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Laboratory Research

Stress-strain Analysis of Premolars With Non-carious Cervical Lesions: Influence of Restorative Material, Loading Direction and Mechanical Fatigue

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Clinical Relevance

Stress-strain analysis confirmed that non-carious cervical lesions (NCCLs) restored with resin-based composite or combining resin-based composite with a ceramic laminate have a more favorable biomechanical behavior. Removal of occlusal interferences reduces stress-strain pattern in the cervical tooth structure and NCCL restorative material.

SUMMARY

Noncarious cervical lesions (NCCLs) are characterized by a loss of dental structure at the cementoenamel junction (CEJ) caused by stress, biocorrosion, and attrition. Variations in occlusal loading can promote different stress and strain patterns on the CEJ. Restoration of NCCLs is part of lesion management; however, there is still no conclusive restorative protocol for NCCLs. This study aimed to evaluate the stress and strain distribution of

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maxillary premolars with NCCLs according to three factors: 1) restorative technique; 2) direction of occlusal loading; and 3) mechanical fatigue. Three-dimensional (3D) finite element analysis (FEA) and strain gauge testing were used to assess stress and strain, respectively. 3D-FEA orthotropic, linear, and elastic models were generated: sound tooth (SO); unrestored NCCL; or NCCL restored with glass ionomer; flowable composite resin; nanofilled composite resin (CR); lithium disilicate ceramic; and nanofilled composite resin core associated with a lithium disilicate laminate (CL). A 150-N compressive static load was applied in two conditions: axially in both cusps (Al); and at a 45° angle to the long axis of the tooth applied to the palatine cusp (Ol). For the experimental tests, specimens were treated as described previously, and one strain gauge was attached to the buccal surface of each tooth to record tooth strains before and after cyclic loading (200,000 cycles, 50 N). FEA showed that the association of NCCL and Ol resulted in higher stress values. CR and CL restorations showed the closest biomechanical behavior to SO for both loading types. Loaded Al or Ol specimens showed higher strain values after mechanical fatigue. Lower stress and strain were observed with Al when compared with Ol. The restoration of NCCLs with composite resin only or associated with ceramic laminates seems to be the best approach because the results for those groups were similar in biomechanical behaviors to sound teeth.

INTRODUCTION

The dental structures in the cervical region are more vulnerable to wear because enamel is very thin at this site, and cementum and dentin are not very resistant.[1] This specific tissue loss is a common finding, reported in up to 60% of patients, and is most prevalent in maxillary posterior teeth, mainly premolars.[2,3] Cervical wear is classified as a noncarious cervical lesion (NCCL), which is a pathological process characterized by loss of dental hard tissues near the cementoenamel junction (CEJ).[4] Multiple factors can be associated with this process, such as stress (abfraction: parafunction and traumatic occlusion), friction (wear: toothbrush/dentifrice abrasion), and biocorrosion (chemical, biochemical, and electrochemical degradation: extrinsic and intrinsic acids).[4]

The multifactorial etiology of NCCLs results in varying and unclear management protocols that are still controversial.[5] The treatment of NCCLs may be multidisciplinary, including occlusal analysis and adjustment or replacement of lost dental structures, associated with instructing patients about oral habits, which is essential to the success of rehabilitating NCCLs.[6] Distinct occlusal loading conditions can lead to changes in the stress distribution patterns at the cervical region.[7,8] The stress concentration and fatigue process may result in rupture of brittle structures, such as enamel,[8,9] while also favoring gaps at the interface of restorative materials and dental structures, with possible restorative failures.[10] However, simple restoration of cervical lesions does not treat the etiological factors.[11]

Loss of dental structures either by caries, fractures, coronal preparations, or noncarious wear is a key factor for altering the biomechanical behavior of teeth.[12,13] Therefore, restorative materials that present mechanical properties similar to dental tissues can be advantageous for repairing NCCLs and restoring the stress-strain pattern of sound teeth.[13] Although several studies have analyzed and described restorative protocols for NCCLs,[10,13,14] the literature is still missing deeper investigations considering the effect of different materials and restorative techniques for these lesions. However, consensus exists regarding the use adhesive materials with mechanical and optical properties similar to tooth structures,[6] which can improve biomechanical behavior[13] and esthetics and reduce hypersensitivity.[11]

Composite resins,[6] glass ionomer cements,[10] and flowable resins[14] are the materials most commonly used for replacing lost enamel and dentin at the cervical region. Nevertheless, the survival rate of these restorations can be influenced by chemical degradation and attrition,[15,16] a reduction in hardness,[16] stress concentration during mastication,[17,18] shrinkage stress,[19,20] deficiencies in enamel margins,[21] color mismatch,[21] and reduced adhesion to sclerotic dentin, which is usually present at the base of NCCLs.[22,23]

Although composite resins present good biomechanical behaviors due to their ability to mimic dentin,[13] enamel properties are more closely mimicked by ceramic materials.[24] The advances of indirect restorative materials has resulted in satisfactory bond strengths among glass ceramics, composite resin cements, and dental structures.[25,26] The introduction of strengthened glass ceramics with notable optical properties and good survival rates[27,28] has allowed for their use in areas subjected to high mechanical efforts demanding esthetics.[28] In addition, glass ceramics present excellent surface smoothness.[29] This aspect is relevant due to the high frequency (69.5%) of NCCLs in which the gingival wall angle is at gingival or subgingival levels[30] because the proximity of restorations to the periodontal margin can increase gingival bleeding, insertion loss, and gingival recession.[31] However, well-finished restorations and smoother materials have been shown to accumulate less plaque and remain free of periodontal pathologies.[32]

Thus, the purpose of this study was to evaluate the stress and strain distribution of maxillary premolars with NCCLs using three-dimensional (3D) finite element analysis (FEA) and strain gauge testing according to three factors: 1) restorative technique; 2) direction of occlusal loading; and 3) mechanical fatigue. The hypotheses tested was that the biomechanical behavior of premolars with NCCLs is not affected by restorative materials with different elastic moduli, occlusal loading direction, or cyclic loading.

METHODS AND MATERIALS

Finite Element Analysis

3D finite element linear elastic analysis was performed using anatomically based geometric representations for pulp, dentin, enamel, periodontal ligament, and cortical and medullar bones.[33] Fourteen models were generated (Rhinoceros 3D software, Rhinoceros, Miami, FL, USA) simulating sound tooth (SO); unrestored buccal saucer-shaped NCCLs (UN); and NCCLs restored with resin-modified glass ionomer (GI); flowable composite resin (FR); conventional nanofilled composite resin (CR); lithium disilicate glass ceramic (LD); and conventional nanofilled composite resin core associated with a 0.5-mm lithium disilicate glass ceramic laminate (CL).

The models were exported to the processing analysis software (ANSYS 12.0, Ansys Workbench 12.0.1, Canonsburg, PA, USA) using the Standard for the Exchange of Product Data (STEP) format (Figure 1). The following steps were performed in this software: preprocessing (definition of mechanical properties, volumes, connection types, mesh for each structure, and boundary conditions), processing (data calculation), and postprocessing (analysis of results by stress distribution criteria). All dental structures and restorative materials were considered homogeneous and linearly elastic. Enamel and dentin were considered orthotropic and the other structures isotropic (Table 1).[10,34-40]

After testing the mesh conversion to define the appropriate mesh refinement level, volumes corresponding to each structure were meshed with the controlled and connected elements. The meshing process involved division of the studied system into a set of small discrete elements defined by nodes. Solid quadratic tetrahedral elements of 10 nodes were used (Figure 2A). The mesh conversion test was initiated using the software automatic meshing and was continued by gradually decreasing the size of the elements. For each test stage, the results were generated by equivalent stress criterion (von Mises) to verify the higher stress values of dentin. The mesh was considered satisfactory when, even reducing the dimension of elements, the higher stress levels were similar to the results observed with the previous mesh refinement. The number of elements used varied depending on the different volumes, so that the final model accurately represented the original geometry (Table 2). Due to the adhesive properties of the restorative materials used, restorations were bonded to dental structures by considering a mesh connection with dentin and enamel.

The boundary conditions consisted of developing a displacement/restriction model using load application. Loading of models (150 N) was applied to specific surfaces previously defined in the computer-aided design software, as follows: Axial loading (Al) was equally distributed on both cusps, simulating homogeneous contact distribution (Figure 2B); oblique loading (Ol) simulated occlusal interference on the palatine cusp of the model,[8] with the load applied at a 45° angle to the long axis of the tooth (Figure 2C). Models were restrained at the base and lateral surfaces of cortical and trabecular bone to avoid displacement (Figure 2D). Stress distribution analysis was performed using equivalent stress criterion (von Mises). After complete stress analysis in all structures, the results were plotted in transparency, except for enamel, dentin, and restorative materials, for better visualization. The FEA strain values of the restorative materials were also measured on all nodes corresponding to the surfaces where the strain gauge was fixed on the laboratory strain gauge test to allow comparisons.

Strain Gauge Test and Cyclic Loading

For the strain gauge test, 25 intact human maxillary single-rooted premolars, free of cracks and defects, were selected (gathered following an informed

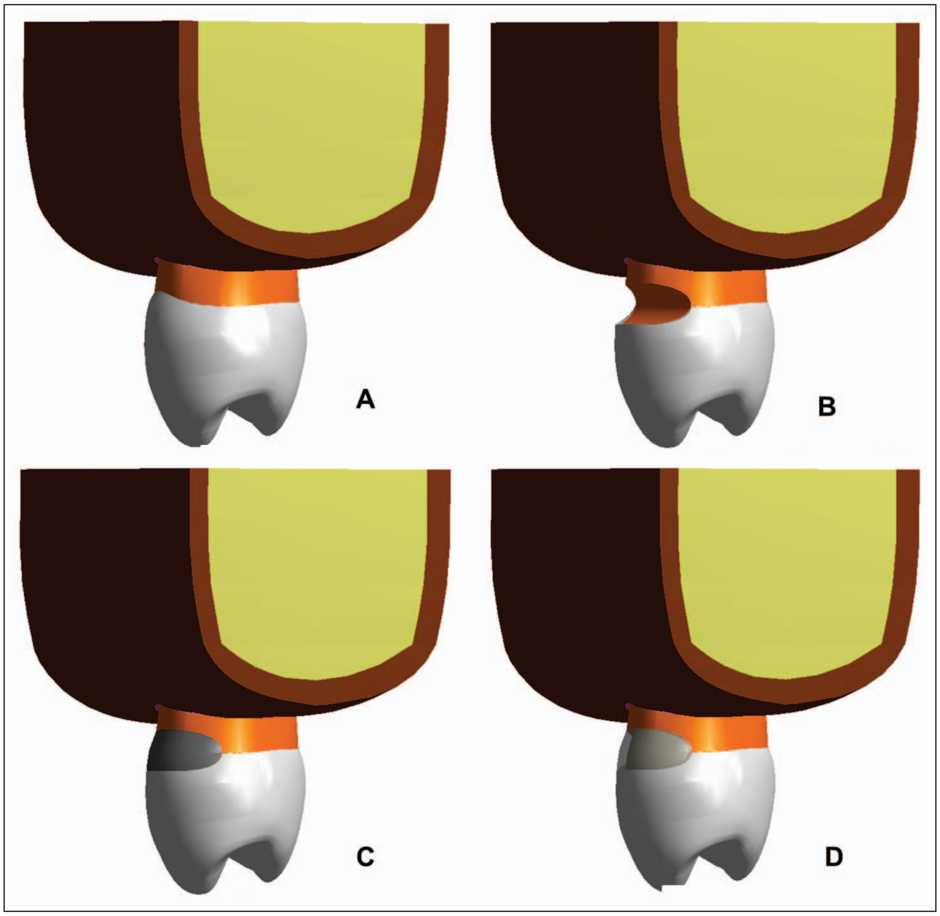

Figure 1. *Volume for the different CAD models. (A): Sound tooth. (B): Unrestored NCCL. (C): NCCL restoration with single material. (D): NCCL restored with two materials.*

Table 1: *Mechanical Properties of Orthotropic and Isotropic Structures*

Structure	**Orthotropic Structures**		
	Longitudinal	**Transversal**	***Z***
		Elastic Modulus (MPa)	
Enamel[34]	73,720	63,270	63,270
Dentin[34]	17,070	5610	5610
		Shear Coefficient (MPa)	
Enamel[34]	20,890	24,070	20,890
Dentin[34]	1700	6000	1700
		Poisson Ratio (v)	
Enamel[34]	0.23	0.45	0.23
Dentin[34]	0.30	0.33	0.30
		Isotropic Structures	
	Elastic Modulus (MPa)	**Poisson Ratio (v)**	
Flowable resin[35]	5300	0.28	
Glass ionomer[10]	10800	0.30	
Lithium disilicate[36]	65000	0.23	
Pulp[37]	2.07	0.45	
Periodontal ligament[38]	68.9	0.45	
Cortical bone[39]	13,700	0.30	
Medullar bone[39]	1370	0.30	
Hybrid composite resin[40]	22,000	0.27	

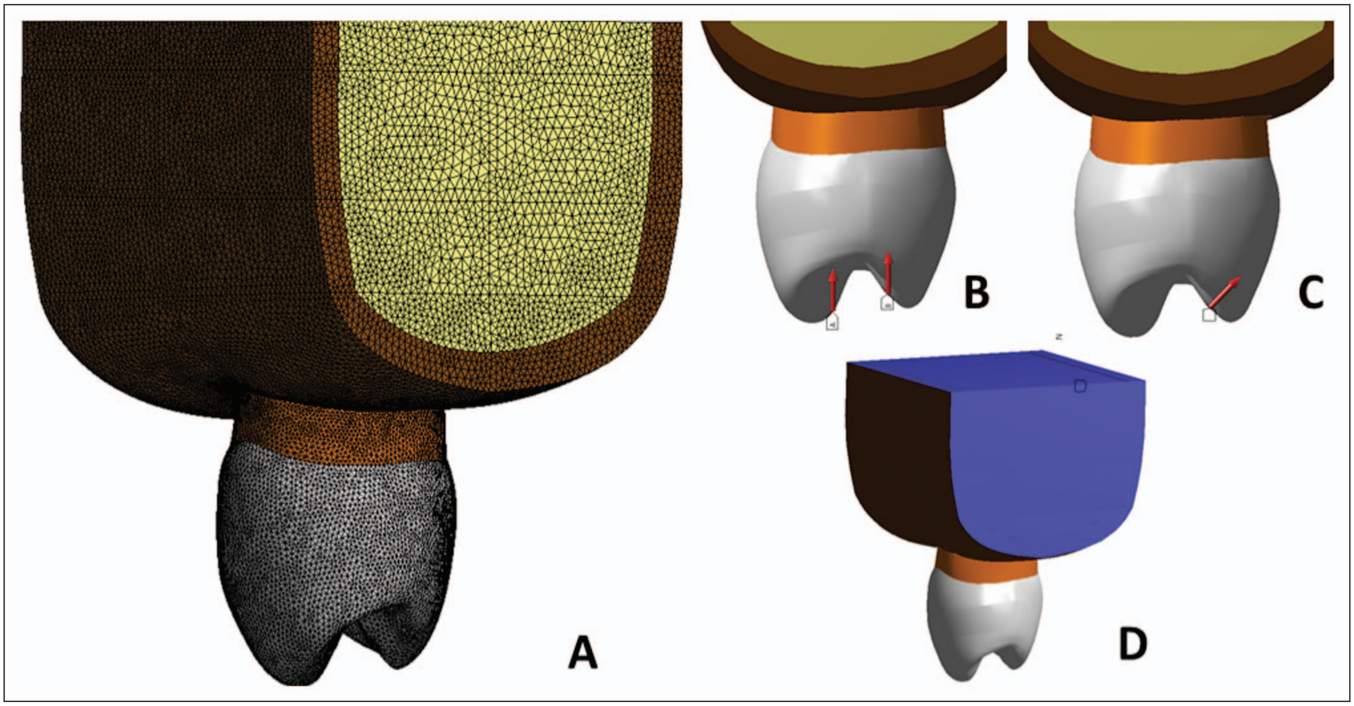

Figure 2. *3D-FEA model generation and boundary conditions. (A): Meshing of the models. (B): Axial loading. (C): Oblique loading. (D): Displacement restriction (null displacement in the blue area).*

consent approved by the Committee for Ethics in Research: No. 539.002). Teeth of similar size and shape were selected by crown dimensions after measuring the bucco-lingual and mesio-distal widths in millimeters, allowing a maximum deviation of 10% from the determined mean, providing greater standardization of samples. The roots of the specimens were covered with a 0.2-mm layer of polyether-based impression material (Impregum Soft, 3M ESPE, St Paul, MN, USA) and embedded in a polystyrene resin cylinder, simulating the periodontal ligament and alveolar bone, respectively.[41]

One strain gauge (PA-06-038AB-120LEN, Excel Sensors, São Paulo, SP, Brazil) was positioned parallel to the long axis at the buccal surface of the tooth, 2.0 mm above the CEJ. The base material of the gauges consisted of a polyimide and metal constantan film, with temperature self-compensation for steel, and the strain gauge grid had an area of 1 mm^2 and electrical resistance of 120 Ω. Strain gauges used for this study had a gauge factor of 2.13. The gauge factor is a proportional constant for the electrical resistance variation and strain. For strain gauge attachment, enamel was etched with 35% phosphoric acid (Scotch Bond Etchant, 3M ESPE) for 30 seconds, rinsed with water, and air dried. Then, the strain gauge was bonded to the tooth structure using cyanoacrylate-based adhesive (Super Bonder, Loctite, São Paulo, SP, Brazil) and connected to a data acquisition system (ADS0500IP, Lynx, São Paulo, SP, Brazil). In addition, a control specimen with one strain gauge attached but not subjected to load application was mounted adjacent to the test tooth to compensate for dimensional alterations due to temperature fluctuations from the gauge electrical resistance or local environment.[42]

The 25 sound teeth were subjected to a nondestructive axial (Al) and oblique (Ol) 0- to 150-N ramp-load at 0.5 mm/min, applied using a 4.0-mm diameter sphere and knife-shaped tip, respectively, in a mechanical testing machine (DL 2000, EMIC, São José dos Pinhais, PR, Brazil). All sound specimens were then submitted to 200,000 cycles (2

Table 2: *Number of Elements and Nodes for Each Model*

Model	Nodes	Elements
Sound tooth (SO)	2,473,693	1,709,931
Unrestored NCCL (UN)	2,444,468	1,688,610
Restorative technique with unique material (GI, FR, CR, and LD)	2,475,971	1,710,237
Restorative technique with two materials (CL)	2,479,488	1,711,624

Abbreviations: SO, sound tooth; UN, unrestored noncarious cervical lesions; GI, glass ionomer; FR, flowable composite resin; CR, nanofilled composite resin; LD, lithium disilicate ceramic; NCCL, noncarious cervical lesions; CL, nanofilled composite resin core associated with a lithium disilicate laminate.

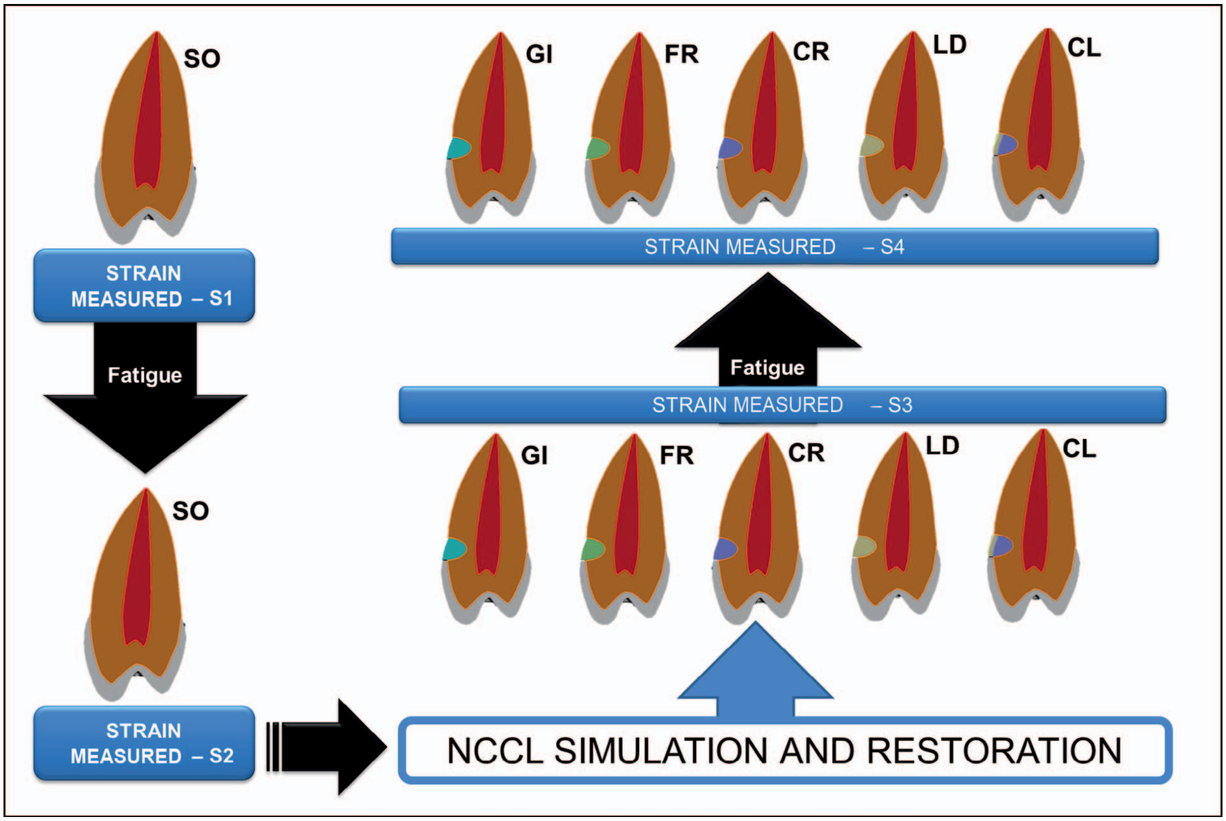

Figure 3. *Strain gauge test and mechanical fatigue scheme.*

Hz) of Ol on the palatine cusps (50 N), simulating approximately 10 months of clinical service.[43] Following mechanical aging, the specimens were resubmitted to Al and Ol up to 150 N, as described before, and the strains were measured (Figure 3).

Then, the strain gauges were removed and saucer-shaped NCCLs were simulated in the buccal wall of all specimens using diamond burs (No. 3118, KG Sorensen, São Paulo, SP, Brazil), creating 2.5-mm deep and 2.5-mm wide cavities. Afterward, the specimens were divided into five groups according to the materials used to restore the NCCLs (n=5): GI, FR, CR, LD, and CL. Selective etching of enamel was performed using 35% phosphoric acid for 15 seconds (Scotch Bond Etchant, 3M ESPE), and a self-etching adhesive system (Scotch Bond Universal, 3M ESPE) was used for hybridization, except with the GI group. The GI (Riva Light Cure, SDI, Victoria, Australia), FR (Filtek Z350 XT Flow, A3 Shade, 3M ESPE), and CR (Filtek Z350 XT, A3 Shade, 3M ESPE) were inserted in 2.0-mm increments, photoactivated for 20 seconds using an LED curing unit (Radii-Call, SDI) with a 1200 mW/cm^2 output, until complete filling of the cavity. For the indirect restorations, impressions of the NCCLs were made using vinyl-polysiloxane (Express, 3M ESPE), and stone casts were poured in type IV dental stone (Durone IV, Dentsply, Petrópolis, RJ, Brazil). For the CL specimens, a composite resin core was built, and after taking impressions and pouring stone casts as described previously, 0.5-mm ceramic laminates were obtained. All LD and CL specimens were restored using lithium disilicate glass-ceramic veneers or laminates, respectively (IPS e.Max Press, MO 1 shade, Ivoclar Vivadent, Schaan, Liechtenstein). The internal surfaces of the ceramic restorations were etched with 9.5% hydrofluoric acid for 20 seconds (Condicionador de Porcelanas, Dentsply). Then, the surfaces were rinsed with water for 30 seconds, and 35% phosphoric acid was applied for 60 seconds (Scotch Bond Etchant, 3M ESPE), followed by water rinsing and air drying. A silane coupling agent (Monobond Plus, Ivoclar Vivadent) was actively applied to the restoration and left to react for 1 minute, followed by luting with a light-cure resin cement (Variolink Veneer, Ivoclar Vivadent) that was light activated for 60 seconds.

New strain gauges (PA-06-038AB-120LEN, Excel Sensors) were then attached to the restorations, as described previously. All restored specimens were again submitted to Al and Ol up to 150 N for strain measurements. Sequentially, specimens were resubmitted to 200,000 cycles (2 Hz) of Ol on the palatine cusp (50 N). Finally, the strain of the specimens was measured for both compressive loading types (Al and Ol) up to 150 N after the second mechanical aging. The strain values were recorded at 4 Hz during the compressive loading, and the data were obtained from strain gauges through data analysis software (AqDados 7.02 and AqAnalisys). The strains were analyzed using a three-way analysis of variance (ANOVA) and a Tukey test for comparisons among study factors and their interactions (Occlusal Loading × Restorative Technique × Mechanical Fatigue). One-way ANOVA and paired *t*-test were used for comparisons between groups before and after restorative procedures (Sound Tooth × NCCL + Restoration). All tests were performed at a 95% confidence level.

RESULTS

The stress distribution for all models under the different restorative conditions and loading directions is presented in Figures 4 through 6. The variation in occlusal loading induced pronounced differences in the stress distribution, regardless of the presence of an NCCL or the restorative material type. For the SO model, Al resulted in homogeneous stress distribution, with no stress peaks located in the tooth structure (Figure 4: SO/Al). Ol resulted in high stress concentrations at the cervical area from the buccal and palatal regions for the SO model, mainly in the dentin and enamel at the CEJ (Figure 4: SO/Ol). The presence of an NCCL changed the stress pattern of the UN model when compared with SO, mainly for the dentin at the bottom of the lesion and in the occlusal wall of enamel (Figure 4: UN/Al). Higher stress concentration was observed when the loss of structure (UN) was combined with Ol (Figure 4: UN/Ol).

Irrespective of the restorative technique and occlusal loading, the replacement of lost tooth tissue with adhesive restorations recovered biomechanical behavior closer to the SO model. For the Al, similar behaviors were verified for all restorative materials (Figure 5). However, when restored models were obliquely loaded on the palatal cusp (Ol), some differences were observed among the restorative materials. The GI model showed lower stress concentration in the restorative material, similar to FR. The LD model presented higher stress concentrations in the restorative material. CR and CL showed similar stress distributions, with biomechanical behavior comparable with the SO model (Figure 6).

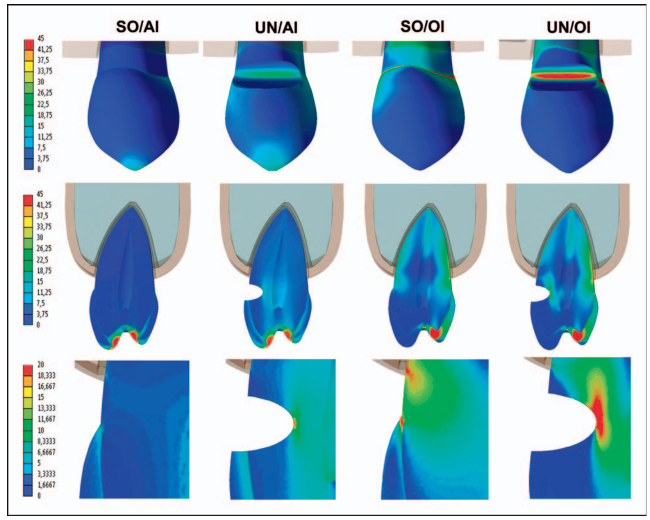

Figure 4. *Stress distribution by von Mises stress for sound tooth (SO) and unrestored NCCL (UN) according to the loading condition: Al, axial loading; Ol, oblique loading.*

The mean strain values for all groups under the different loading conditions are shown in Tables 3 and 4. The deflection of the restorative materials verified by the strain gauge test was significant only for the GI and LD groups, depending on the occlusal loading. Regardless of the restorative material and occlusal loading, strain increased with mechanical fatigue. When comparing the effect of different restorative materials, groups involving restorative techniques with ceramics (LD and CL) showed lower strain values, irrespective of occlusal loading type or fatigue. CR presented intermediate strain values, similar to FR for both Al and Ol. GI showed the highest strain values for Al and Ol, whereas there was no statistically significant difference for the FR group when evaluating Al (Table 3).

When analyzing, by a paired statistics method, the strain of sound tooth samples compared with their respective restored technique group, GI and CR showed higher strain for both occlusal loadings, irrespective of mechanical fatigue. The specimens restored with FR presented similar strain to SO/Ol before fatigue. After cyclic loading, the same specimens showed higher strains. LD presented similar strain to SO, regardless of loading type and fatigue. CL showed lower strains when compared to SO prior to fatigue for both loading types. However, after fatigue, CL showed no differences to the SO group

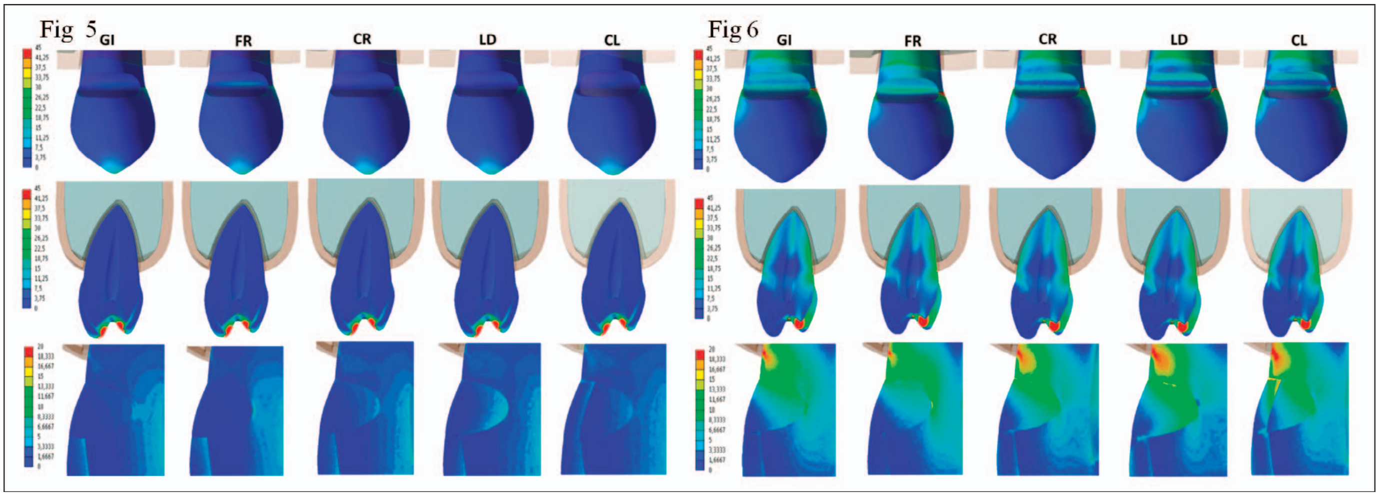

Figure 5. *Stress distribution by von Mises stress with axial loading according to the restorative materials.*
Figure 6. *Stress distribution by von Mises stress with oblique loading according to the restorative materials.*

(Table 4). The FEA strain measurements presented similar patterns when comparing the values obtained experimentally using the strain gauge test before fatigue, validating both methodologies (Figure 7).

DISCUSSION

According to the results, the hypothesis was rejected because the different restorative materials with distinct elastic moduli, different occlusal loading types, and the presence of cyclic loading changed the biomechanical behavior of maxillary premolars affected by NCCLs.

Despite the ease of using direct techniques for restoring NCCLs,[14] etiological factors such as acid degradation and attrition, among others, can also affect direct restorative materials.[15,16] When associated with stress accumulation during function,[17,18] these factors may result in low survival rates for direct restorative procedures in NCCLs.[17,18] Mechanical fatigue increased the strains on the restoration for all materials and loading conditions in the current study. However, when comparing the teeth before (sound) and after restoration following the fatigue process, higher strains were detected for the direct restorative materials, irrespective of loading type. Alternatively, groups restored with indirect materials (LD and CL) presented similar strains when compared with SO after mechanical fatigue.

Another point of concern is related to the surface roughness of direct restorations. The presence of NCCLs may occur concomitantly with root exposure,[44] leading to a strong relationship between gingival tissues and cervical restorations. Thus, restorative techniques using materials with smoother and better surface polishing would favor subsequent periodontal treatment.[32] Indirect ceramic restorations have excellent surface polishing because they are submitted to several polishing steps, in addition to the glazing process, which ensures

Table 3: *Mean Strain Values (μS) and Standard Deviation (SD) Comparing Restorative Technique × Occlusal Loading × Mechanical Fatigue*[a]

Restorative Technique	Oblique Loading		Axial Loading	
	Immediately	Mechanical Aging	Immediately	Mechanical Aging
GI	604.5 (66.5) A,a*	825.3 (172.7) A,b*	363.3 (163.7) A,a	442.4 (171.3) A,b
FR	290.1 (74.5) B,a	410.4 (121.2) B,b	265.2 (83.5) AB,a	324.9 (16.2) AB,b
CR	233.2 (57.3) B,a	315.5 (92.0) B,b	188.0 (45.0) B,a	272.8 (92.0) B,b
LD	156.4 (61.5) C,a*	180.4 (47.9) C,b*	63.7 (15.1) C,a	81.6 (21.6) C,b
CL	85.6 (22.2) C,a	109.1 (31.0) C,b	50.8 (13.8) C,a	87.6 (29.0) C,b

Abbreviations: SO, sound tooth; UN, unrestored noncarious cervical lesions;; GI, glass ionomer; FR, flowable composite resin; CR, nanofilled composite resin; ; LD, lithium disilicate ceramic; NCCL, noncarious cervical lesions;CL, nanofilled composite resin core associated with a lithium disilicate laminate.
[a] *Uppercase letters for vertical comparisons (restorative techniques). Lowercase letters for horizontal comparisons (mechanical aging).*
* *Significant influence of the occlusal loading for horizontal comparisons. Three-way analysis of variance and Tukey test;* $p < 0.05$.

Table 4: *Mean Strain Values (μS) and Standard Deviation (SD) Comparing Sound Tooth × NCCL + Restoration*

Restorative Technique	Occlusal Loading	Mechanical Aging	SO Strain	Material Strain	*p* Value
GI	Axial load	Immediately	85.7 (9.6)	363.3 (163.7)	.013*
		Fatigue	150.0 (34.8)	442.4 (171.3)	.016*
	Oblique load	Immediately	254.3 (36.5)	604.5 (66.5)	<.001*
		Fatigue	285.2 (43.9)	825.3 (172.7)	.001*
FR	Axial load	Immediately	75.2 (24.1)	265.2 (83.5)	.010*
		Fatigue	135.0 (38.2)	324.9 (16.2)	<.001*
	Oblique load	Immediately	200.0 (80.5)	290.1 (74.5)	.128
		Fatigue	174.8 (49.3)	410.4 (121.2)	.010*
CR	Axial load	Immediately	93.5 (37.2)	188.0 (45.0)	.003*
		Fatigue	118.1 (76.7)	272.8 (92.0)	.019*
	Oblique load	Immediately	149.2 (36.7)	233.2 (57.3)	.049*
		Fatigue	163.0 (81.0)	315.5 (92.0)	.014*
LD	Axial load	Immediately	90.1 (30.7)	63.7 (15.1)	.07
		Fatigue	103.4 (33.9)	81.6 (21.6)	.143
	Oblique load	Immediately	163.1 (53.4)	156.4 (61.5)	.453
		Fatigue	164.2 (56.9)	180.4 (47.9)	.374
CL	Axial load	Immediately	81.4 (15.5)	50.8 (13.8)	.014*
		Fatigue	138.4 (46.2)	87.6 (29.0)	.103
	Oblique load	Immediately	155.1 (43.1)	85.6 (22.2)	.012*
		Fatigue	244.7 (109.1)	109.1 (31.0)	.058

Abbreviations: SO, sound tooth; UN, unrestored noncarious cervical lesions;; GI, glass ionomer; FR, flowable composite resin; CR, nanofilled composite resin; ; LD, lithium disilicate ceramic; NCCL, noncarious cervical lesions;CL, nanofilled composite resin core associated with a lithium disilicate laminate .
** Significant difference between sound tooth (before) and NCCL + restoration (after). One-way analysis of variance and paired t-test; $p < 0.05$.*

notably smoother surfaces.[45] Improvements in the surface smoothness of direct restorative materials is a constant research subject for glass ionomers and composite resins.[16,21,46] However, direct restorations, especially ionomer-based materials, still present poor surface roughness.[21] On the other hand, direct materials do not damage periodontal tissues if restoration finishing and polishing is performed properly, allowing for a satisfactory restoration and surface roughness.[32]

Occlusal loading influenced the stress distribution and strain patterns. Loading applied on the palatine cusp was the main factor responsible for concentrating stresses in the tooth, especially at the cervical region. Ol also resulted in higher stress concentration on the material when compared with Al. The first condition can clearly represent what happens in clinical situations of teeth with premature contacts, which is relevant for the formation and progression of NCCLs.[8,47] This finding was also verified using the strain gauge test, when specimens were submitted to cyclic loading simulating a nonphysiologic occlusal contact, resulting in higher deformation. The present results support the importance of performing occlusal adjustments prior to restoring NCCLs. Even when NCCLs are already restored, fine adjustments of occlusal contacts should be properly performed to reduce stress concentration in dental structures. Lower stress accumulation at the cervical region and restoring the tooth may benefit the longevity of the selected restorative protocol.[48]

The loss of tooth structure at the cervical area is considered a relevant factor in the modification of the biomechanical behavior of teeth. It is important to observe the mechanical properties of dental tissues and restorative materials when restoring the loss of tooth structure. The ideal material should recover the biomechanical behavior of the lost structure, resulting in a similar mechanical pattern to sound tooth structures.[13,24] Flowable composite resins have been indicated for restoring NCCLs due to their low viscosity, which is commonly obtained by reducing the filler content and/or modifying agents, which facilitates material insertion and adaptation to the cavity walls.[3] However, this material has a low elastic modulus and an increased organic matrix, which promotes lower stress concentration; this tends to increase polymerization shrinkage and result in higher residual shrinkage stress on dental tissues.[49,50]

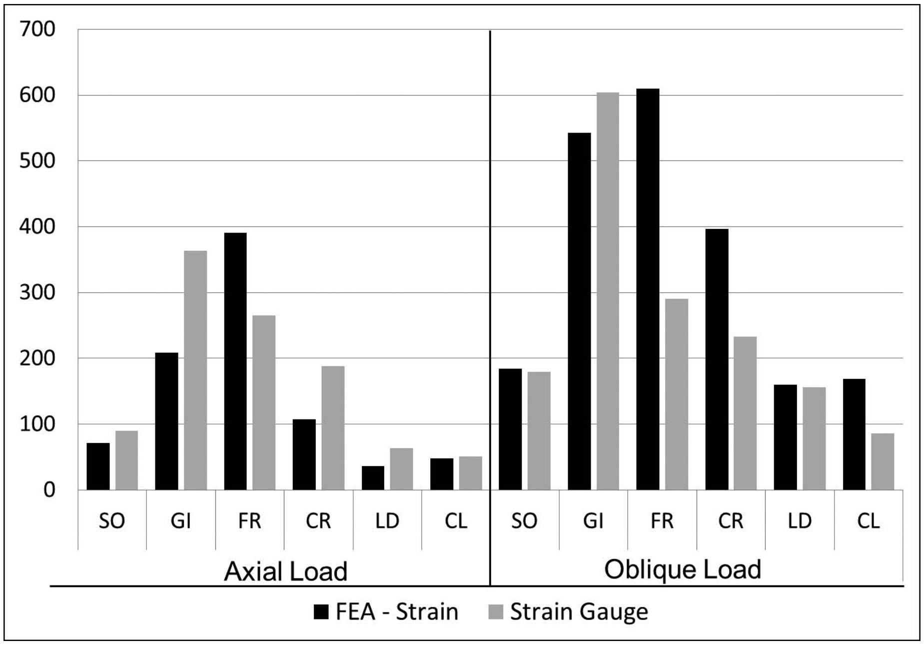

Figure 7. *Strains measured by FEA and strain gauge method on the same region of teeth.*

Glass ionomers and resin-modified ionomers also appear as options for restoring NCCLs because they present adhesion to tooth structures, acceptable biocompatibility and esthetics, and provide a good relationship with dentin hypersensitivity.[48] Glass ionomers have advantages, such as low viscosity, fluoride release, and an easy insertion technique.[14] However, poor strength and hardness are the main disadvantages in using GIs when restoring NCCLs.[51] In addition, FRs and GIs do not present similar mechanical properties when compared with dentin or enamel. These materials are more prone to deformation due to their lower elastic moduli, accumulating lower stress. For this reason, tooth structures can experience higher stress and strain concentration when restored with these materials.

Most conventional composite resins present similar elastic moduli to dentin; adhesive restorations can help to compensate for this stress generated by dental tissue loss.[52] Although widely used, composite restorations present some limitations, such as polymerization shrinkage, marginal discoloration, microleakage, and postoperative sensitivity.[14,19,20] The strain presented by the nanofill composite used to restore NCCLs in this current study was similar to that observed for the flowable composite restorations. The lithium disilicate glass ceramic, unlike composite resins, presented an elastic modulus that was closer to enamel. Because this material is more rigid, the restorations accumulated more stress and did not present high strains. Thus, when NCCLs are restored using only LD, higher stress concentration may occur on the gingival wall of the lesion.

The restorative technique combining composite resin and ceramic for restoring NCCLs is based on the principle of recovering the biomechanical behavior of sound tooth using materials with similar properties to the lost tissues. Therefore, a composite resin core was used, simulating lost dentin, and a thin ceramic laminate was used to simulate enamel in the cervical region. The results for the CL group confirmed this principle, presenting a stress and strain pattern similar to a sound tooth. Despite the excellent results obtained with the association of a composite resin core and ceramic laminate, the use of nanofilled composite resin alone also presented as a good alternative when restoring NCCLs. Moreover, high success rates were observed for NCCLs restored with direct composite restorations,[53] and restorative techniques using ceramics are usually more expensive.

Nondestructive methods are useful for analyzing the biomechanical behavior of teeth associated with dental tissue loss, distinct occlusal conditions, and different restorative materials.[13,54] FEA and the strain gauge test allow for the evaluation of the effects caused by the different treatments during physiological and nonphysiological occlusal situations, analyzing the relation between stress and strains. Thus, different factors can be evaluated in the same specimen, preventing destructive damage.[13,55,56] However, these methodologies present some limitations. For FEA, the use of homogeneous and static models does not consider the consequences of polymerization shrinkage; and the strain gauge test also presents limitations, given that it only performs measurements of deformations on the external surface, without reflecting internal structure deformations. High standard deviations were verified with this technique, due to specimen variability. Because of these limitations, correlation of the methodologies is important for validating the results. Further clinical studies that take into consideration the restorative aspects evaluated in this investigation would be of benefit.

CONCLUSION

Within the limitations of this *in vitro* study, it was concluded that the presence of NCCLs associated with Ol resulted in high stress concentration in the cervical region. Ol was the main factor affecting the biomechanical behavior of teeth with NCCLs. Restorative techniques using materials with similar mechanical proprieties for the replacement of the lost tooth structures showed stress-strain patterns that were similar to sound teeth when subjected to an axial loading.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies. The approval code for this study was #539.002.

Conflict of Interest

The authors declare no conflict of interest.

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