavior of the restored tooth and the morphologic aspects of the dentin bond. The finite element analysis was an important complementary tool for understanding the stress distribution. Observations made with the numeric model were successfully validated by the experimental setup. By design, the most important mechanical events of our experimental setup appeared within the buccolingual plane, which supports performing the numeric analysis in a 2-dimensional plane strain model. The numeric simulation of a buccolingual cross-section was clearly demonstrated by Morin et al[23] and validated in a companion paper by experimental strain measurement.[24] Figure 9 strengthens this validation because it reveals the numerous cracks that were generated in the palatal enamel. Such flaws were typically found at the level of the fossa, which happens to be the area of maximum tensile stresses in the numeric model. It may be assumed that the different patterns of these cracks created some variations during the strain gauge measurements. Opening of these cracks certainly occurred during the measurement that was made after the tooth preparation, and it can possibly explain the higher standard deviation observed for all samples at this step (Fig 4). Because the tooth stiffness was restored after the placement of the veneer, the effect of these cracks was attenuated during further measurements.

The results of strain measurements demonstrated that the tooth totally recovered its stiffness when a porcelain veneer was placed as an enamel substitute. The use of ceramic as a restorative material was certainly a key element in this regard since the elasticity modulus of feldspathic porcelains presents a good match with enamel. In a similar study, Reeh and Ross[14] concluded that the tooth stiffness could not be totally restored when using composite veneers bonded to enamel. To support this fact, our model was used to calculate the surface tangential and principal stresses that would have been generated in the situation of a composite veneer using the mechanical properties of current miniparticle hybrids (Fig 10). The maximum stress encountered in the palatal fossa is 172 MPa instead of the 115 MPa at the same location for the natural tooth or the tooth restored with porcelain. This emphasizes the biomimetic behavior of porcelain bonded to tooth with regard to mechanical loads, because both the tangential stresses along the palatal surface and the principal stress proved to be highly similar to the original tooth. One could deplore the fact that ceramic is a brittle material and presents a low tensile strength. Enamel is even more fragile. Nevertheless, in the situation of facial veneers placed on maxillary teeth, both ceramic and facial enamel are mainly subjected to compressive forces, as demonstrated by the principal stress distribution

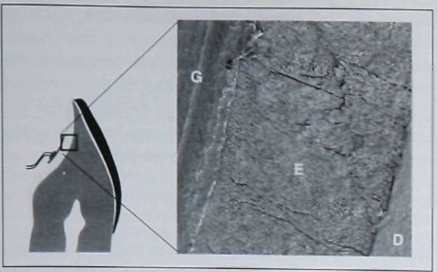
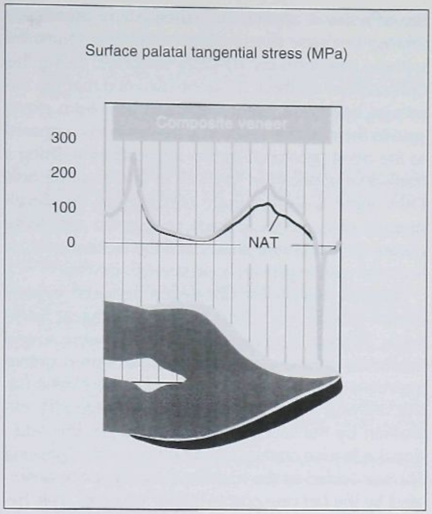


Fig 9 *(Above)* SEM view of palatal enamel cracks above the strain gauge *(G)*. This specific location appears to be the area of maximum tensile stresses in the numeric model. The full thickness of enamel *(E)* is cracked but the flaws never propagate into dentin *(D)*.

Fig 10 *(Right)* Graphic representation of the palatal surface tangential stress for a tooth restored with a composite veneer. The plot of tangential stresses *(gray line)* proceeds along the palatal surface from the cervical area (left) to the incisal edge (right). The original stress distribution of NAT *(black line)* is reported as a reference.



during loading. This may explain in part the very good clinical behavior of facial porcelain laminates[25–31] and the increased porcelain crack propensity reported by some clinicians when placing veneers on mandibular teeth. The facial half of mandibular incisors may be put under tension by functional loads. The elimination of proximal enamel did not influence the palatal compliance for any of the experimental groups, although it could have been assumed that the removal of the strong bond to marginal enamel would affect the tooth stiffness. Our result is in accordance with previous work on natural teeth,[32] which states that the reduction of proximal enamel does not seriously increase the crown deformation. It is concluded that removal of facial enamel may more seriously affect the strength of the tooth than the removal of interproximal enamel.

Even the unbonded veneer without proximal surfaces (NO-DBA in condition W/PROX) exhibited a normal compliance. This unexpected fact may be attributed to the test design and especially to the direction of force application. For this reason, the maximum tensile stresses along the resin-dentin interface were calculated using the values of stress in x and y directions and the xy-shear stress. These did not exceed 8 to 9 MPa for most of the interface. The unbonded veneers in our experiment (NO-DBA) were placed without proceeding to dentin etching and priming, but the tooth preparation was coated with an adhesive resin (Optibond FL Adhesive) prior to the placement and seating of the restoration. It is presumed that the use of the adhesive resin alone can initially create a significant bond by frictional forces that is at least able to withstand the interfacial stresses generated in the present experimental setup. However, this weak bond did not seem to survive the cyclic thermal load because the compliance increased in the last experimental step for the NO-DBA teeth. In spite of their very similar mechanical behavior and the absence of significant microleakage, the 2 DBA application modes showed very different properties under SEM examination. For samples luted with the traditional method (I-DBA), a partial debonding systematically occurred on extensive areas of the interface between the hybrid layer and the composite. Similar failure modes were observed in a previous investigation[10]; they were explained by the collapse of the uncured dentin-resin hybrid layer caused by pressure that was a result of the seating of the restoration. The hybrid layer may be weakened superficially as a consequence of the lower resin content of the compacted collagen fibers. Such structural defects and the intrinsic weakness of the hybrid layer have been shown to be associated with handling conditions of the DBA.[33] Since the dentin remains sealed in areas of debonding, such failure is not detectable in microleakage.

Our study demonstrates that the phenomenon of hybrid layer collapse can be avoided in vitro when the adhesive is applied and cured before impression taking, because the resulting interface appeared without discontinuity (D-DBA samples). Using this optimization method, it can be assumed that the improved bond will better withstand long-term exposure to thermal and functional loads when compared to the bond generated by the same adhesive using a traditional application method. In addition, the new DBA application technique may prevent the development of bacterial leakage and dentin sensitivity during the temporary phase, and the technique is associated with improved bond strength in vitro.[11,12,34]

Another significant difference between experimental groups was found in the luting agent thickness. Thicker interfaces (> 200 μm) were found when the adhesive was applied and cured before impression taking when compared to the classic luting method (≈ 125 μm). This was logically explained by the fact that the thickness of this additional adhesive coating (about 80 μm with Optibond FL) was added to the traditional luting space generated by the lab procedures (about 120 μm). This hypothesis was validated because the thickness of the luting composite alone was not significantly different between groups (125 vs 122 μm). This fact has clinical relevance, as both the clinician and dental technician are continuously challenged by the problem of tooth reduction and restorative material bulk. A confined and superficial dentin exposure gives only a limited space for the restorative materials, including the bonding agent. The application and curing of the DBA would significantly reduce the space left for the ceramic buildup. Considering that a low ratio of ceramic to luting agent thickness can negatively influence the stress distribution within the porcelain,[35,36] the new DBA application method may not be indicated for superficial dentin exposure. On the other hand, deeper preparation surfaces (ie, in the presence of Class III cavities) can be lined with the DBA before impression taking because sufficient space will be left for the restorative material to maintain a reasonable ratio of thicknesses between the ceramic and the luting agent. The adhesion between the precured bonding agent and the newly applied luting agent was not an issue in the present experimental conditions because they could barely be differentiated under SEM examination (Fig 7). Only the stereomicroscope allowed the successful evaluation of their respective thicknesses because of their different optical behaviors. We can therefore recommend roughening the adhesive (using a coarse diamond bur at low speed) just before luting procedures and drying the surface with alcohol. It should be remembered that all recommendations mentioned in the present article are based on the use of a filled adhesive such as Optibond FL. Our clinical experience has shown that the use of an unfilled resin is not adapted to the new application mode; because of the reduced thickness and stiffness of the resin (related to the absence of filler), the roughening procedure can easily destroy the hybrid layer and expose dentin.

Conclusions

Experimental strain gauge, optical and SEM evaluation, and finite element analysis were used to characterize both the mechanical behavior and interfacial properties of dentin-bonded porcelain veneers that were subjected to functional and cyclic thermal loads. Observations made with the numeric model were successfully validated by the experimental setup.

- Maximum tensile stresses were found on the palatal surface, especially in the palatal fossa, where enamel cracks were detected.
- The removal of facial enamel negatively affected the stress and strain distribution, whereas the removal of interproximal surfaces did not seriously increase the crown deformation.
- The facial half of the tooth, including the veneer, was mostly subjected to compressive stresses. The use of the porcelain as an enamel substitute proved to be essential to restore the original stiffness and mechanical behavior of the intact tooth.
- The application mode of the DBA was not critical to the recovery of tooth stiffness. However, SEM observations clearly demonstrated that the traditional DBA application method (DBA applied to dentin just before the placement of the veneer and cured through the porcelain, with the luting composite) was associated with bonding failures between the hybrid layer and the overlying resin.
- Unbroken and continuous interfaces were obtained with an alternative DBA application mode (same DBA applied to dentin and cured before taking the impression for the veneer). The latter generated enlarged luting thicknesses (> 200 μm) because of the presence of the precured adhesive (thickness ≈ 80 μm) when compared to the traditional method (thickness ≈ 125 μm).

The biomimetic behavior of porcelain veneers bonded to teeth using an improved application mode of DBAs was demonstrated by the present experimental trial; this promising treatment modality seems to restore the biomechanical and structural integrity of the tooth.

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