



Cumulative effects of successive restorative procedures on anterior crown flexure: Intact versus veneered incisors

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Objective: When successive restorative procedures (eg, porcelain veneers, interdental resin composite restorations, and endodontic treatment) are carried out on the same tooth, significant effects on crown flexure can be expected. **Method and materials:** Dentin-bonded porcelain veneers (experimental group) were assessed in vitro using functional and cyclic thermal loads. They were compared to natural teeth (control group) with respect to 2 parameters: coronal flexure (investigated using experimental strain gauges) and morphology of the tooth-restoration interface (scanning electron microscopic evaluation). For both veneered and natural teeth, crown deformation was recorded at 5 sequential experimental steps: intact tooth (baseline), Class III cavities, Class III resin composite restorations, endodontic treatment, and endodontic restoration (without posts). **Results:** No significant differences in crown flexure were found between natural and veneered incisors when compared across experimental steps. The main effect for experimental steps was highly significant. When averaged across all specimens (natural and veneered teeth), the endodontic treatment step resulted in the highest crown flexure ($1.55\times$ the baseline value). The unrestored Class III cavities and the endodontic restoration were next highest ($1.30\times$ and $1.28\times$ the baseline value, respectively). The lowest crown flexures were found after restoration of the Class III cavities ($1.13\times$ the baseline value). No measurable microleakage or gaps were detected at the ceramic-resin, resin-enamel, or resin-dentin interfaces (Optibond FL, Kerr). **Conclusion:** Each subsequent reduction in tooth structure resulted in a substantial increase in crown flexibility, even after restoration. Endodontic procedures were responsible for most of the loss in crown stiffness. Extensive proximal cutting and restorations seemed to minimally affect crown flexure. Porcelain veneers showed perfect biomimetic behavior, because cumulated restoration procedures had the same effect on natural and veneered incisors. (Quintessence Int 2000;31:5–18)

Key words: anterior tooth, flexure, resin composite restoration, stiffness, veneer

CLINICAL RELEVANCE: Successive restorative procedures, especially endodontics and extensive use of resin composite restorations, can have a negative influence on crown flexure. Veneered incisors behave like natural teeth because porcelain veneers allow the maintenance of, or even an increase in, crown rigidity.

Simulation or recovery of the biomechanics of the original tooth by a restoration has become the primary goal of restorative dentistry.^{1,2} A natural tooth's unique ability to withstand masticatory and thermal loads during a lifetime is the result of the structural and physical interrelationship between an extremely hard tissue (enamel) and a more pliable softer tissue (dentin).

The recognition of this interrelationship has led to a growing concern about the biomechanical response of intact hard tissue to restorative procedures. A red flag was raised when researchers focused their attention on the biomechanical side effects of amalgam restorations on posterior teeth (ie, cuspal fractures and cracked-tooth syndromes).^{3–5} In response, a number of studies^{6–9} analyzing biophysical stress and strain have shown that (1) restorative procedures can make the tooth crown more deformable and (2) the tooth can be strengthened by increasing its resistance to crown deformation. Based on these principles, tooth reinforcement was obtained by some form of complete or

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Figs 1a and 1b Combined endodontic and restorative procedures.



Fig 1a The maxillary right central incisor is nonvital and has an old resin composite restoration.



Fig 1b Endodontic procedures were followed by internal bleaching, replacement of the old resin restoration, and restoration of the endodontic access cavity. Despite a good esthetic result, the effect of such extended direct composites on crown flexure and tooth biomechanics must be questioned.

partial coverage (extracoronary strengthening) at the expense of the intact tooth substance.¹⁰⁻¹² Today, adhesive technology has proven its efficiency in simultaneously reestablishing cuspal stiffness and allowing maximum preservation of the remaining hard tissue (intracoronary strengthening).¹³⁻¹⁵

The flexural properties of anterior teeth can be studied with methods similar to those used for posterior teeth, providing that the geometric and loading configurations of incisors are reproduced. A functional load on the incisal edge was used to demonstrate that anterior esthetic techniques often involve the labial and interproximal reduction of enamel, making the tooth crown more deformable.^{1,16,17} The effect of varying enamel reductions was quantitatively determined by the crown flexure, which can be measured under simulated conditions by bonded strain gauges.^{1,16,17} These studies demonstrated that bonded resin composite restorations permitted the recovery of tooth stiffness, which is not possible with amalgam restorations.

However, the physical properties of resin composites create some limitations. One limitation is the elastic modulus, which, for an average microfilled hybrid, can be up to 80% lower (about 16 GPa) than the elastic modulus of enamel (about 84 GPa).^{18,19} The enamel shell proves to be instrumental in the way stresses are distributed within the crown.¹² When a more flexible material replaces the enamel shell, only partial recovery of crown rigidity can be expected. Studies by Reeh et al¹¹ and by Reeh and Ross¹⁷ showed a recovery of only 76% to 88% in crown stiffness after the placement of composite restorations and composite veneers. On the other hand, it was demonstrated that crown rigidity can

be recovered 100% when feldspathic porcelain (elastic modulus about 70 GPa) is used as an enamel substitute, as is the case in porcelain veneer restorations.²⁰

Recently, the indications for adhesive restorations have been significantly broadened to include endodontically treated teeth.²¹⁻²⁴ As a result, it is not uncommon to carry out several treatment modalities on the same tooth, for example, endodontic treatment, composite restorations (Figs 1a and 1b), and veneering. Significant effects on crown flexure are expected when restorative procedures succeed each other on the same tooth. There have been few investigations that have studied the combined effects of porcelain veneers, interdental composite restorations, and root canal treatment on incisor biomechanics. In the present *in vitro* study, the nondestructive strain gauge method was combined with scanning electron microscopy (SEM) to evaluate variations in crown compliance and tooth-restoration interfacial properties when successive restorative procedures were carried out on intact and veneered incisors.

METHOD AND MATERIALS

Fourteen freshly extracted mandibular incisors were collected, scaled, and stored in saline solution and 0.2% azide at 4°C. Care was taken to prevent dehydration during the preparation and testing. The teeth were mounted in a special positioning device with a hard plaster (Vel Mix Stone, Kerr), so that the root was embedded up to 1.0 mm below the facial level of the cemento-enamel junction.

Experimental groups

The 14 specimens were randomly divided into 2 groups: (1) seven teeth were kept intact (control group, NAT); (2) the other 7 specimens (experimental group, VEN) were prepared for a laminate veneer restoration.

The specimens in the VEN group were prepared by totally removing enamel from the buccal surface, reducing 1.5 to 2.0 mm of the incisal edge and creating a moderate interdental wrapping (penetrating half of the proximal surface). The extensive removal of enamel and exposure of dentin does not represent a traditional approach for veneer preparation. This risky experimental design was chosen to create a maximum challenge for the tooth-restoration complex.

The dentin bonding procedures (total-etch, Optibond FL, Kerr) were carried out immediately after the completion of tooth preparation and before the final impression was taken. This special chronology allowed the immediate and direct curing of the dentin bonding agent (DBA). 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 and before the final impression itself.^{20,25,26} A substantial clinical advantage is that this precautionary measure protects the pulpodentinal organ and prevents sensitivity and bacterial leakage during the provisional phase.

After the preparations were completed (including application of the DBA), the prepared surfaces were rubbed with an alcohol pad (to remove the inhibition layer at the surface of the DBA). Impressions were made with addition silicon material (Express, 3M Dental) and poured in a vacuum-mixed improved stone (Vel Mix Stone).

The ceramic laminates were fabricated by using a refractory die technique (Ducera-Lay Superfit refractory die material, Duceram) and a feldspathic porcelain (Creation, Klema). The final thickness of the veneers was standardized as much as possible to reproduce the average thickness of enamel. Measurements made on mandibular incisors by Ferrari et al²⁷ were used as the reference (ie, 0.5 to 0.6 mm for the middle third of the crown and 0.8 to 1.0 mm in the incisal area) (Fig 2). Figures 3a to 3c illustrate a typical prepared tooth and the corresponding veneer.

The veneers were tried on the teeth, and traditional luting procedures were performed. This included etching the porcelain for 90 seconds with 10% ammonium bifluoride gel (Bident Retentionsgel, Dentsply/DeTrey) and etching the enamel for 30 seconds with 35% phosphoric acid (Ultraetch, Ultradent). The same filled adhesive resin (Optibond, Kerr) was used again with a photopolymerizing resin composite (Herculite

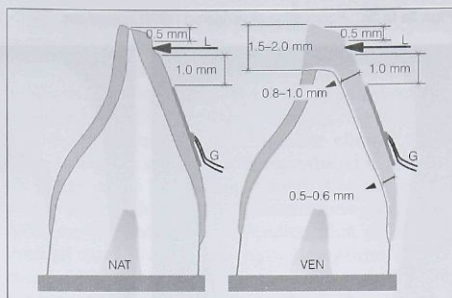


Fig 2 Schematic representation (section) of tooth specimens. Natural (NAT) = control; veneered (VEN) = experimental. The strain gauge (G) was positioned in the same area on both NAT and VEN specimens, approximately 1 mm above the load area (L). The ceramic thickness of VEN specimens was standardized to simulate facial enamel thickness, except for incisal overlap (about 1.5 to 2.0 mm).

XRV Enamel A3, Kerr) as the luting agent. Before use, the luting composite was maintained at body temperature to improve its rheologic properties. The restorations were seated with finger pressure.

After the excess luting material was removed, the margins were covered with a glycerin jelly and the polymerization tip was applied for 120 seconds on each side of the tooth (palatally first and then facially). The margins were then finished with a scalpel to remove excess resin and with carbide finishing burs.

Experimental setup

A small depression was created 0.5 mm from the incisal edge and centered mesiodistally on the buccal surface of each tooth or veneer (see Fig 2). A strain gauge (type FLG-02-11-1L, Tokyo Sokki Kenkyujo) was bonded to each specimen, on the buccal surface of the crown, following the longitudinal axis of the tooth. The upper edge of the gauge backing was positioned approximately 1.0 mm above the edge of the incisal depression (see Fig 2). The gauges were bonded with an acid-etch technique (surface conditioning for 60 seconds with 35% phosphoric acid for enamel or for 90 seconds with 10% ammonium bifluoride for the ceramic).

During measurement, each test specimen was wired into half of a Wheatstone bridge circuit, together with an intact reference tooth to utilize the common mode rejection. A special device allowed standardized positioning (Fig 4) for load application in a closed-loop servohydraulic universal testing machine (MTS Systems). Loading was applied

Figs 3a to 3c Fabrication of veneered (VEN) specimens.



Fig 3a Facial view before the impression is taken. The facial enamel has been totally removed, and the exposed dentin surface is covered and protected by the dentin bonding agent (Optibond FL).



Fig 3b Restoration during insertion. The restoration and tooth preparation are characterized by moderate interdental wrapping and flat incisal overlap.



Fig 3c Lingual view of the restored tooth.

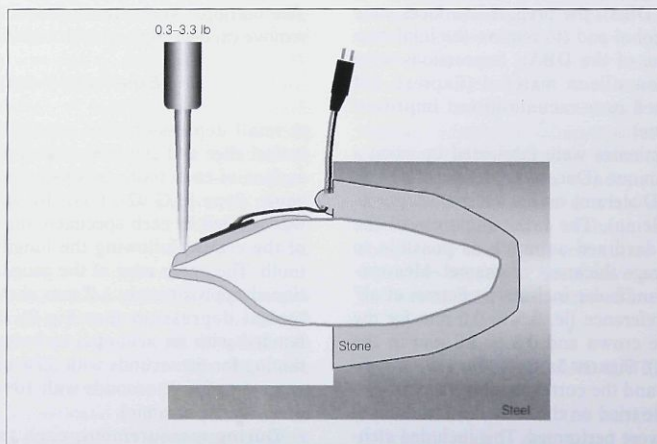


Fig 4 Schematic representation (section) of tooth specimen embedded in stone and positioned for the loading test.

perpendicular to the long axis of the tooth, in the direction of the lingual surface, which corresponds to an extreme loading configuration for mandibular incisors. A realistic biting load can be separated into a horizontal and a vertical component. The horizontal component induces bending, and thus would be the major challenge for the incisor.

The force was controlled with a digital function generator to allow a ramp loading from 0.30 to 3.30 lb in 4 seconds. Force-strain curves were generated, and the compliance (ratio between maximum strain and maximum load) was calculated. The measurement was repeated 5 times for each specimen and for each experimental step. The recorded force-strain curves were linear and were reproducible during the repeated runs.

Experimental steps

The load measurements described above were made for each of the 14 samples at 5 consecutive stages of successive restorative procedures (Fig 5a), yielding 350 measurements:

1. **BASELINE:** "Intact" teeth, either natural (NAT; $n = 7$) or veneered (VEN; $n = 7$).
2. **CL-III:** Large proximal cavities (approximately 1.5 to 2.0 mm deep and 3.0 mm high) were cut with standardized round burs (801-016 and 801-023, Brasseler) with a lingual access. The cavities extended buccally above the proximal contact area (Figs 5b to 5d). Preparations were completed with a 1.0-mm circular bevel. For the VEN group, the incisal and buccal bevels involved the ceramic restoration.
3. **CL-III REST:** Each cavity was restored with Optibond FL (total-etch technique) and Herculite XRV enamel A3 as a restorative, placed in 2 increments. For the VEN group, an additional procedure was carried out to promote adhesion to the preexisting veneer. The beveled ceramic was first abraded with 50- μ m aluminum oxide (Microetcher, Danville Engineering), etched for 60 seconds with 35% phosphoric acid, and silanized (Scotchprime, 3M Dental).
4. **ENDO:** Consecutive endodontic access preparations were then cut in all 14 teeth (Fig 5e). Canals were enlarged and shaped with the stepback technique.
5. **ENDO REST:** A 1-mm-thick glass-ionomer base (Vitremar, 3M Dental) was placed at the entrance of the canal. This was followed by the restoration of the endodontic access cavity, using the adhesive procedures and materials mentioned earlier. In this procedure, the restorative material was placed and cured in 1 increment.

All specimens were then subjected to thermocycling (1,000 cycles between 5°C and 55°C with a 30-second dwell time). This last experimental step 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 the thermal variations generated a cyclic mechanical load that resulted from differential thermal expansion of the luting composite (in the range of $30/^{\circ}\text{C} \times 10^{-6}$)²⁸ when compared to feldspathic porcelain ($13.5/^{\circ}\text{C} \times 10^{-6}$) and tooth ($11/^{\circ}\text{C} \times 10^{-6}$).²⁹

Dye infiltration and qualitative microscopic evaluation

At the end of the experiment, the teeth were subjected to a dye infiltration test; the restored crown was immersed in a 0.5% cresyl blue solution for 24 hours. The specimens were then horizontally sectioned with a low-speed diamond saw blade (Isomet, Buehler). The sectioned surfaces were immediately etched for 1.5 minutes with 35% phosphoric acid and replicated with a polyvinyl siloxane material (Express) for the fabrication of gold-coated resin specimens.

The gold-coated replicas were analyzed under the SEM for a qualitative evaluation of the dentin-resin, ceramic-resin, and enamel-resin interfaces. Microleakage evaluation was performed directly on the specimen sections with the use of a charge-coupled device camera (Sony DXC-151A). The camera was attached to a stereomicroscope (Olympus SZH10), and the resulting images were analyzed with image analysis software (Optimas 5.22).

RESULTS

Analysis of data

Natural variations of teeth can strongly affect the absolute strain gauge measurements. Accordingly, the baselines used for measuring changes in crown flexure were the intact and veneered incisors (without proximal cavities or endodontic access). Data are presented in terms of relative compliance (RC). *Relative compliance* is defined as the crown compliance (strain/load) in the test condition relative to the crown compliance at baseline and is derived by dividing test strain by baseline strain.^{1,20} Thus, RC reflects changes in compliance relative to the baseline measurement for the same tooth. An increase in strain results in an increase in RC.

The differences in the relative compliance were compared by using an analysis of variance (ANOVA),

Figs 5a to 5e Experimental conditions: opened Class III cavities (CL-III); restored Class III cavities (CL-III REST) (Herculite XRV); opened endodontic access and preparation (ENDO); restored endodontic access cavity (ENDO REST) (Herculite XRV).

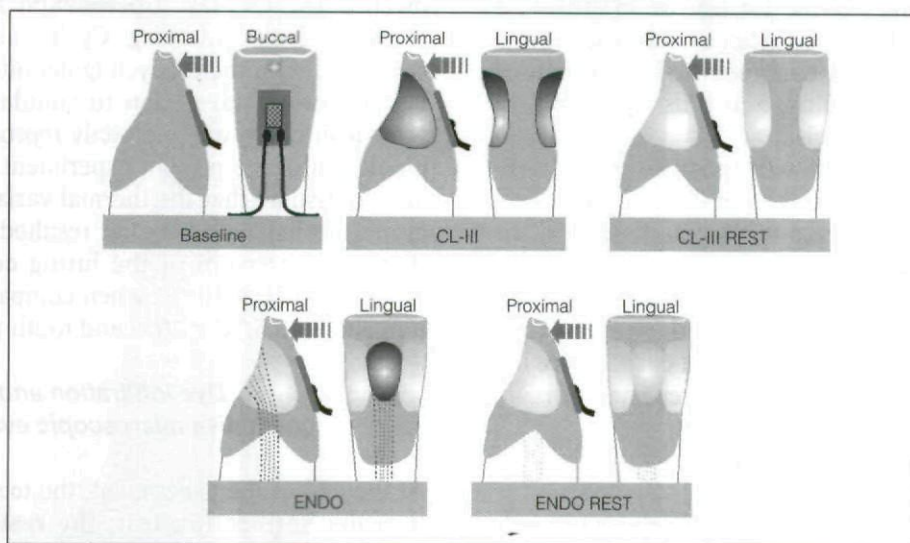
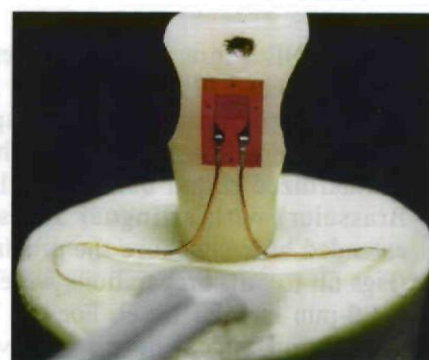


Fig 5a Schematic representation of experimental setup. (arrows) Force application point.



Figs 5b to 5d Views of the same control specimen (not veneered) at step CL-III.

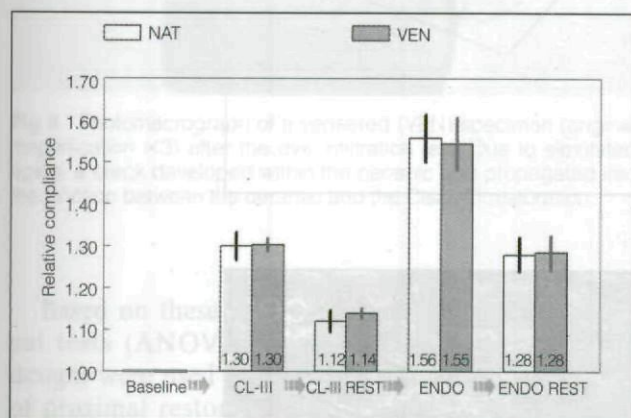


Fig 5e View of the same control specimen (not veneered) at step ENDO. This last situation features restored interdental cavities.

TABLE 1 Outcome of statistical tests

Comparison	Factor	ANOVA	Post-hoc tests and significance
I. Between-subject	Initial state (veneered or not)	$P = 0.81$	NAT and VEN not different
II. Within-subject	Experimental step	$P < 5 \times 10^{-5}$	CL-III REST < ENDO REST = CL-III < ENDO
III. Interaction of I and II	Initial state $\times$ step	$P = 0.70$	NAT vs VEN does not vary across stages

ANOVA = analysis of variance; NAT = natural; VEN = veneered; CL-III REST = restored Class III cavity; ENDO REST = restored endodontic access cavity; CL-III = unrestored Class III cavity; ENDO = unrestored endodontic access cavity.

**Fig 6** Relative compliance results (mean $\pm$ SD) for both control and experimental (veneered) specimens at each experimental step.

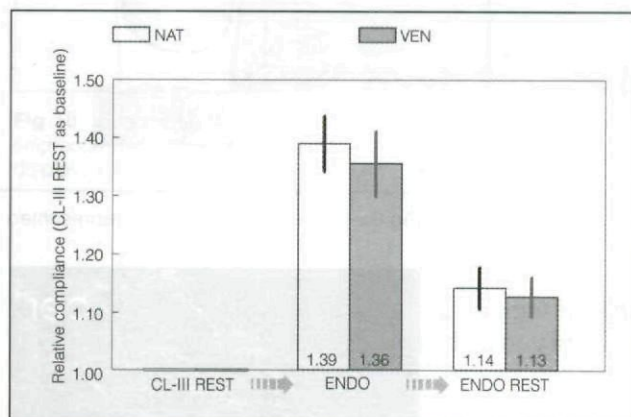
specifically, a between- and within-subjects design, where the between-tooth factor was the original state of the tooth (NAT versus VEN), and the within-tooth factor was the experimental stage (BASELINE versus CL-III versus CL-III REST, etc).

After the ANOVA was used to determine the significance of the initial state (NAT or VEN), the experimental stage, and the interaction of initial state and experimental stage, the experimental stage was examined to see why it was significant. The latter was done by using standard errors from the ANOVA and by applying Bonferroni's method within the experimental step effect. During comparison of the 4 experimental steps, 6 comparisons were made, each with a type I error rate of 0.05/6 (0.0083). A comparison was declared significant if $P < 0.0083$.

Crown flexure

Data are presented graphically in Fig 6. The results of the statistical analysis are summarized in Table 1.

The mean RC increased by a factor of 1.30 after Class III preparations. For both the NAT and VEN groups, the parameter was back to $\times 1.13$ the initial value after placement of the composite restorations. Similar changes were found when the endodontic

**Fig 7** Relative compliance results for both control and experimental specimens at steps ENDO and ENDO REST. (New computations using step CL-III REST as baseline.)

access cavity was prepared and restored: The RC increased from 1.13 (CL-III REST) to 1.55 and returned to $\times 1.28$ the baseline value.

In the ANOVA, the main effect on RC for the original state of the tooth (intact versus veneered) was not statistically significant across experimental steps ($P = 0.81$). The interaction between the original state of the tooth and the experimental stage was also not significant ($P = 0.71$): Both NAT and VEN had the same pattern across the experimental steps. The main effect on RC for the experimental steps was highly significant ($P < 10^{-4}$). When averaged across all samples (NAT and VEN), post hoc tests showed that ENDO had the highest RC (1.55), CL-III and ENDO REST were the next highest (1.30 and 1.28, respectively), and CL-III REST showed the lowest RC (1.13).

To explore the effect of the endodontic procedures alone (not combined with Class III restorations), additional computations were carried out using stage CL-III REST as a baseline for measuring changes in crown flexure. The results are presented in Fig 7. The mean RC increased by a factor of 1.37 after endodontic preparation. For both the NAT and VEN groups, the parameter was back to $\times 1.13$ the value of CL-III REST after the restoration of the endodontic access.

Figs 8a to 8e Scanning electron microscopic views of demineralized specimen section replicas after simulated aging.

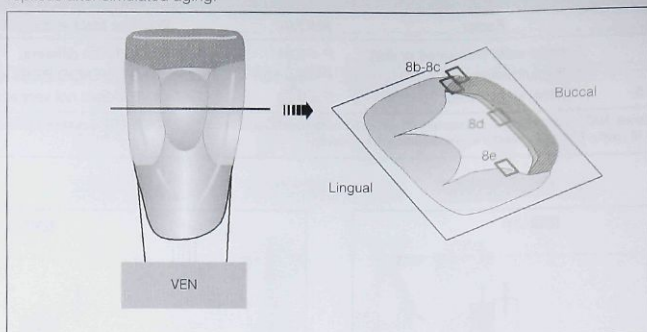
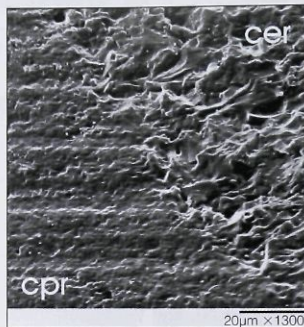
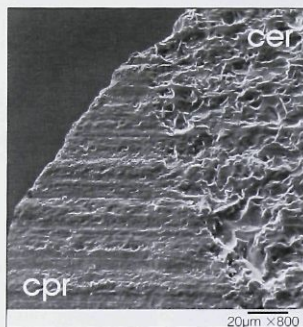


Fig 8a Selected locations are represented.



Figs 8b and 8c Detailed views of resin composite (cpr)-ceramic (cer) interfaces at the junction between a Class III restoration and veneer.

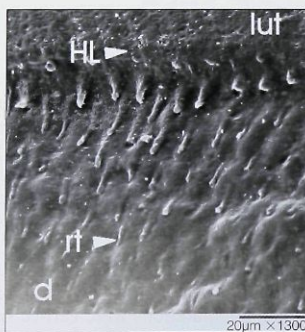


Fig 8d High magnification of the resin-dentin interface at the junction between veneer luting composite (lut) and dentin (d). A well-formed, 4-µm-thick, acid-resistant hybrid layer (HL) can be seen under the luting agent, as can extremely long resin tags (rt).

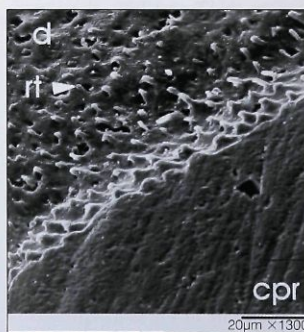


Fig 8e High magnification of the resin-dentin interface at the junction between a Class III restoration (cpr) and dentin (d). (rt) Resin tags.



Fig 9 Photomicrograph of a veneered (VEN) specimen (original magnification $\times 3$) after the dye infiltration test. Due to simulated aging, a crack developed within the ceramic and propagated into the junction between the ceramic and the Class III restoration.

Based on these new computations, similar statistical tests (ANOVA, between- and within-subjects design) were used to compare the independent effects of proximal restorations (CL-III and CL-III REST) and endodontics (ENDO and ENDO REST). The effect of endodontic preparation alone (1.37) appears to be significantly higher ($P = 0.0015$) than the effect of the Class III preparations (1.30). However, this difference disappears after restoration, because both CL-III REST and ENDO REST exhibit the same RC of 1.13 ($P = 0.76$).

Dye infiltration and quantitative microscopic evaluation

Despite simulated aging, no measurable microleakage or gaps could be detected (Fig 8a) at the ceramic-resin (Figs 8b and 8c), resin-enamel, or resin-dentin interfaces (Figs 8d and 8e). The only exception was 1 specimen from the VEN group, which had a ceramic crack that propagated into the proximal area (Fig 9). A significant number of minor cracks were found within the remaining enamel of NAT specimens (Fig 10). Similarly, 4 of the 7 veneers exhibited minor cracks, showing a pattern very similar to that of the enamel cracks (Figs 11a and 11b).

All specimens showed a well-organized hybrid layer with a thickness of 3 to 4 μm and resin tags. This "interdiffusion zone" was always in continuity with the dentin underneath. No obvious differences could be detected among the different types of restoration and interfaces (proximal versus endodontic versus facial locations). Veneered specimens exhibited long resin tags at the interface between luting composite and dentin (see Fig 8d). They did not show a discontinuity at either the dentin-resin interface or between

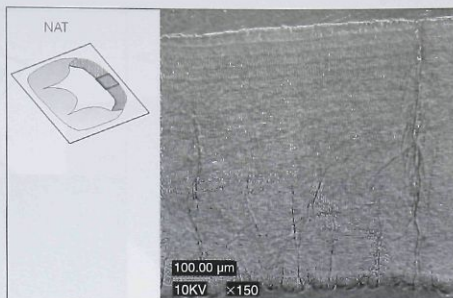


Fig 10 Scanning electron microscopic view of a demineralized section replica of a natural (NAT) specimen. The facial enamel displays multiple cracks.

the precured adhesive and the luting composite. The specific morphologic aspects described were very consistent for all specimens.

DISCUSSION

Intertooth variation is reduced when a series of restorative procedures are evaluated sequentially, using the unaltered tooth as its own control. This method allows smaller sample sizes that yield statistical significance. As demonstrated by Reeh et al,¹¹ destructive tests, such as loading to failure, can fail to show statistically significant differences. On the other hand, strain gauge data provide much greater insight into the performance of both tooth and restorative materials.

Effect of tissue removal

Each subsequent reduction in tooth structure (CL-III and ENDO) resulted in a substantial increase in crown flexibility. The type of cavity preparation led to differences in the loss of tooth stiffness. Combined with the data of 2 similar studies,^{1,20} the results of the present analysis yield significant information on the effect of different tissue reductions on anterior crown flexure (Fig 12). Substantial reduction of facial enamel (ie, veneer preparation) or endodontic access cavities is more likely to affect crown rigidity than is the interdental reduction of enamel or Class III cavities. Considering that extensive proximal cavities were carried out in the present trial, it can be concluded that extensive proximal preparation seems to minimally affect crown flexure. The greater effect of endodontic access preparation could be related to the fact that hard tissue is removed from a more critical location of the tooth.

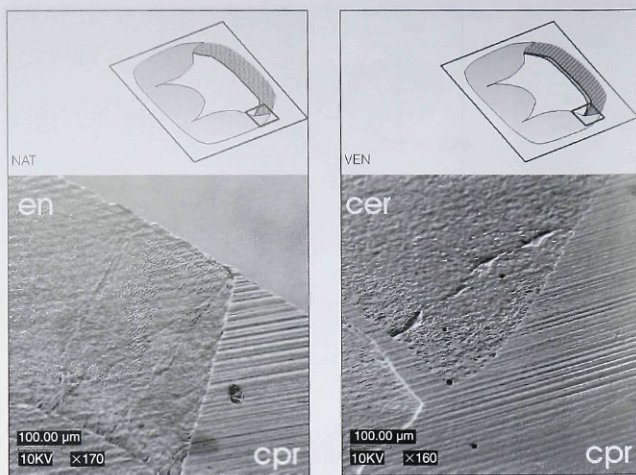


Fig 11a (left) Scanning electron micrographic view of a demineralized specimen section replica at the junction between the facial enamel (en) and a Class III composite (cpr). (NAT) Natural specimen.

Fig 11b (right) Scanning electron micrographic view of a demineralized specimen section replica at the junction between the facial ceramic (cer) veneer and a Class III composite (cpr). (VEN) Veneered specimen. The similarity of enamel and ceramic cracks shown in Figs 11a and 11b is striking.

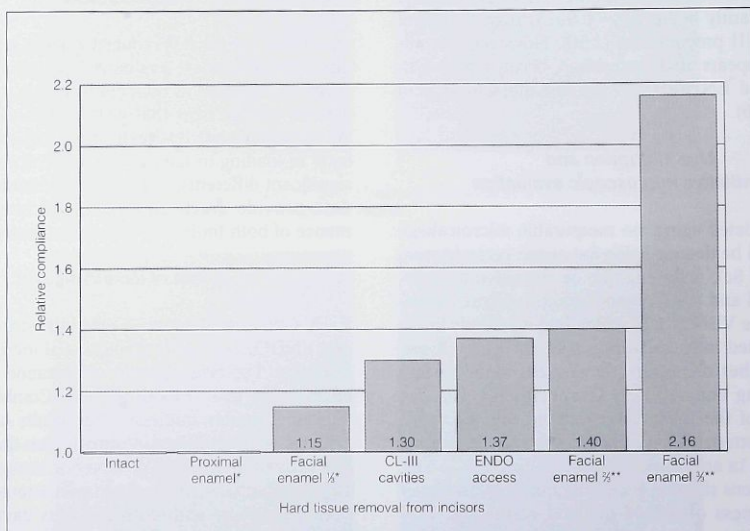


Fig 12 Relative compliance results for natural incisors after removal of coronal tissues. *Results of study by Magne and Douglas.²⁰ **Results of study by Magne et al.¹ (Other data are from the present study.)

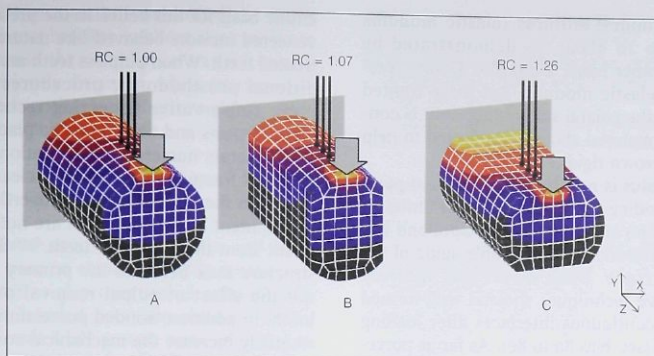


Fig 13 Simplified 3-dimensional finite-element analysis (stress along the z-axis) simulating the experimental setup. The tooth is schematized as a circular cross-sectioned cantilever beam (A). Constant load is applied vertically at the upper end of the beam (gray arrow). The relative compliance (RC) of beams A, B, and C were calculated from the average strain recorded at 3 selected finite-element nodes. Beam A was used as the baseline (RC = 1.00). Material removed from the sides of beam A (situation of beam B) has a limited effect on stress and strain distribution (RC = 1.07). The same amount of material removed from the upper and lower sides of beam A (situation of beam C) has a significant effect on stress and strain distribution (RC = 1.26).

This point can be made clearer if the tooth is considered as a cantilever beam. The simple and schematic 3-dimensional finite-element model shown in Fig 13 illustrates that removing the same amount of material can have a very different effect on the flexibility and stress distribution within the beam. Stress distribution is not affected when the material is removed from the lateral sides of the beam ("proximally"), whereas a significant increase in flexibility and stress concentration occurs when the material is removed from the upper and lower sides of the beam ("facially" and "palatally"). It would seem that the same principle applies to the teeth in the present experimental setup because, by design, most mechanical events occur in the buccolingual plane.

However, the behavior of anterior teeth must be differentiated from the behavior of posterior teeth. In a similar study on posterior teeth, Reeh et al⁵⁰ showed the negligible effect of endodontic procedures (5% reduction in crown stiffness) and the dramatic effect of proximal tooth preparation (60% reduction in crown stiffness with a mesio-occlusodistal preparation). On posterior teeth, the loss of marginal ridge integrity is the most important contribution to the loss of tooth strength. Such conclusions cannot be extended to the anterior dentition, because of the different anatomy and loading configuration of incisors.

Effect of restoration and cumulative procedures

In each case, composite restorations allowed only partial recovery of relative tooth compliance. The benefits of restoring interdental cavities and endodontic access were approximately 17% (from 1.30 to 1.13) and 27% (from 1.55 to 1.28), respectively. As previously described for cavity preparations and the removal of material (Fig 13), the greater effect of restoring the endodontic access can be explained by the fact that a significant amount of restorative material is placed in the critical area involving the palatal surface.

The cumulative effect of restorative procedures becomes important as enamel is progressively replaced by composite. In the last stage of this experiment, when Class III and endodontic restorations were placed successively (ENDO REST), the crown flexibility was not statistically different from that of the unrestored Class III restorations (CL-III). In other words, the restored tooth at the end of the experiment was as flexible as the tooth with 2 widely opened Class III cavities. This emphasizes the critical role of the restorative's elastic modulus in relationship to the elastic modulus of enamel (about 80 GPa). The marketplace is characterized by numerous composites that possess varying degrees of stiffness, ranging from 5 to 21 GPa.¹⁸ Materials with attractive optical properties

can feature very modest stiffness (elastic modulus ranging from 9 to 16 MPa), as demonstrated by Herculite. On the other hand, Z100 (3M Dental) presents the highest elastic modulus but more limited esthetics. As far as the palatal side of the tooth is concerned, the stiffest material should be selected to help in the recovery of crown rigidity.

The elastic modulus is not the only important parameter. Efficient bonding to dentin also contributes to the recovery of crown stiffness.¹¹ Using Optibond FL, the present study demonstrated favorable aging of the dentin-resin interface. Both direct and indirect (veneers) restorative techniques showed well-formed hybrid layers and continuous interfaces after loading and thermocycling (see Figs 8a to 8e). As far as porcelain veneers are concerned, the good adhesion between the luting composite and the dentin was expected, because an optimized bonding technique was used (immediate application of the dentin bonding agent before impression taking), as suggested by other studies.^{20,25,26}

It was more unexpected to observe the reliable bond of Class III and endodontic restorations. The adhesion of direct composite fillings is usually impaired by the composite polymerization shrinkage and stresses resulting from thermal dimensional changes.^{31,32,33} New approaches in direct restorations include the use of a flowable composite as a low-elastic modulus liner. It has the ability to deform and compensate for the aforementioned stresses and reduce microleakage.^{34,35} A similar "stress-breaker effect" may have occurred in the present experiment because of the use of Optibond FL. Because of its low viscosity and filler content, this specific product seemed to act as an intermediate resin and has showed less leakage³⁶ and improved bond strength^{37,38} than other systems.

Natural versus veneered incisors

No significant differences were noted between natural and veneered incisors throughout the experimental steps. Such a result is expected if veneered teeth are considered to be characterized by their "natural" behavior, showing a stress distribution within veneered incisors that cannot be differentiated from the stress distribution within intact incisors.²⁰ This is the essence of *biomimetics*²—when restorations behave functionally as natural teeth with regard to strain and stress transfer, unlike teeth restored with extensive resin composite restorations.

The results of the present experiment also demonstrate that veneering and endodontic procedures are compatible. Porcelain veneers are usually not recommended for nonvital teeth. It is difficult to find a sci-

entific basis for this belief. In the present trial, pulpless veneered incisors behaved like natural endodontically treated teeth. When pulpless teeth are treated with traditional prosthodontic procedures (instead of the more conservative veneering techniques), various types of posts and cores must be placed. This, in turn, may generate numerous complications, such as cracks and root fractures.³⁹ It has been clearly demonstrated that both the biomechanical properties and the moisture content of nonvital teeth are not significantly different from those of vital teeth.^{40,41} The loss of tooth structure thus becomes the primary cause of failure, not the effect of pulpal removal on the remaining tooth. In addition, bonded porcelain veneers may substantially increase the mechanical coronal resistance⁴² and restore the original tooth stiffness.²⁰ It appears reasonable to assume that a similar effect would be found on a pulpless tooth.

Adhesion to the preexisting ceramic restoration is critical when other restorative procedures succeed veneering of an incisor. Surface roughening by etching has the strongest effect on ceramic-resin bond strength.⁴³ However, intraoral use of hydrofluoric acid cannot be recommended. In the present experiment, surface roughening was obtained by sandblasting only, which represents a safer procedure. The stability of the bond can be attributed to the silanization procedure, because chemical coupling is extremely efficient on silica-based dental ceramics,⁴⁴ such as Creation.

After completion of the experiments, a number of specimens displayed minor cracks in enamel or ceramics, which were not present before the testing. The similarities in the enamel and ceramic cracking (see Figs 11a and 11b) indicate again the biomimetic behavior of porcelain veneers. Cracking constitutes an unavoidable aging process that can be attributed to repeated mechanical and thermal loads.^{45,46} As explained in the "Method and Materials" section, thermal variations can generate a cyclic mechanical load resulting from differential thermal expansion of the composite compared to that of the traditional feldspathic porcelain or the tooth.

Strength and compliance

This study was based on a nondestructive approach and, by design, was not able to address the problem of tooth strengthening. However, it can be expected that higher flexibility (generating higher strains and therefore higher stresses) will be associated with lower strength. On the hand, higher rigidity could be associated with higher strength but also more problematic failures⁴⁷ (eg, root fractures). In that sense, it can be assumed that the Class III restorations strengthened the tooth compared to the situation with the opened (unfilled) Class III cav-

ities. But Class III restorations weakened the tooth compared to the intact baseline (without any cavities or restorations), because the compliance was not totally recovered. As previously discussed, when enamel parts are replaced by composite, loss of crown rigidity (and possibly loss of strength) is expected.

CONCLUSION

In vitro experimental strain gauge, optical, and SEM evaluations were used to characterize the mechanical behavior and interfacial properties of natural teeth (NAT) and dentin-bonded porcelain veneers (VEN). Both of the NAT and VEN groups were subjected to sequential restorative procedures (Class III cavities and endodontic treatment), as well as simulated aging (thermocycling):

1. Large Class III cavity preparations increased crown flexibility by 30%.
2. Endodontic preparation alone was the greatest contributor to the loss of tooth stiffness (crown flexibility increased by 38%).
3. Only 88% of the original crown stiffness was recovered when Class III cavities or endodontic access cavities were restored with composites.
4. The combination of Class III restorations and endodontic preparation increased crown flexibility by 55%. In this situation, only 78% of the original crown stiffness could be recovered when the endodontic access was restored with composite.
5. During the sequential restorative procedures, natural teeth and veneered teeth showed similar variations in crown flexibility. Veneered incisors should be considered to be similar to natural teeth and restored accordingly.
6. All interfaces (ceramic-resin, resin-enamel, and resin-dentin) showed negligible aging, in terms of leakage, degradation, and discontinuity.

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REFERENCES

1. Magne P, Versluis A, Douglas WH. Rationalization of incisor shape: Experimental-numerical analysis. *J Prosthet Dent* 1999;81:345-355.
2. Magne P, Douglas WH. Rationalization of esthetic restorative dentistry based on biomimetics. *J Esthet Dent* 1999; 11:5-15.
3. Cameron CE. The cracked tooth syndrome. *J Am Dent Assoc* 1964;68:405-411.
4. Cameron CE. The cracked tooth syndrome: Additional findings. *J Am Dent Assoc* 1976;93:971-975.
5. Cavel WT, Kelsey WP, Blankenau RJ. An in vivo study of cuspal fracture. *J Prosthet Dent* 1985;53:38-42.
6. Hood JAA. Methods to improve fracture resistance of teeth. In: Vanherle G, Smith DC (eds). *International Symposium on Posterior Composite Resin Restorative Materials*. St Paul, MN: 3M, 1985:443-450.
7. Douglas WH. Methods to improve fracture resistance of teeth. In: Vanherle G, Smith DC (eds). *International Symposium on Posterior Composite Resin Restorative Materials*. St Paul, MN: 3M, 1985:433-441.
8. Morin DL, Douglas WH, Cross M, DeLong R. Biophysical stress analysis of restored teeth: Experimental strain measurements. *Dent Mater* 1988;4:41-48.
9. Morin DL, Cross M, Voller VR, Douglas WH, DeLong R. Biophysical stress analysis of restored teeth: Modelling and analysis. *Dent Mater* 1988;4:77-84.
10. Malcolm PJ, Hood JAA. The effect of cast restorations in reducing cusp flexibility in restored teeth [abstract]. *J Dent Res* 1971;56:D207.
11. Reeh ES, Douglas WH, Messer HH. Stiffness of endodontically treated teeth related to restoration technique. *J Dent Res* 1989;68:1540-1544.
12. Linn J, Messer HH. Effect of restorative procedures on the strength of endodontically treated molars. *J Endod* 1994; 20:479-485.
13. Morin D, DeLong R, Douglas WH. Cusp reinforcement by the acid-etch technique. *J Dent Res* 1984;63:1075-1078.
14. McCulloch AJ, Smith BG. In vitro studies of cusp reinforcement with adhesive restorative material. *Br Dent J* 1986; 161:450-452.
15. Macpherson LC, Smith BG. Reinforcement of weakened cusps by adhesive restorative materials: An in-vitro study. *Br Dent J* 1995;178:341-344.
16. Douglas WH. The esthetic motif in research and clinical practice. *Quintessence Int* 1989;20:759-745.
17. Reeh ES, Ross GK. Tooth stiffness with composite veneers: A strain gauge and finite element evaluation. *Dent Mater* 1994;10:247-252.
18. Willems G, Lambrechts P, Braem M, Celis JP, Vanherle G. A classification of dental composites according to their morphological and mechanical characteristics. *Dent Mater* 1992;8:310-319.
19. Craig RG, Peyton FA, Johnson DW. Compressive properties of enamel, dental cements, and gold. *J Dent Res* 1961;40: 936-945.
20. Magne P, Douglas WH. Porcelain veneers: Dentin bonding optimization and biomimetic recovery of the crown. *Int J Prosthodont* 1999;12:111-121.

21. Baratieri NL, et al. Direct Adhesive Restorations on Fractured Anterior Teeth, ed 2. Santiago, Chile: Quintessence, 1998.
22. Magne P, Dietschi D, Holz J. Esthetic restorations for posterior teeth: Practical and clinical considerations. *Int J Periodont Rest Dent* 1996;16:104-119.
23. Dietschi D, Spreafico R. Adhesive Metal-free Restorations. Chicago: Quintessence, 1997:61-77.
24. Belser UC, Magne P, Magne M. Ceramic laminate veneers: Continuous evolution of indications. *J Esthet Dent* 1997;9:197-207.
25. Bertschinger C, Paul SJ, Luthy H, Scharer P. Dual application of dentin bonding agents: Its effect on the bond strength. *Am J Dent* 1996;9:115-119.
26. Paul SJ, Scharer P. The dual bonding technique: A modified method to improve adhesive luting procedures. *Int J Periodont Rest Dent* 1997;17:536-545.
27. Ferrari M, Patroni S, Balleri P. Measurement of enamel thickness in relation to reduction for etched laminate veneers. *Int J Periodont Rest Dent* 1992;12:407-413.
28. Versluis A, Douglas WH, Sakaguchi RL. Thermal expansion coefficient of dental composites measured with strain gauges. *Dent Mater* 1996;12:290-294.
29. Craig RG. Restorative Dental Materials, ed 6. St Louis: Mosby, 1980:55, 76.
30. Reeh ES, Messer HH, Douglas WH. Reduction in tooth stiffness as a result of endodontic and restorative procedures. *J Endod* 1989;15:512-516.
31. Ciucchi B, Bouillaguet S, Delaloye M, Holz J. Volume of the internal gap formed under composite restorations in vitro. *J Dent* 1997;25:305-312.
32. Van Meerbeek B, Perdigao J, Lambrechts P, Vanherle G. The clinical performance of adhesives. *J Dent* 1998;26:1-20.
33. Dietschi D, Herzfeld D. In vitro evaluation of marginal and internal adaptation of class II resin composite restorations after thermal and occlusal stressing. *Eur J Oral Sci* 1998;106:1033-1042.
34. Ferdianakis K. Microleakage reduction from newer esthetic restorative materials in permanent molars. *J Clin Pediatr Dent* 1998;22:221-229.
35. Leinfelder K. Current developments in materials and techniques. Presented at the Star of the North Meeting (Minnesota Dental Association), Minneapolis, 26 April 1999.
36. Swift EJ Jr, Triolo PT Jr, Barkmeier WW, Bird JL, Bounds SJ. Effect of low-viscosity resins on the performance of dental adhesives. *Am J Dent* 1996;9:100-104.
37. Tjan AH, Castellnuovo J, Liu P. Bond strength of multi-step and simplified-step systems. *Am J Dent* 1996;9:269-272.
38. Wakefield CW, Draughn RA, Sneed WD, Davis TN. Shear bond strengths of six bonding systems using the pushout method of in vitro testing. *Oper Dent* 1998;23:69-76.
39. Assif D, Bitenski A, Pilo R, Oren E. Effect of post design on resistance to fracture of endodontically treated teeth with complete crowns. *J Prosthet Dent* 1993;69:36-40.
40. Sedgley CM, Messer HH. Are endodontically treated teeth more brittle? *J Endod* 1992;18:332-335.
41. Papa J, Cain C, Messer HH. Moisture content of vital vs. endodontically treated teeth. *Endod Dent Traumatol* 1994;10:91-93.
42. Andreasen FM, Daugaard-Jensen J, Munksgaard EC. Reinforcement of bonded crown fractured incisors with porcelain veneers. *Endod Dent Traumatol* 1991;7:78-83.
43. Roulet JF, Soderholm KJ, Longmate J. Effects of treatment and storage conditions on ceramic/composite bond strength. *J Dent Res* 1995;74:381-387.
44. Hayakawa T, Horie K, Aida M, Kanaya H, Kobayashi T, Murata Y. The influence of surface conditions and silane agents on the bond of resin to dental porcelain. *Dent Mater* 1992;8:238-240.
45. Magne P, Kwon KR, Belser UC, Hodges JS, Douglas WH. Crack propensity of porcelain laminate veneers: A simulated operatory evaluation. *J Prosthet Dent* 1999;81:327-334.
46. Magne P, Versluis A, Douglas WH. Effect of luting composite shrinkage and thermal loads on the stress distribution in porcelain laminate veneers. *J Prosthet Dent* 1999;81:335-344.
47. Stokes AAN, Hood JAA. Impact fracture characteristics of intact and crowned human central incisors. *J Oral Rehabil* 1993;20:89-95.

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