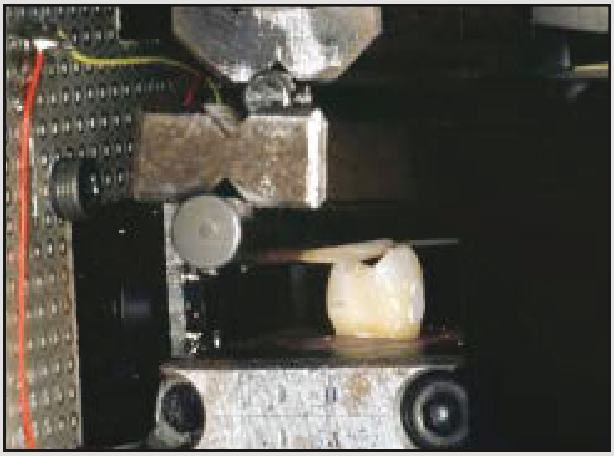
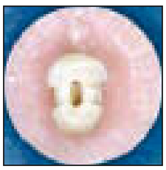


Effect of Restorative, Endodontic, and Fatigue Treatments on the Cuspal Deflection of Maxillary Premolars Subjected to Different Cyclic Occlusal Forces: An In Vitro Study



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This study aimed to determine the effect of adhesive direct composite restorations, endodontic treatments, and fatigue treatments on the cuspal deflection of maxillary premolars subjected to different cyclic occlusal forces. Thirty intact maxillary second premolars were selected. Ten teeth were left untreated (group IN), 10 teeth were subjected to endodontic and restorative treatment (group FL), and the remaining 10 teeth were subjected to endodontic, restorative, and fatigue treatments (group FT). All teeth were subjected to 5 occlusal compressive loading forces (98, 147, 196, 245, and 294 N) with a universal testing device. A total of 15 experimental groups were obtained with 3 tooth conditions (IN, FL, FT) and 5 different occlusal loading values. Deflection amounts (µm) were measured with laser sensors and recorded, and obtained data were statistically analyzed with one-way analysis of variance at a significance level of .05. Mean cuspal deflection values (µm) and SDs of experimental groups ranged as follows: IN-98 (24.4 ± 19.8), IN-147 (34.8 ± 28.9), IN-196 (43.8 ± 34.7), IN-245 (54.5 ± 46.4), IN-294 (60.3 ± 50.6), FL-98 (56 ± 49.1), FL-147 (62.6 ± 49.6), FL-196 (72.4 ± 52.1), FL-245 (81.3 ± 56), FL-294 (92.2 ± 60.9), FT-98 (77.2 ± 80.9), FT-147 (83.4 ± 81.3), FT-196 (92.6 ± 83.7), FT-245 (102.7 ± 85.4), and FT-294 (124.2 ± 89.5). Mean values of three main experimental groups were as follows: IN (43.5 µm), FL (72.9 µm) and FT (96.0 µm). Significant differences were found between the three main groups and relevant subgroups ($P < .001$). Highest cuspal deflection values (CDV) were obtained in FT groups. Lowest CDV were obtained in IN groups. FL groups showed higher deflection values than IN groups. CDV increased progressively as the teeth were restored and subjected to fatigue treatment. (Int J Periodontics Restorative Dent 2015;35:221–229. doi: 10.11607/prd.1802)

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Endodontic treatment causes irreversible changes in the architectural anatomy of teeth. The chemical and mechanical properties of enamel and dentin also are modified.[1–3] Several in vivo,[4,5] ex vivo,[6] and in vitro[7–9] studies have demonstrated that endodontic treatment makes teeth more brittle due to the dehydration of dentin.[10] Loss of soft (pulp chamber) and hard (marginal ridges) tissues due to caries causes an increase in cuspal height and a reduction in the thickness of cavity walls.[11–13] These structural deficiencies may lead to a greater risk of tooth fracture. As reported by Morin et al[14] and Panitvisai and Messer,[15] mesio-occlusodistal (MOD) cavities represent the worst case in terms of fracture risk when nonadhesive (ie, conventional) restorations are employed.

Aspects of endodontically treated and adhesively restored teeth have been investigated in both noninvasive[14,15] and invasive[16] studies with use of different materials and techniques. In a noninvasive study, Panitvisai and Messer[15] found that the cuspal deflection increases as the cavity turns from occlusal to

Table 1 Study group design

Tooth condition (n = 10)	Occlusal loading force applied (N)				
IN	98	147	196	245	294
FL	98	147	196	245	294
FT	98	147	196	245	294

IN = intact; FL = filled with composite resin after endodontic treatment;
FT = filled with composite resin after endodontic treatment and subjected to fatigue treatment.

mesio-occlusal (MO)/occlusodistal (OD) or MOD, and recommended a full crown coverage.

In their in vitro study, Cobankara et al[17] applied cyclic loading on intact mandibular molars until fracture ocurred and reported that restorative materials such as amalgam, direct composite, ceramic inlay, polyethylene ribbon fiber, or composite resin could not adequately compensate for the loss of fracture resistance; however, ceramic inlays gave the best results. A similar result was found in a study of Hitz et al,[18] in which mandibular first molars were subjected to thermal cycling and loaded until failure. They found that the resistance against fracture was lower than that of intact teeth, even in teeth restored with ceramic inlays.

Fatigue is a process involving nucleation, propagation, and coalescence of cracks[19]; however, limited information is available about the behavior of endodontically treated teeth restored with adhesive direct resin composite restorations and subjected to cyclic fatigue treatment.

Thus, the aim of this study was to evaluate the effect of adhesive direct composite restorations, endodontic treatments, and fatigue treatments on the cuspal deflection of maxillary premolars subjected to different cyclic occlusal loading forces. The null hypothesis was that no difference exists in the elastic behavior of endodontically treated teeth restored with MOD restorations after cyclic fatigue treatment.

Method and materials

Assignment of experimental groups

Occlusal surfaces of 30 maxillary second premolar teeth were to be subjected to five different occlusal loading force values (98, 147, 196, 245, 294 N) in three different tooth conditions (n = 10): intact (IN), filled with composite resin after endodontic treatment (FL), and filled with composite resin after endodontic treatment and subjected to fatigue treatment (FT). Thus, a total of 15 experimental groups were obtained (Table 1).

Tooth selection and preparation

A total of 30 human maxillary second premolars were extracted for orthodontic reasons from patients ages 15 to 29 years old who gave informed and signed consent for the study. All selected teeth had similar dimensions, no caries, no restorations, and no cracks that might affect the deflection amount under compressive loading. The teeth were examined visually, radiographically, and by means of transillumination in order to eliminate any defective ones. After being extracted, selected tooth specimens were stored in 0.9% sodium chloride (NaCl) saline solution at 20°C and were kept in that solution during all preparations and testing procedures to prevent dehydration.

Thirty cylindrical resin blocks containing 30 tooth specimens were prepared as follows: *(1)* A cylindrical, open-ended, hollow brass matrix, 3 cm in diameter and 4 cm long, was obtained; *(2)* one of its open-ended sides was placed onto a glass surface and fixed with sticky wax (Dentsply). *(3)* Freshly poured autopolymerizing acrylic resin (Meliodent, Heraeus Kulzer) was injected into the matrix cavity. *(4)* Roots of each tooth specimen were embedded into the resin-filled cylindrical brass matrices 2 mm below the cementoenamel junction (CEJ), with their long axes positioned perpendicular to the horizontal plane.

Embedded tooth specimens were transferred to a milling machine equipped with a parallelometer (Fresart, Artiglio) and smooth surfaces of 3 to 4 mm^2 were formed onto the middle thirds of buccal and lingual surfaces using a cylindrical diamond bur (Fig 1). These surfaces were coated with a thin opaque varnish layer to provide an effective reading for the laser device.

Fig 1 (right) *Smooth surfaces formed onto buccal and lingual sides of tooth specimens.*

Fig 2 *Standardized endodontic access cavity and mesio-occlusodistal cavity preparation.*

Endodontic instrumentation and cavity preparation

Endodontic access cavities were prepared for tooth specimens in the FL and FT groups in a standard configuration. Instrumentation of root canals was performed with nickel-titanium (NiTi) rotary files (ProFile, Dentsply Maillefer), and sodium hypochlorite (NaClO) was used for irrigation. Canal obturation was performed with a vertically condensed gutta-percha technique and with a canal filling paste (Pulp Canal Sealer, Kerr).

Following endodontic procedures, the marginal ridges of all tooth specimens were reduced with a cylindrical diamond bur (Fig 2). The width of the occlusal cavity isthmus was set equal to one-third of the intercuspal distance, and the buccolingual width of each proximal box was equal to one-third of the tooth width. Heights of proximal cavities were set so that the floor of preparation was located 1 mm above the CEJ. Sharp internal edges of the cavities were rounded and no bevel was made on the outer edges of the preparations.

After completion of cavity preparations, tooth specimens were restored with composite resins. Enamel and dentin surfaces of prepared cavities were etched with 36% orthophosphoric acid (DeTrey Conditioner 36, Dentsply) for 40 and 20 seconds, respectively. Etched surfaces were thoroughly rinsed with abundant water spray and gently dried with air spray. The one-bottle light-curing total-etch bonding system (XP Bond, Dentsply) was applied onto etched surfaces and light cured (Swiss Master Light, EMS) for 20 seconds with a light intensity of 800 mW/cm^2.

A thin layer of flowable composite resin (Esthet-X flow, Dentsply) was applied onto the cavity floor as a build-up material and light cured as previously described for the bonding agent. Cavity margins were refined with fine-grit burs to eliminate excess flowable composite. Self-locking matrices (Automatrix, Dentsply) were attached around tooth specimens, and the cavities were filled with microhybrid composite resin (Esthet-X HD, Dentsply) using an incremental layering technique. Each resin layer with a maximum thickness of 2 mm was light cured as previously described for the bonding agent. Completed restorations were finished and polished with PoGo polishers (Dentsply). All specimens were stored in a physiologic saline solution for 24 hours.

Cyclic fatigue treatment procedure

The fatigue treatment procedure in group FT was performed using a custom-made device consisting of a water chamber at 37°C. Cyclic forces varying between 10 and 200 N were applied onto occlusal surfaces of tooth specimens (50,000 cycles) at 2 Hz frequency level.

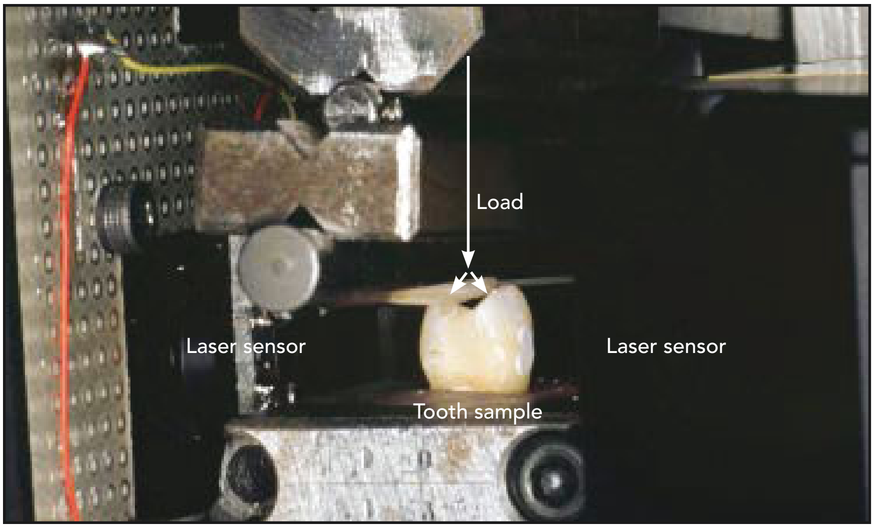

Fig 3 *Loading procedure with universal testing machine and custom-made joint.*

Table 2 Mean cuspal deflection values of experimental groups

	Mean cuspal deflection (µm) ± SD		
Load (n)	**Intact**	**Filled**	**Fatigue treated**
98	24.4 ± 19.8	56.0 ± 49.1	77.2 ± 80.9
147	34.8 ± 28.9	62.6 ± 49.6	83.4 ± 81.3
196	43.8 ± 34.7	72.4 ± 52.1	92.6 ± 83.7
245	54.5 ± 46.4	81.3 ± 56.0	102.7 ± 85.4
294	60.3 ± 50.6	92.2 ± 60.9	124.2 ± 89.5

Loading procedure

A universal testing machine (Instron 1195; Instron) was used to apply compressive loads to occlusal surfaces of tooth specimens (Fig 3). The resin blocks comprising tooth specimens were placed and clamped perpendicular onto the horizontal plane of the machine. A cylindrical stainless steel bar was fixed at the removable upper piece of the machine. The bar and the resin blocks were uniaxially positioned so that the side of the bar simultaneously contacted the lingual slopes of buccal cusps and the buccal slopes of lingual cusps of tooth specimens. Five different loading forces (98, 147, 196, 245, and 294 N) were respectively applied onto occlusal surfaces of 30 tooth specimens.

Measurement of cuspal deflection

The cuspal deflection was measured by means of a laser sensor system (Laser Twin Sensor, LMI Technologies). Two laser beams were simultaneously directed to the buccal and lingual sides of tooth specimens just onto the smoothed surfaces coated with an opaque varnish layer (OVL). The OVL served as a guide plane for avoiding measurement errors due to the fact that laser beams can penetrate the opalescent enamel layer. Deflections values were measured 10 seconds after load was applied to obtain the stabilization of deflected cusps, and the sum of both buccal and lingual cusp deflection amounts were recorded for each tooth. Deflection measurements were repeated for each loading force, and obtained length values (µm) were recorded.

Statistical analysis

Data obtained from testing were analyzed with the SPSS 15.0 for Windows statistical software program (SPSS). The analysis of variance (ANOVA) test was used to determine differences among groups. Differences were considered statistically significant at a confidence level of 95% ($P < .05$).

Results

Mean cuspal deflection values (µm) and SDs of experimental groups are presented in Table 2. Descriptive statistics (mean, maximum, minimum, and SDs) are depicted in Table 3. Comparisons among groups using ANOVA are presented in Table 4. Graphic charts of 15 experimental groups and 3 main groups are shown in

Table 3 Descriptive statistics of experimental groups

Descriptive statistics split by load (N)	Mean (µm)	SD	Standard error	Minimum	Maximum	No. missing
Intact, total	43.565	38.142	6.031	1.453	156.100	0
Intact, 98	24.392	19.815	7.006	1.453	50.600	0
Intact, 147	34.839	28.859	10.203	4.652	82.500	0
Intact, 196	43.789	34.707	12.271	10.114	90.000	0
Intact, 245	54.489	46.360	16.391	12.910	138.900	0
Intact, 294	60.316	50.616	17.896	15.940	156.100	0
Filled, total	72.906	52.566	8.311	4.970	178.250	0
Filled, 98	55.996	49.071	17.349	4.970	144.700	0
Filled, 147	62.560	49.633	17.548	8.900	149.540	0
Filled, 196	72.439	52.114	18.425	12.800	155.440	0
Filled, 245	81.344	56.020	19.806	16.000	170.000	0
Filled, 294	92.189	60.941	21.546	23.420	178.250	0
Fatigue, total	96.006	81.539	12.892	8.900	307.000	0
Fatigue, 98	77.167	80.931	28.613	8.900	261.200	0
Fatigue, 147	83.385	81.328	28.754	12.700	267.100	0
Fatigue, 196	92.591	83.722	29.600	19.500	277.600	0
Fatigue, 245	102.657	85.443	30.209	23.010	291.600	0
Fatigue, 294	124.229	89.478	31.635	26.880	307.000	0

Table 4 Analysis of variance performed between experimental groups (95% confidence interval)

	Sum of squares	Mean square	F	*P*	Lambda	Power
Load	23,572.424	5,893.106	0.625	.6475	2.502	0.182
Subject (group)	329,781.532	9,422.329	–	–	–	–
Category for cuspal deflection	55,260.749	27,630.374	27.771	< .0001	55.543	1.000
Category for cuspal deflection * load	799.755	99.969	0.100	.9991	0.804	0.076
Category for cuspal deflection * subject	69,644.697	994.924	–	–	–	–

Figs 4 and 5, respectively. Obtained values ranged as follows: IN-98 (24.4 ± 19.8), IN-147 (34.8 ± 28.9), IN-196 (43.8 ± 34.7), IN-245 (54.5 ± 46.4), IN-294 (60.3 ± 50.6), FL-98 (56 ± 49.1), FL-147 (62.6 ± 49.6), FL-196 (72.4 ± 52.1), FL-245 (81.3 ± 56), FL-294 (92.2 ± 60.9), FT-98 (77.2 ± 80.9), FT-147 (83.4 ± 81.3), FT-196 (92.6 ± 83.7), FT-245 (102.7 ± 85.4), and FT-294 (124.2 ± 89.5). Mean values of the three main experimental groups were as follows: IN (43.5 µm), FL (72.9 µm), and FT (96.0 µm). Significant differences were found among three main groups and relevant subgroups ($P < .001$; Table 4).

Discussion

Posterior teeth deflect under compressive loading due to their structural design. Endodontic access cavities and loss of proximal walls due to caries, especially in MOD cavities,[13,15,20] may increase their tendency to deflect under chewing

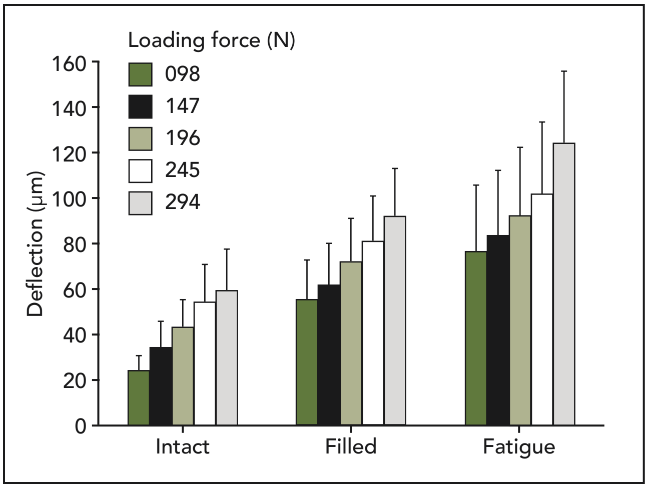

Fig 4 *Cell bar chart presenting mean deflection values of 15 experimental groups, split by loads.*

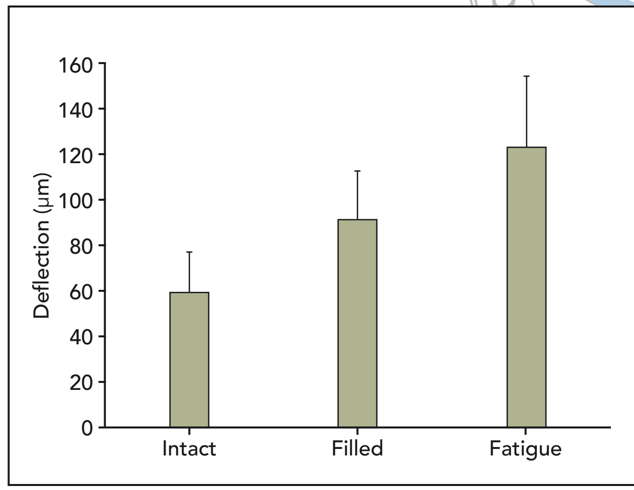

Fig 5 *Cell bar chart presenting mean deflection values of three main experimental groups under maximum load.*

forces. Coronal restorations preventing residual tooth structures from such stresses are highly recommended.

In the past, full-crown coverage was indicated as the gold standard for postendodontic restoration treatment.[21,22] Contrary to nonadhesive restorative materials, which require full cuspal coverage, minimally invasive and conservative adhesive materials or restorations have become increasingly popular in actual restorative dentistry.[23]

Little is known about the long-term behavior of restorations, since acrylic resin-tooth interfaces are vulnerable to progressive damage by occlusal loads, as was substantiated by scanning electron microscopy analyses revealing typical fatigue fracture patterns.[24] *Fatigue* can be defined as the failure of mechanical properties after repeated applications of stress, at a level well below the ultimate fracture strength of the material or interface.[19,24,25]

In most in vitro studies, destructive methods are used[9,11,25,26] to evaluate the resistance of the tooth-restoration complex. Nevertheless, the anatomical variability may strongly influence the results of such investigations due to the size and morphology differences of natural teeth. In vitro fractures induced by compressive loading in adhesively restored teeth may occur with values ranging from 302 to 502 N.[16] There is little accordance in the literature about biting forces because a wide range of clenching force values are reported,[27] ranging from 338 N[28] to 720 N[29] up to 1,221 N,[30] whereas older studies report lower values between 13 and 66 N[31] up to a maximum of between 147 and 261 N.[32,33] However, some authors[25] suggest that tooth fracture seems to occur mostly due to a fatigue phenomenon: Over time, repeated stress can greatly reduce the resistance to fracture, even under forces far below the loading force normally required to break a healthy tooth.[24,34]

Nowadays, several in vitro studies about postendodontic restorations are available in the literature with both destructive[17,18,35] and nondestructive[15,36,37,40] techniques. Some interesting clinical trials[12,40] also were carried out to assess the reliability of adhesive techniques and materials comparing them with the traditional prosthetic procedures. Measurements of cuspal deflection under load have been used in order to investigate both polymerization shrinkage[41] and the mechanical properties of the tooth-restoration complex.[1,15,36,37,40]

In particular, the evaluation of nondestructive evaluation of teeth deflection in terms of cuspal deflection under axial load seems to be a valuable method for predicting the capacity of the tooth-restoration complex to withstand intraoral stresses. The rationale for this approach is that, since there is a linear relationship between fatigue and static loading,[41,42] the lower the amount of deflection, the lower the fatigue of the tooth-restoration complex and the better the prognosis.[43]

The present study focused on the last aspect to assess differences of postendodontic adhesive restorations immediately after placement and after cyclic fatigue treatment, to provide information about the changes in mechanical behavior of the tooth-restoration complex over time. The original nondestructive protocol employed in the present study adopted a load range between 98 and 294 N, which is similar to the range normally registered under physiological condition for maxillary premolars.[36] Maxillary premolars were selected for the present study because they hold the highest risk of fracture, as reported in the literature.[40] Since cuspal deflection was tested on the same tooth samples in condition of integrity and following endodontic treatment/coronal restoration, the variability bias from tooth to tooth was eliminated or strongly reduced.[15,36,371]

Several papers[1,5,7,14,15,36,38,40] reported a remarkable difference in static load resistance between sound teeth and restored ones, so a restricted number of samples was considered sufficient to assess the null hypothesis.

According to the selected method of measurement, small flat surfaces were created on the buccal and lingual sides of each sample to enable the laser beams to measure more accurately each cuspal displacement without being misled by tooth anatomy. Otherwise, the convex shape of tooth surfaces could have caused unreliable data following a possible vertical micromovement of the tooth during load. Total deflection was recorded as the sum of the deflection of both cusps, without considering the concept of "cuspal independence" reported by Sakaguchi et al.[45]

The preparation of endodontic access cavities by removing marginal ridges was meant to simulate the worst condition for the prognosis of the teeth. However, no deflection test was performed on open MOD cavities, as the weakening of cusps was reported several times in the literature.[5,9,14,15,40,43] Such a test could have led to a great loss of samples without being really significant.

The flowable composite layer was used to reduce polymerization shrinkage on residual cusps.[41] The 24-hour delay in deflection testing after endodontic and restorative treatments was meant to let the restorations complete their polymerization reactions and settle the stress of composite contraction.

Load application followed the long axis of the tooth in order to simulate the normal occlusal relationship of maxillary second premolars with their antagonist teeth and to standardize as much as possible the test conditions. In addition, since deflection was studied to investigate fatigue, angulated load was avoided, as it was less likely to occur in the oral cavity than axial load.

The results obtained in the present study indicate an increase in deflection under compressive load in all endodontically treated and adhesively restored teeth compared to the intact ones. Greater deformation values were found after mechanical fatigue treatment. Standard deviation values were quite high compared to the mean deflection values, as a consequence of anatomical variability: Each tooth actually reacts differently under load, depending on its size, morphology, and age.

All restored teeth deflect more than the intact ones; bonded coronal restorations then contribute to partly recover the initial properties. Such an increase in cuspal deflection was smaller immediately after restoration placement, and the differences between the groups are greater at higher load values. Significant differences were found between the three experimental conditions. This fact can be related to the different mechanical properties (ie, e-modulus) of dental tissues versus composite material and to the formation of microcracks as load was applied repeatedly.[19]

Comparing the results of previous similar studies,[5,15,38,39,43] slight differences in deflection values can be found. A variety of factors involved may contribute to this fact, such as different types of deflection sensors (strain gauges or differential transformers versus laser sensors), load range, load application mode, restorative material, and MOD preparation design. The results are comparable to those obtained in similar studies[36,37] with different composite materials.

Although data comparison with similar studies is difficult, the study by Cobankara et al[17] confirmed a lower fracture resistance after cyclic loading treatment in teeth restored with ceramic or composite materials compared to intact ones, concluding that the most interesting option was represented by ceramic inlays. Analogous results were observed by Hitz et al[18] in a similar study. Different conclusions were drawn in a work by Kuijs et al,[46] in which ceramic and direct and indirect composite employed in the replacement of maxillary premolar cusps were compared by measuring the fracture load after fatigue treatment. The three materials performed in a similar way, suggesting that the treatment choice should be based on criteria other than fatigue resistance.

Fennis et al[47] compared the response to fatigue of composite restorations in premolars with a MOD cavity and a simulated buccal fracture, with or without lingual cuspal coverage. Although the group with cuspal coverage showed better survival rates against fatigue, the fractured specimens of this group were mostly unrepairable due to cracked ends below the CEJ. The authors suggested caution in reducing residual cusps.

The cuspal deflection values obtained in restored teeth might provide ideas in the selection of actual adhesive systems and composite materials as alternatives to prosthetic solutions, even in borderline situations such as postendodontic MOD cavities. Even if deformation values become greater after fatigue treatment, restorations appear to be able to withstand the stress during function.

Further investigations are needed to assess the behavior of composite or ceramic inlay restorations under compressive forces. The results of the present in vitro study should be confirmed in clinics by monitoring the behavior of tested restorative materials in randomized clinical trials.

Conclusions

The highest cuspal deflection values (CDVs) were obtained in the FT groups. The lowest CDVs were obtained in the IN groups. FL groups showed higher deflection values than IN groups. CDVs increased progressively as the teeth were restored and subjected to fatigue treatment.

Acknowledgments

The authors reported no conflicts of interest related to this study.

References

1. González-López S, De Haro-Gasquet F, Vílchez-Díaz MA, Ceballos L, Bravo M. Effect of restorative procedures and occlusal loading on cuspal deflection. Oper Dent 2006;31:33–38.
2. Huang TJ, Schilder H, Nathanson D. Effect of moisture content and endodontic treatment on some mechanical properties of human dentin. J Endod 1992;18:209–215.
3. Sedgley CM, Messer HH. Are endodontically treated teeth more brittle? J Endod 1992;7:332–335.
4. Cavel WT, Kelsey WP, Blankenau RJ. An in vivo study of cuspal fracture. J Prosthet Dent 1985;53:38–42.
5. Hansen EK. In vivo cusp fracture of endodontically treated premolars restored with MOD amalgam or MOD resin filling. Dent Mater 1988;4:169–173.
6. Vire DE. Failure of endodontically treated teeth: Classification and evaluation. J Endod 1991;17:338–342.
7. Howe CA, McKendry DJ. Effect of endodontic access preparation on resistance to crown-root fracture. J Am Dent Assoc 1990;121:712–715.
8. Lewinstein I, Grajower R. Root dentin hardness of endodontically treated teeth. J Endod 1981;7:421–422.
9. Wendt SL Jr, Harris BM, Hunt TE. Resistance to cusp fracture in endodontically treated teeth. Dent Mater 1987;3:232–235.
10. Helfer AL, Melnik S, Schilder H. Determination of the moisture content of vital and pulpless teeth. Oral Surg Oral Med Oral Pathol 1972;34:661–670.
11. Burke FJ. Tooth fracture in vivo and in vitro. J Dent 1992;20:131–139.
12. Ferrari M, Cagidiaco MC, Grandini S, De Sanctis M, Goracci C. Post placement affects survival of endodontically treated premolars. J Dent Res 2007;86:729–734.
13. Patel DK, Burke FJ. Fractures of posterior teeth: A review and analysis of associated factors. Prim Dent Care 1995;2:6–10.
14. Morin D, DeLong R, Douglas WH. Cusp reinforcement by the acid-etch technique. J Dent Res 1984;63:1075–1078.
15. Panitvisai P, Messer HH. Cuspal deflection in molars in relation to endodontic and restorative procedures. J Endod 1995;21:57–61.
16. Sorrentino R, Monticelli F, Goracci C, et al. Effect of post-retained composite restorations and amount of coronal residual structure on the fracture resistance of endodontically-treated teeth. Am J Dent 2007;20:269–274.
17. Cobankara FK, Unlu N, Cetin AR, Ozkan HB. The effect of different restoration techniques on the fracture resistance of endodontically-treated molars. Oper Dent 2008;33:526–533.
18. Hitz T, Ozcan M, Göhring TN. Marginal adaptation and fracture resistance of root-canal treated mandibular molars with intracoronal restorations: Effect of thermocycling and mechanical loading. J Adhes Dent 2010;12:279–286.
19. Baran G, Boberick K, McCool J. Fatigue of restorative materials. Crit Rev Oral Biol Med 2001;12:350–360.

20. González-López S, Vilchez Díaz MA, de Haro-Gasquet F, Ceballos L, de Haro-Muñoz C. Cuspal flexure of teeth with composite restorations subjected to occlusal loading. J Adhes Dent 2007; 9:11–15.
21. Abou-Rass M. Post and core restoration of endodontically treated teeth. Curr Opin Dent 1992;2:99–107.
22. Dietschi D, Duc O, Krejci I, Sadan A. Biomechanical considerations for the restoration of endodontically treated teeth: A systematic review of the literature, part II (evaluation of fatigue behavior, interfaces, and in vivo studies). Quintessence Int 2008;39:117–129.
23. Bitter K, Kielbassa AM. Post-endodontic restorations with adhesively luted fiber-reinforced composite post systems: A review. Am J Dent 2007;20:353–360.
24. De Munck J, Van Landuyt K, Peumans M, et al. A critical review of the durability of adhesion to tooth tissue: Methods and results. J Dent Res 2005;84:118–132.
25. Frankenberger R, Krämer N, Petschelt A. Fatigue behaviour of different dentin adhesives. Clin Oral Investig 1999;3:11–17.
26. Belli S, Cobankara FK, Eraslan O, Eskitascioglu G, Karbhari V. The effect of fiber insertion on fracture resistance of endodontically treated molars with MOD cavity and reattached fractured lingual cusps. J Biomed Mater Res B Appl Biomater 2006;79:35–41.
27. Koc D, Dogan A, Bek B. Bite force and influential factors on bite force measurements: A literature review. Eur J Dent 2010;4:223–232.
28. Kogawa EM, Calderon PS, Lauris JR, Araujo CR, Conti PC. Evaluation of maximal bite force in temporomandibular disorders patients. J Oral Rehabil 2006; 33:559–565.
29. Gibbs CH, Anusavice KJ, Young HM, Jones JS, Esquivel-Upshaw JF. Maximum clenching force of patients with moderate loss of posterior tooth support: A pilot study. J Prosthet Dent 2002; 88:498–502.
30. Ferrario VF, Sforza C, Zanotti G, Tartaglia GM. Maximal bite force in healthy young adults as predicted by surface electromyography. J Dent 2004;32: 451–457.
31. De Boever JA, McCall WD Jr, Holden S, Ash M Jr. Functional occlusal forces: An investigation by telemetry. J Prosthet Dent 1978;40:326–333.
32. Anderson DJ. Measurement of stress in mastication. J Dent Res 1956;35: 664–670.
33. Gibbs CH, Mahan PE, Lundeen HC, et al. Occlusal forces during chewing—Influences of biting strength and food consistency. J Prosthet Dent 1981;46: 561–567.
34. Jantarat J, Palamara JE, Messer HH. An investigation of cuspal deformation and delayed recovery after occlusal loading. J Dent 2001;29:363–370.
35. Oskoee SS, Oskoee PA, Navimipour EJ, Shahi S. In vitro fracture resistance of endodontically-treated maxillary premolars. Oper Dent 2007;32:510–514.
36. Cerutti A, Flocchini P, Madini L, Mangani F, Putignano A, Docchio F. Effects of bonded composites vs. amalgam on resistance to cuspal deflection for endodontically-treated premolar teeth. Am J Dent 2004;17:295–300.
37. Acquaviva PA, Madini L, Krokidis A, Gagliani M, Mangani F, Cerutti A. Adhesive restoration of endodontically treated premolars: Influence of posts on cuspal deflection. J Adhes Dent 2011;13: 279–286
38. Reeh ES, Douglas WH, Messer HH. Stiffness of endodontically-treated teeth related to restoration technique. J Dent Res 1989;68:1540–1544.
39. Mannocci F, Bertelli E, Sherriff M, Watson TF, Ford TR. Three-year clinical comparison of survival of endodontically treated teeth restored with either full cast coverage or with direct composite restoration. J Prosthet Dent 2002;88:297–301.
40. Cara RR, Fleming GJ, Palin WM, Walmsley AD, Burke FJ. Cuspal deflection and microleakage in premolar teeth restored with resin-based composites with and without an intermediary flowable layer. J Dent 2007;35:482–489.
41. Reeh ES, Messer HH, Douglas WH. Reduction in tooth stiffness as a result of endodontic and restorative procedures. J Endod 1989;15:512–516.
42. Naumann M, Sterzenbach G, Pröschel P. Evaluation of load testing of postendodontic restorations in vitro: Linear compressive loading, gradual cycling loading and chewing simulation. J Biomed Mater Res B Appl Biomater 2005;74:829–834.
43. Garoushi S, Lassila LV, Tezvergil A, Vallittu PK. Static and fatigue compression test for particulate filler composite resin with fiber-reinforced composite substructure. Dent Mater 2007;23:17–23.
44. Zidan O, Abdel-Keriem U. The effect of amalgam bonding on the stiffness of teeth weakened by cavity preparation. Dent Mater 2003;19:680–685.
45. Sakaguchi RL, Brust EW, Cross M, DeLong R, Douglas WH. Independent movement of cusps during occlusal loading. Dent Mater 1991;3:186–190.
46. Kuijs RH, Fennis WM, Kreulen CM, Roeters FJ, Verdonschot N, Creugers NH. A comparison of fatigue resistance of three materials for cusp-replacing adhesive restorations. J Dent 2006;34:1 9–25.
47. Fennis WM, Kuijs RH, Kreulen CM, Verdonschot N, Creugers NH. Fatigue resistance of teeth restored with cuspal-coverage composite restorations. Int J Prosthodont 2004;17:313–317.