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Loading Standardization of Postendodontic Restorations *In Vitro*: Impact of Restorative Stage, Static Loading, and Dynamic Loading

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Clinical Relevance

Dentists should read scientific papers carefully when searching for evidence for a specific treatment approach regarding postendodontic restoration, since inappropriate methodology may result in misleading clinical recommendations.

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SUMMARY

Objective: The load capability of post-restored endodontically treated teeth (ETT) can be determined at different restorative stages. It was the aim of this study to compare the load capability of ETT at these stages.

Materials and Methods: Maxillary central incisors were divided into 4 groups (n=10) and endodontically treated. Specimens were restored with: (I) only glass fiber posts (GFP); (II) GFP and composite build-up with 2 mm ferrule; (III and IV) with additional adhesively luted all-ceramic crowns. Group (I) to (III) were statically loaded, and group (IV) was exposed to thermomechanical loading (TML) and subsequent static loading.

Results: The lowest median load level of 73 N was determined for group (I). The maximum

median load value of 331 N was found for group (III). The comparison of Fmax [N] of group (I), (II) and (III) revealed significant differences between the groups (p<0.001). The specimens of group (IV) failed at significantly lower load values (p<0.005) as similarly restored specimens of group (III) which were only statically loaded. The stage of restoration and TML loading prior to static loading had a significant impact on fracture patterns (p=0.006).

Conclusion: Every additional restorative step towards a final crown-restored ETT significantly increased the load capability. TML prior to load-to-fracture testing of the complete restorative complex, ie. post, core and crown, significantly decreased maximum load capability.

INTRODUCTION

In vitro studies are a valuable tool to determine mechanical properties of dental restorations and to allow preclinical risk assesment.[1,2] The ability to isolate specific variables in laboratory studies — compared with *in vivo* studies—enables the identification of parameters that are critical for clinical success.[3] Evaluation of load capability and failure mode of postendodontic restorations are commonly used as outcome parameters in *in vitro* studies.[4] Recently, numerous articles have been published investigating load behavior of endodontically treated teeth (ETT), primarily restored with adhesively luted, fiber-reinforced composite post systems.[4,5] *In vitro* tests show a significant influence of different post systems and materials on maximum load capability and failure mode. However, due to the variety of testing conditions, the results of these studies are hard to compare.[5–7] A recently published systematic review highlighted the variations of test parameters existing for *in vitro* testing of postendodontic restorations.[8] The most frequent specimen design was a combination of tooth, post, core buildup, and crown restoration (46%) followed by post-and-core restored specimens without crown (25%). Relevant recommendations derived from these studies can only be drawn when the specimens are finally restored.[9,10] However, the impact of specimen design used *in vitro* (a complex of tooth and post with or without core and with or without crown restoration) on maximum load capability is still not determined.[8]

Due to its efficiency, linear compressive loading until catastrophic failure is commonly used (~60%) to determine load capability of ETT.[8] However, this approach does not consider fatigue or aging, which are essential parameters during intraoral biodegradation of restorations of all kinds. The results and conclusions of quasi-static testing are affected, in part, by unknown variables, and correlations to clinical failure modes are unidentified.[11] Fatigue studies are assumed to be the most relevant source of information regarding the comparison of techniques and materials used for postendodontic restorations.[3] In recent studies, thermomechanical fatigue loads were used for preloading that assessed the meaning of the quasi-static load test. The most popular dynamic load test is the chewing simulation (thermomechanical loading [TML]) introduced originally for wear testing of dental biomaterials.[12] A modification of the thermomechanical protocol with an applied load of 30 N for 1.2 million cycles and simultaneous thermocycling of 10,000 cycles was specified for load testing of postendodontic restorations.[9,13–17]

It is important to note that no generally accepted test standard has been introduced to date for *in vitro* testing of postendodontic restorations. Thus, it was the aim of the present investigation to compare the maximum load capability and the mode of fracture of ETT at different restorative stages of postendodontic reconstruction. The teeth were restored either with a post, post-and-core, or post-and-core plus final crown restoration. The influence of the loading protocol, ie, with or without TML, on load capability of the crowned ETT was evaluated.

The following null hypotheses were assumed: 1) Maximum load capability of ETT is not influenced by the restorative stage; 2) Dynamic loading by TML does not influence load capability of finally crown-restored ETT.

MATERIALS AND METHODS

A total of 40 sound human maxillary central incisors with a minimum root length of 15 mm were selected. Teeth were stored for a maximum of one year in 0.1% thymol solution. To ensure an even distribution of specimen dimension among the experimental groups, the buccolingual and mesial-distal extensions at the cementoenamel junction (CEJ) were measured and the cross-sectional area was calculated as the product of these two parameters. According to these data, teeth were equally allocated to four groups (n = 10). Endodontic treatment was performed by gradual reaming to International Standards Organization size 60 and intermittent rinsing with 2.5% sodium hypochlorite. Roots were filled by the lateral condensation technique with gutta-percha (Roeko, Langenau, Germany) and a sealer (AH 26, Dentsply DeTrey, Konstanz, Germany). The teeth were decoronated perpendicular to the long axis, 1 mm coronal from the most incisal point of the approximal CEJ under continuous water cooling using a diamond bur.

All specimens were blocked out with wax 2 mm below the finish line to imitate biologic width and to ensure a 2-mm ferrule preparation. To simulate a human periodontium, the roots of the teeth were covered with a 0.1-mm-thick layer of autopolymerizing silicone (Anti-Rutsch-Lack, Wenko, Wensselaer, Germany).[13] The teeth were embedded in autopolymerizing acrylic resin (Technovit 4000, Kulzer, Wehrheim, Germany), orienting their long axis facially 135° from the horizontal line.

In all groups, gutta-percha was removed (Gates Glidden burs (Dentsply Maillefer, Tulsa, USA)) leaving at least a 4-mm root canal filling apically. The root canal was prepared with a tapered drill of 1.4-mm maximum diameter (Fiberpoints Root Pins post kit, Schuetz-Dental, Rosbach, Germany) to achieve an intraradicular post length of 8 mm. All specimens received glass-fiber reinforced composite posts (Fiberpoints Root Pins Glass, Schuetz-Dental; diameter, 1.4 mm; length, 13 mm,) luted with a self-adhesive resin cement (RelyX Unicem, 3M ESPE, Seefeld, Germany) without dentin pretreatment. Posts were cleaned using 70% ethanol. The luting composite was filled in the root canal with an elongation tip by slowly pulling out the tip during cement application. Afterward the post was slowly inserted. The post was kept in place pressing the tip of the curing unit on top of the post. Light-curing was performed for two seconds (Optilux light curing unit, Demetron Research Corp, Danbury, CT, USA). Excess material was removed. Final light-curing was performed for one minute. Afterward the following protocols were performed.

Group 1 (Post Only)

The coronal portion of the post with a height of 5 mm was covered with a provisional filling material (Cavit, 3M ESPE). No further treatment was performed.

Group 2 (Post-and-Core)

After post placement, all specimens received a direct core buildup of a height of 5 mm (LuxaCore-Dual, DMG, Hamburg, Germany) using the corresponding bonding system (LuxaBond-Total Etch, DMG) according to the manufacturers' instructions.

Group 3 and Group 4 (Post-and-Core Restored With All-Ceramic Crowns)

The specimens were built up and prepared as in group 2. Twenty all-ceramic crowns (Empress II, Ivoclar Vivadent, Schaan, Liechtenstein) were fabricated in the original dimension of each tooth according to manufacturers' instructions. The crowns were adhesively cemented with a self-adhesive resin cement (RelyX Unicem, 3M ESPE).

Loading Protocol

Specimens of group 4 were exposed to dynamic loading by parallel thermal cycling and mechanical loading (TML; 1.2×10^6 cycles of mechanical loading, 3 mm palatally below incisal edge with a load between 1 and 49 N; 6000 simultaneous thermocycles between +5°C and +55°C for two minutes each in distilled water). The specimens that survived TML and all specimens of groups 1 to 3 were subjected to static linear loading in a universal material-testing machine (Zwick 1446, Roell, Ulm, Germany; cross-head speed of 1 mm/min) at an angle of 135° to tooth axis until failure occurred. Failure was defined as 10% loss of maximum applied force. For even stress distribution, a 0.3-mm-thick tinfoil was positioned between the steel piston and the specimens.

For all specimens, load capability F_{max} [N] was measured. Fracture patterns were recorded after a visual inspection (2.5× magnification).

Statistical Analysis

A nonparametric Kruskal-Wallis test was used, followed by the Mann-Whitney test as post hoc testing to study statistical differences in the maximum load capability F_{max} between the groups.

Fracture lines at or above the crestal bone level were judged as restorable. To test for differences in the fracture behavior—restorable or not restorable—among the groups, the χ^2 test was applied. All tests were two-sided with $\alpha = 5\%$.

RESULTS

Table 1 displays specimen characteristics, cycles until failure, mean load capability values (F_{max}) for all groups, and *p*-values of the statistical analysis. There was an equal distribution of the specimen characteristics within the groups. Thus, an even distribution for the risk to fail during specimen stressing can be assumed. Three specimens of group 4 failed during TML and were included with 0 N for further statistical analysis because no subsequent

Table 1: *Root Size and Length; Cycles Until Failure for TML Group 4 and Load Capability Values After Static Linear Loading for All Groups; n.p. = Not Performed*

Group	n	Cross-Section Area [a] (SD), mm^2	Root Length (SD), mm^2	TCML Early Failure, n	Cycles Until Early Failure, n	F_{max} Median Value (Min/Max), N	P*
1	10	43.4 (4.5)	21.6 (1.6)	n.p.	—	73 (27/92)	A
2	10	43.4 (4.5)	22.5 (2.8)	n.p.	—	132 (85/377)	A
3	10	43.3 (4.6)	22.5 (1.6)	n.p.	—	331 (210/474)	A, B
4	10	43.3 (5.0)	22.9 (1.5)	3	825,847 391,799 391,902	241 (0/289)	B

[a] *at level of CEJ*
* *pairwise comparison* p-*value of* A $\leq$ *0.001;* B = *0.005.*

static linear loading was performable.[18] The number of cycles until failure is shown in Table 1. The F_{max} values among the four groups were significantly different ($p<0.001$) (Figure 2).

The lowest median load level of 73 N was determined for group 1 (post only). The maximum median load value of 331 N was found for group 3 (crown/no TML). The specimens of group 4 (dynamically loaded crown) failed at significantly lower load values ($p<0.005$) than similarly restored specimens of group 3 that were only statically loaded. The comparison of F_{max} [N] of groups 1, 2, and 3 revealed highly significant differences among the groups ($p<0.001$). Due to minimum F_{max} of 0 N in group 4, no significant differences were found among the groups 1, 2, and 4.

The respective fracture patterns are presented in Figure 1. The groups showed a statistically significant difference regarding the type of failure (χ^2: $p=0.006$). All fracture patterns were judged as re-restorable, given that fracture lines were located above the level of simulated crestal bone (Figure 1). In group 1 only bending of the post was observed. The post-and-core group 2 revealed mostly horizontal fractures of the composite core and two oblique fractures at the level of the finishing line palatally

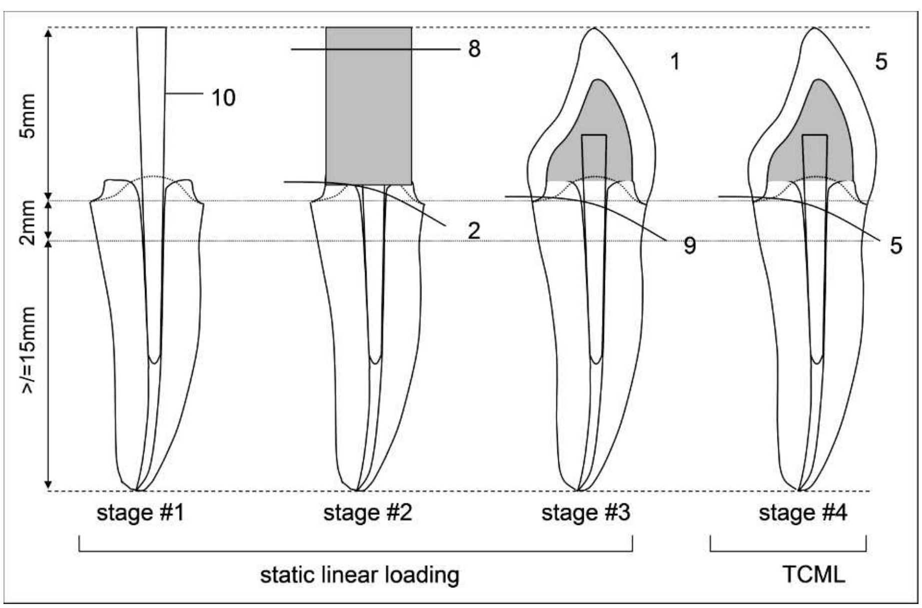

Figure 1. *Sectional view of experimental groups. Fracture lines of the specimens and frequencies of each fracture mode are indicated. Numbers lateral of the crown in groups 3 and 4 indicate crown fracture; interrupted line represents crestal bone level simulation.*

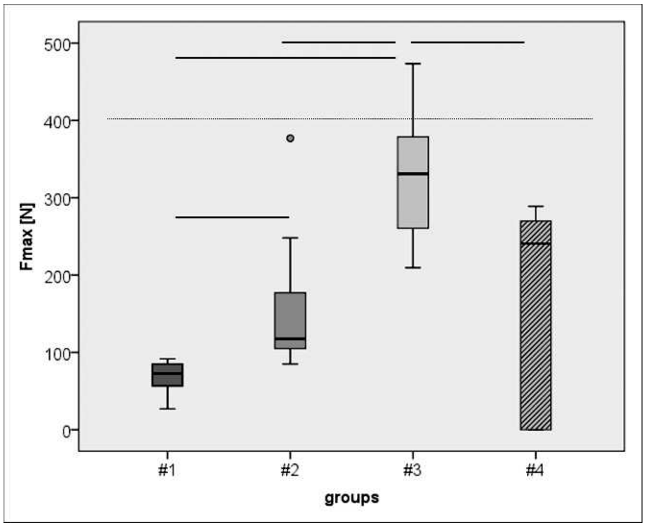

Figure 2. *Box plots illustrate the results of static linear loading (median, 25th and 75th percentiles); only group 4 was dynamically loaded before. Continuous line = p<0.05; interrupted line at 400 N level = maximum bite force observed clinically.*

and close to the simulated crestal bone level facially. In group 3 mainly oblique tooth fractures were found (Figure 3), whereas in group 4 an equal number of crown loosening and oblique fractures were observed. In groups 3 and 4 no glass fiber post fractured.

DISCUSSION

The present *in vitro* study was conducted to evaluate the impact of the restorative stage represented by the tested specimens and the type of loading, ie, dynamic with subsequent linear loading or linear loading only, on the maximum load capability of ETT. Specimens were restored with adhesively luted glass fiber posts only, posts and composite core buildups, or posts and composite core buildups with final crown restorations. The maximum load capability significantly depended on the simulated restorative stage of the restoration and dynamic loading (TML). A 4.5-fold linear increase of the maximum load-to-fracture from 73 N (post) up to a median value of about 331 N (post-and-core with all-ceramic crown restoration) was observed when linear loads were applied. TML prior to linear compressive loading significantly decreased the maximum load capability. Thus, both null hypotheses were rejected. The stage of restoration and dynamic loading (TML) prior to linear compressive loading had a significant impact on load capability and failure modes of post-restored ETT.

Figure 3. *Cross-section of a sample of group 3 with typical fracture line starting on the palatal aspect at the crown margin; after oblique progression of fracture line, the fracture ends facially at the level of crestal bone simulation.*

Human teeth were used because it was shown that substitutes are likely to behave differently in regard to the maximum load capability and mode of fracture.[19,20] Maxillary central incisors are an appropriate model for testing the restorative system in a worst-case scenario.[8] They can be regarded as a high-risk tooth type, given that shear forces in the anterior maxillary region are significantly higher compared with the posterior region.[21,22]

Glass fiber posts were used because *in vitro* and *in vivo* studies document their suitability when a minimum of 2-mm ferrule is provided.[23,24] Moreover, the potential of a self-adhesive cement to effectively bond to root canal dentin has been shown.[25] Esthetic requirements recommend a tooth-colored post system to improve the translucent properties of an all-ceramic crown restoration. In this context the teeth were restored with a well-investigated all-ceramic crown system.[26,27]

The load capability at different stages of post-endodontic restoration of fiber post–restored specimens was also evaluated by Cormier and others.[28] A significant increase of the maximum load values was recorded, starting from the stage of post cementation to the stage of final crown restoration. However, the test condition provided, ie, load angulation, cross-head speed, tooth type, type of fiber post, and absence of TML as dynamic loading, limits the comparability to the present investigation. In accordance with our results, the stage of restoration caused a 2- to ~3.5-times increase of load capability, respectively, when a core buildup or a crown was added to the endodontic post.

To specify the material properties (eg, flexure strength, fracture toughness) of an endodontic post, a three-point loading test is advisable. The test arrangements used for load-to-fracture testing of ETT equates to the one-sided clamped beam test recommended for the determination of the modules of elasticity of small solid samples.[29] The load-bearing capacity, ie, the maximum load capability (F_{max}), is dependent on specimen design such as the lever arm, the specimen diameter and shape, and the moduli of elasticity of the materials involved. The concept of adhesive reconstruction of ETT is to create mechanically homogeneous units, so-called monoblocks.[30] Dependent on the number of bonding interfaces, endodontic monoblocks were classified as primary, secondary, or tertiary.[30] Irrespective of accomplishing the "ideal monoblock," the maximum load capability depends on the interaction among post, resin cement, core buildup composite, and crown restoration in order to evenly distribute loading stresses. It would be expected that with homogeneous units the increase of the maximum capability depends only on the diameter of the samples. Accordingly, the increase of the specimens' diameter from 1.8 mm (post, coronal level, group 1) to the cross-section dimension in stage of crown restoration, which averages 6.5 mm (Table 1) at the CEJ (groups 3 and 4), maximum load capability would theoretically have to increase 170 times.[31] Our results indicate only a 4.5-fold increase of F_{max}, which supports the impact of the interaction of the materials used—more precisely, the ability to appropriately bond to one another. In other words, adhesively restored ETT with post-and-core and crown restoration did not act as a monoblock. Consequently, to test the beneficial interaction of materials used for the reconstruction of ETT *in vitro,* the specimens have to be prepared in a comparable clinical manner and tested in a stage of final restoration.

The damage of the post in group 1 can be explained by bending the post during loading and fracturing the outer layer of the matrix subjected to the highest amounts of shear forces. Thus, the F_{max} values were determined by the flexural strength of the post material. In the post-and-core stage (group 2), maximum load capability did significantly increase. Due to the predominant cohesive failure of the composite core, load values were limited by the cohesive strength of the composite core material. Recently, the impact of various composite resin core materials on fracture strength of post-and-core restorations was confirmed when the same glass fiber–reinforced post was used.[32] The maximum load capability at the stage of final crown restoration is in a range comparable to that found in previous studies.[33,34]

The fracture patterns in the crown-restored groups 3 and 4 correspond to patterns found earlier.[24] There was no post fracture observed, although an unusual number of crown losses in group 4 was apparent. The fracture lines continued from the palatal aspect of the crown margin to the facial aspect of the root on the simulated crestal bone level. Due to tension palatally and compression facially caused by the palatal loading, an adhesive failure of the luting cement between tooth and restoration occurred. However, the marginal continuity of adhesively cemented lithium-disilicate ceramic crowns is more stress resistant when posts and cores were used compared with the restoration of ETT without posts even when cyclic loading was performed.[17] Recently, it was affirmed that the addition of a crown did not affect the strength of the restoration.[35] We believe that the maximum load capability is less affected by the strength of the post than by the (tensile) strength of the surrounding hard tissue that is directly correlated to its amount.[34] The most important requirement to achieve the maximum load capability of ETT is a remaining minimum of 2-mm cervical tooth structure, the so-called ferrule effect. To provide the ferrule effect, crown cementation is advisable.[36] Therefore, the evaluation of maximum load capability of postendodontic restorations requires a crowned specimen.

Additionally, our results show an influence of the TML because the maximum load capability was significantly reduced for the crowned specimens. The applied load of 49 N for 1.2×10^6 cycles as mechanical loading with simultaneous thermocycling and the failure rate of 30% after TML are comparable to results of other studies recently published.[8,15,17,37] Repeated stress application is more clinically relevant[38] because in the oral environment mechanical and thermal stresses on the dental materials occur cyclically. Due to that, laboratory testing has moved toward laboratory simulation, which includes simultaneous thermal cycling and mechanical loading (TML) as a quasi-representation of oral condition[1] In most studies static loading was used,[8] although it is known that thermal cycling and in particular mechanical loading affect the results of load-to-fracture tests significantly.[9,39]

In principle, dynamic (cyclic) load application provokes the fatigue phenomenon, a time-dependent aging of the materials used for postendodontic reconstruction, such as core buildup composite resins, fiber-reinforced composite posts, and all-ceramic systems. For both thermocycling (TC) only and TML, a load-capability-reducing effect is evident.[40–43] As a function of the rigidity of the post, damage of the bond strength of a post bonded to root dentin was found after cyclical mechanical loading.[44] The durability of the marginal fit of fiber post and composite resin core–restored ETT significantly decreased with cyclic loading.[45] The fracture modes observed in group 4 did indicate, besides a fatigue behavior of the ceramic material initially, a debonding failure of the crown impaired by the TML.

The present investigation supports the need for standardization of *in vitro* testing embedded in a systematic approach to evaluate the materials involved in postendodontic restoration. The correlation between physical properties of the materials and the clinical behavior was only rarely shown. For the establishment of standards for postendodontic restorations further studies are needed to investigate several parameters influencing the load-to-failure behavior, as, for example, the simulation of the periodontal ligament. Some standards should be paid attention: The dental structure of interest should be "structurally representative." The test has to simulate the clinical situation as closely as possible. Best-case/worst-case scenarios are needed.[46] Thus, in the prediction of the clinical behavior of a postendodontic restorative complex more scientific work is necessary. Instead of unstandardized *in vitro* research, a validation of laboratory tests with clinical data achieved in high-level clinical studies is urgently needed.

CONCLUSION

Every additional restorative step toward a final crown-restored endodontically treated tooth increases significantly the load capability. Thermomechanical loading prior to load-to-fracture testing as performed in the present study for the complete restorative complex "post, core buildup, and crown" includes fatigue effects that significantly decrease the maximum load capability. The stage of restoration and type of loading, ie, linear or dynamic loading, should be given attention when load values of different *in vitro* studies are interpreted.

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