Effect of restorative technique and load type on biomechanical behavior of maxillary premolar with non-carious cervical lesions

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Abstract. *The aim of this study was investigate the biomechanical behavior on premolars, according to three factors: restorative technique; direction of occlusal loading and; mechanical fatigue.*
Materials and Methods: 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 2mm below of cementum-enamel junction (CEJ), to record dentin strains before and after mechanical fatigue (200,000 cycles, 50N).
Results: Ol concentrate higher tensile stress and strain than Al. Non-restored NCCL presented increased stress and strain pattern. CR and CL showed greater stress distribution on the same pass that they were resistant to fatigue.
Conclusion: The tooth structures were lower damaged when the NCCLs restored with CR or CL. Ol and mechanical fatigue promote higher stress/strain concentration.

***Key-words**: Biomechanical Behavior, Finite Element Analysis, Mechanical Fatigue, Non Carious Cervical Lesions, Premolar, Restorative Materials.*

1. INTRODUCTION

The non-carious cervical lesions (NCCL) are multifactorial pathological process, unrelated to dental caries, characterized by the loss of dental hard tissue near the cement-enamel junction (CEJ). The factors associated with this process are stress, friction and biocorrosion (Grippo et al., 2012). The dental tissue on the cervical region is very vulnerable, because the enamel on this region is very thin and cementum and dentin are not resistant to the NCCL etiological factors (Walter et al., 2014). In addition, varying the position of the occlusal load, it results on marked variations on the stress distribution patterns on the cement-enamel junction (Rees, 2002).

The management of NCCL may be multifactorial, and it is important consider the dental structure loss replacement, occlusal analysis and patients instructions (Kim et al., 2009). The most commonly restorative material used for NCCL are composite resin (Kim et al., 2009), glass ionomer (Ichim et al., 2007) and flowable resin (Peres, 2010). However, the survival of these restorations can be undermined by external factors such as compression and tensile stress caused during the masticatory strength (Heymann et al., 1991), chemical degradation and attrition (da Silva et al., 2013), and shrinkage stress (Bicalho et al., 2013). The improvement of adhesive systems and (LI, 2010) and the advent of lithium-disilicate reinforced ceramic enable ceramics to be widely used in dentistry, due to this good mechanical properties and excellent optical properties (Soares et al., 2014).

Nondestructive methods, as finite element analysis (FEA) and strain gauge test are useful to analyze the biomechanical behavior associated with dental tissue loss, different occlusal conditions, and the effects of restorative materials. These permit to evaluate different factors in the same sample, preventing damages to the original specimens (Soares et al., 2013).

The propose of this study was to evaluate the influence of different restorative materials, occlusal loading direction and cyclic load on stress distribution and strain pattern of maxillary premolars by 3D finite element analysis and strain gauge test. The hypothesis is that restorative materials of lower elastic modulus, oblique load and fatigue cyclic load concentrate higher stress and strain in the tooth structure.

2. METHODS AND MATERIALS

2.2. 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.33 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).

Tabela 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[35]	5.3	0.28		Yamand et al., 2003
Glass Ionomer[10]	10.8	0.3		Ichim, et al., 2007
Lithium Disilicate[36]	65.0	0.23		Eraslan et al., 2009
Pulp[37]	2.07	0.45		Rubin et al., 1983
Periodontal Ligament[38]	68.9	0.45		Weinstein et al., 1980
Cortical Bone[39]	13,700	0.30		Carter et al., 1977
Medular Bone[39]	1,370	0.30		Carter et al., 1977
Hybrid Composite Resin[40]	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. Solid quadratic tetrahedral elements of 10 nodes were used. 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 Maximum Principal Stress.

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 1mm2 and electrical resistance of 120 Ω. Strain gauges used for this study had a gauge factor of 2.13 and were 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.43 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. 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.

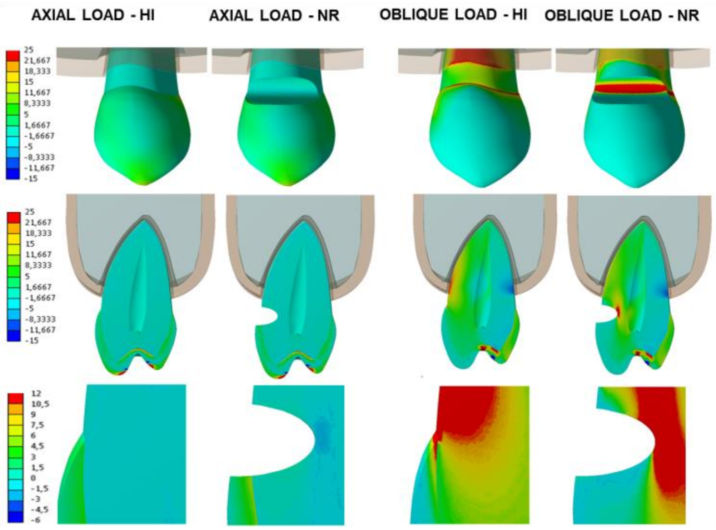

Figure 1. Stress distribution by Maximum Principal Stress for Sound tooth (SO) and Unrestored NCCL (UN) according to the loading condition: Al- Axial loading; and Ol- Oblique loading.

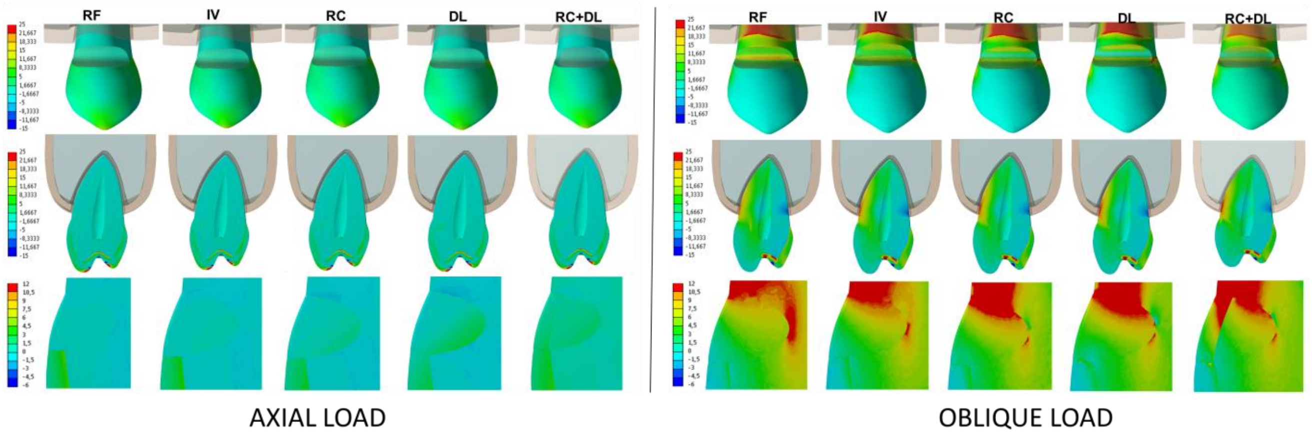

Figure 2. Stress distribution by Maximum Principal Stress with axial and oblique loading according to the restorative materials.

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 (Table 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***
CR	435.58 (121.91) ^{Aa*}	536.71 (172.18) ^{Aa*}	132.03 (44.52) ^{Aa}	171.31 (76.11) ^{Aa}
CL	483.68 (147.76) ^{ABa*}	642.34 (155.97) ^{ABa*}	112.25 (27.47) ^{Aa}	152.00 (35.78) ^{Aa}
FR	643.09 (197.18) ^{BCa*}	830.56 (230.80) ^{BCb*}	94.38 (23.35) ^{Aa}	158.43 (22.50) ^{Ab}
GI	694.08 (202.90) ^{Ca*}	1149.56 (244.82) ^{Cb*}	233.72 (32.14) ^{Ba}	470.53 (118.53) ^{Bb}
LD	786.75 (145.74) ^{Ca*}	882.46 (121.41) ^{Ca*}	155.73 (23.70) ^{Aa}	161.97 (42.07) ^{Aa}

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
NCCL	Axial Load	Immediately	135.57 (19.48)	383.76 (93.59)	0.003*
		Fatigue	200.85 (82.60)	719.60 (109.98)	0.001*
	Oblique Load	Immediately	546.33 (252.57)	912.19 (111.65)	<0.001*
		Fatigue	826.43 (254.78)	1095.30 (172.50)	0.002*
CR	Axial Load	Immediately	100.97 (37.56)	132.03 (44.52)	0.813
		Fatigue	178.27 (35.24)	171.31 (76.11)	0.441
	Oblique Load	Immediately	574.96 (175.49)	435.58 (121.91)	0.037*
		Fatigue	764.84 (310.34)	536.71 (172.18)	0.036*
CL	Axial Load	Immediately	107.76 (30.69)	112.25 (27.47)	0.423
		Fatigue	216.37 (34.66)	152.00 (35.78)	0.018*
	Oblique Load	Immediately	722.81 (266.81)	483.68 (147.76)	0.090*
		Fatigue	935.22 (104.23)	642.34 (155.97)	0.007*
FR	Axial Load	Immediately	110.82 (37.45)	94.38 (23.35)	0.222
		Fatigue	173.39 (26.90)	158.43 (22.50)	0.214
	Oblique Load	Immediately	727.42 (178.96)	643.09 (197.18)	0.209
		Fatigue	760.16 (301.01)	830.56 (230.80)	0.113
GI	Axial Load	Immediately	105.76 (20.23)	233.72 (32.14)	0.001*
		Fatigue	210.63 (76.77)	470.53 (118.53)	0.008*
	Oblique Load	Immediately	783.31 (180.91)	694.08 (202.90)	0.013*
		Fatigue	876.81 (125.63)	1149.56 (244.82)	0.101
LD	Axial Load	Immediately	100.55 (21.72)	155.73 (23.70)	0.019*
		Fatigue	222.81 (59.38)	161.97 (42.07)	0.041*
	Oblique Load	Immediately	597.48 (143.71)	786.75 (145.74)	0.023*
		Fatigue	712.85 (292.09)	882.46 (121.41)	0.163

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

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6. ACCOUNTABILITY OF INFORMATION

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