INFLUENCE OF RESTORATIVE TECHNIQUES, LOADING TYPE AND MECHANICAL FATIGUE ON THE BIOMECHANICAL BEHAVIOR OF PREMOLAR WITH CERVICAL LESIONS

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Abstract. *This study aimed to evaluate the stress and strain distribution of 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: SO- sound tooth; UN- unrestored NCCL; or NCCL restored with, GI- glass ionomer; FR- flowable composite resin; CR- nanofilled composite resin; LD- lithium disilicate ceramic; and CL- nanofilled composite resin core associated with a lithium disilicate laminate. A 150 N compressive static load was applied in two conditions: Al- axially in both cusps; and Ol- at 45° angle to the long axis of the tooth applied to the palatine cusp. 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, 50N). 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 loading when compared to Ol loading. The restoration of NCCLs with composite resin only or associated with ceramic laminates seems to be the best approach, since the results for those groups were similar in biomechanical behaviors to sound teeth.*

Key-words*: Finite element analysis, Non Carious Cervical Lesions, Premolar, Restorative materials, Strain gauge test.*

1. 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 (Walter et al., 2014). Cervical wear is classified as a “non-carious cervical lesion” (NCCL), which is a pathological process characterized by loss of dental hard tissues near the cement-enamel junction (CEJ) (Grippo & Coleman, 2012). 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) (Grippo & Coleman, 2012).

Loss of dental structures either by caries, fractures, coronal preparations or non-carious wear is a key factor for altering the biomechanical behavior of teeth (Soares et al., 2008). 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 (Soares et al., 2013). Although several studies have analyzed and described restorative protocols for NCCLs, the literature is still missing deeper investigations considering the effect of different materials and restorative techniques for these lesions (Soares et al., 2013).

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 hypothesis was that the use of different restorative materials with distinct elastic moduli, direction of occlusal loading, and the presence of cyclic loading would not change the biomechanical behavior of maxillary premolars affected by NCCLs.

2. METHODS AND MATERIALS

2.1. 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 medular bones. Fourteen models were generated (Rhinoceros 3D software, Rhinoceros, Miami, FL, USA) simulating: SO- sound tooth, UN- unrestored buccal saucer shaped NCCL; and NCCLs restored with, GI- resin modified glass ionomer; FR- flowable composite resin; CR- conventional nanofilled composite resin; LD- lithium disilicate glass ceramic; and CL- conventional nanofilled composite resin core associated with a 0.5 mm lithium disilicate glass ceramic laminate.

The models were exported using the STEP format to the processing analysis software (ANSYS 12.0, Ansys Workbench 12.0.1, Canonsburg, PA, EUA). The following steps were performed in this software: pre-processing (definition of mechanical properties, volumes, connection types, mesh for each structure, and boundary conditions), processing (data calculation) and post-processing (analysis of results by stress distribution criteria). All dental structures and restorative materials were considered homogeneous and linear elastic. Enamel and dentin were considered orthotropic and the other structures isotropic (Tab. 1).

Table 1. Mechanical properties of orthotropic and isotropic structures.

Structures	**Orthotropic Structures**			**Reference**
	Elastic Modulus (MPa)			(Miura et al., 2009)
	LONGITUDINAL	**TRANSVERSAL**	**Z**	
Enamel	73720	63270	63270	
Dentin	17070	5610	5610	
	Shear coefficient (MPa)			
Enamel	20890	24070	20890	
Dentin	1700	6000	1700	
	Poisson Ratio (v)			
Enamel	0.23	0.45	0.23	
Dentin	0.30	0.33	0.30	
Structures	**Isotropic Structures**			
	Elastic Modulus (MPa)	**Poisson Ratio (v)**		
Flowable Resin	5.3	0.28		Yamand et al., 2003
Glass Ionomer	10.8	0.3		Ichim, et al., 2007
Lithium Disilicate	65.0	0.23		Eraslan et al., 2009
Pulp	2.07	0.45		Rubin et al., 1983
Periodontal Ligament	68.9	0.45		Weinstein et al., 1980
Cortical Bone	13,700	0.30		Carter et al., 1977
Medular Bone	1,370	0.30		Carter et al., 1977
Hybrid Composite Resin	22,000	0.27		Shinya et al., 2008

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 (Fig 1 A). Loading of models (150 N) was applied to specific surfaces previously defined in the CAD software, as follows: Al- Axial loading was equally distributed on both cusps, simulating homogeneous contact distribution; Ol- Oblique loading simulated occlusal interference on the palatine cusp of the model,8 with the load applied at a 45º angle to the long axis of the tooth. Models were restrained at the base and lateral surfaces of cortical and trabecular bone to avoid displacement. Stress distribution analysis was performed using equivalent stress criterion (von Mises); which allows analyze the joint of stress present on the tooth structure and restorative material.

2.2. Strain Gauge Test and Cyclic Loading

For the strain gauge test, twenty-five intact human maxillary single-rooted premolars, free of cracks and defects, were selected (gathered following an informed consent approved by the Committee for Ethics in Research: #539.002).

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 cement-enamel junction. The base material of the gauges consisted of a polyimide and metal constantan film, with temperature self-compensation for steel, the strain gauge grid had an area of $1mm^2$ 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, 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 as a compensator for dimensional alterations due to temperature fluctuations from the gauge electrical resistance or local environment.

The twenty-five sound teeth were subjected to a non-destructive axial (Al) and oblique (Ol) 0-150 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 (2Hz) of oblique loading on the palatine cusps (50N), simulating approximately 10 months of clinical service.

Following mechanical aging, the specimens were re-submitted to axial (Al) and oblique (Ol) loading up to 150 N, as described before, and the strains were measured.

Then, the strain gauges were removed and saucer shape NCCLs were simulated in the buccal wall of all specimens using diamond burs (#3118, KG Sorensen, São Paulo, SP, Brazil), creating 2.5 mm deep and 2.5 mm wide cavities. Afterwards, the specimens were divided into five groups according to the materials used to restore the NCCLs (n=5): GI, FR, CR, LD and CL.

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 axial (Al) and oblique (Ol) loading up to 150 N for strain measurements. Sequentially, specimens were re-submitted to 200,000 cycles (2Hz) of oblique loading 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).

3. RESULTS

3.1. Finite Element Analysis

The stress distribution for all models under the different restorative conditions and loading directions is presented in Figs. 1 and 2. The variation in occlusal loading induced pronounced differences in the stress distribution, regardless of the presence of an NCCL or restorative material type (Figs. 1 B and 2). Irrespective of the restorative technique and occlusal loading, the replacement of lost tooth tissue with adhesive restorations recovered biomechanical behavior closer to SO model. However, when restored models were obliquely loaded on the palatal cusp (Ol), some differences were observed among the restorative materials (Fig. 2).

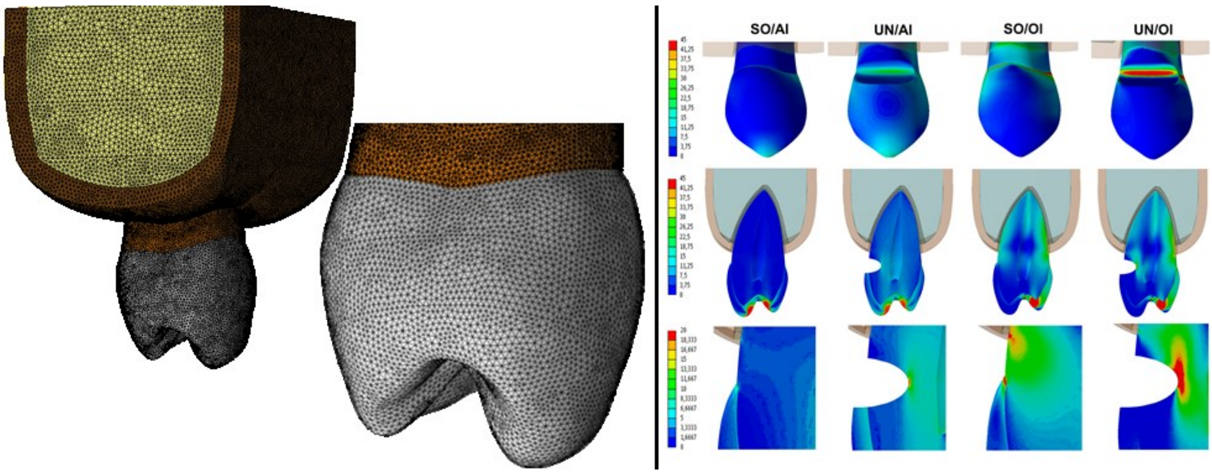

Figure 1. A. Mesh of the structures. B. Stress distribution by von Mises stress for Sound tooth (SO) and Unrestored NCCL (UN) according to the loading condition: Al- Axial loading; and Ol- Oblique loading.

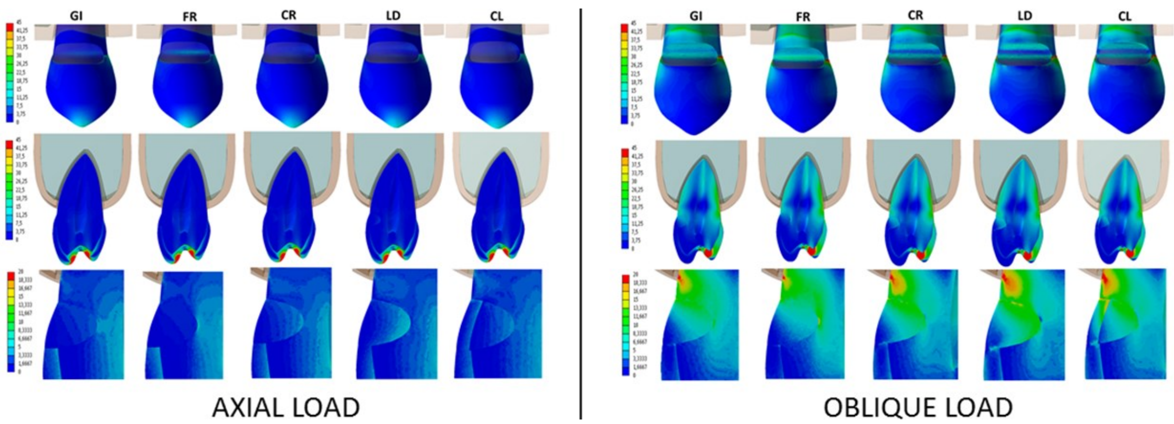

Figure 2. Stress distribution by von Mises stress with axial ando oblique loading according to the restorative materials.

3.2. Strain Gauge Test and Cyclic Loading

The mean strain values for all groups under the different loading conditions are shown in Tables 2 and 3. Regardless of the restorative material and occlusal loading, strain increased with mechanical fatigue. CR presented intermediate strain values, similar to FR for both Al and Ol loading. GI showed the highest strain values for Al and Ol, whereas there was no statistically significant difference for the FR group when evaluating Al (Tab. 2). When comparing the strains of the restored groups to the SO 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 (Table 3).

Table 2. Mean strain values (µS) and standard deviation (SD) comparing: Restorative technique X Occlusal loading X Mechanical Fatigue.

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}

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's Test; p<0.05).

Table 3. Mean strain values (µS) and standard deviation (SD) comparing: Sound tooth X 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)	0.013*
		Fatigue	150.0 (34.8)	442.4 (171.3)	0.016*
	Oblique Load	Immediately	254.3 (36.5)	604.5 (66.5)	<0.001*
		Fatigue	285.2 (43.9)	825.3 (172.7)	0.001*
FR	Axial Load	Immediately	75.2 (24.1)	265.2 (83.5)	0.010*
		Fatigue	135.0 (38.2)	324.9 (16.2)	<0.001*
	Oblique Load	Immediately	200.0 (80.5)	290.1 (74.5)	0.128
		Fatigue	174.8 (49.3)	410.4 (121.2)	0.010*
CR	Axial Load	Immediately	93.5 (37.2)	188.0 (45.0)	0.003*
		Fatigue	118.1 (76.7)	272.8 (92.0)	0.019*
	Oblique Load	Immediately	149.2 (36.7)	233.2 (57.3)	0.049*
		Fatigue	163.0 (81.0)	315.5 (92.0)	0.014*
LD	Axial Load	Immediately	90.1 (30.7)	63.7 (15.1)	0.07
		Fatigue	103.4 (33.9)	81.6 (21.6)	0.143
	Oblique Load	Immediately	163.1 (53.4)	156.4 (61.5)	0.453
		Fatigue	164.2 (56.9)	180.4 (47.9)	0.374
CL	Axial Load	Immediately	81.4 (15.5)	50.8 (13.8)	0.014*
		Fatigue	138.4 (46.2)	87.6 (29.0)	0.103
	Oblique Load	Immediately	155.1 (43.1)	85.6 (22.2)	0.012*
		Fatigue	244.7 (109.1)	109.1 (31.0)	0.058

* Significant difference between sound tooth (before) and NCCL + restoration (after). (One-way analysis of variance and paired t-test; p<0.05)

3.3. Finite Element Analysis (Strain)

The FEA strain measurements presented similar patterns when comparing the values obtained experimentally using the strain gauge test before fatigue, validating both methodologies (Fig. 3).

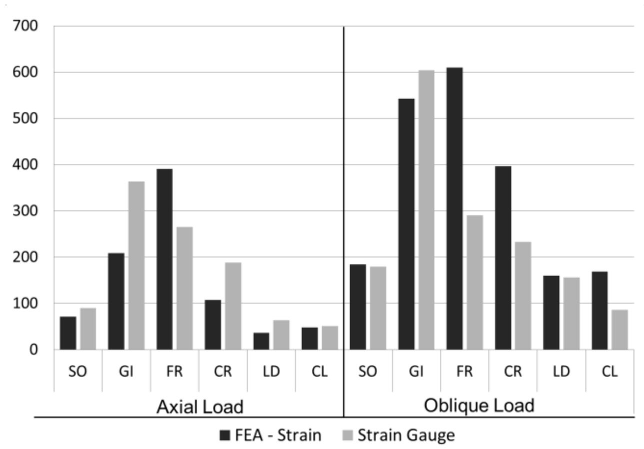

Figure 3. Strains measured by FEA and Strain gauge method on the same region of teeth.

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6. ACCOUNTABILITY OF INFORMATION

All the authors are responsible for the information include on this paper.