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CAD/CAM Polymer vs Direct Composite Resin Core Buildups for Endodontically Treated Molars Without Ferrule

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Clinical Relevance

A no-post, full, anatomically shaped high-performance polymer crown can be used as a long-term provisional crown immediately after root canal treatment. Following recovery of the surrounding tissues and confirmation of endodontic status and prognosis, the polymer restoration can serve as the definitive restoration or as a core buildup under an all-ceramic crown.

SUMMARY

Objectives: The aim of this study was to investigate the restoration of broken-down endodontically treated molars without ferrule effect using glass ceramic crowns on different composite resin core buildups.

Methods and Materials: Forty-five decoronated endodontically treated teeth (no ferrule) were restored with a semidirect buildup using an experimental computer-aided design/computer-aided manufacturing (CAD/CAM) high-performance polymer (HPP group) or with light-curing composite core buildups of Tetric EvoCeram with (TECP group) or without (TEC group) a glass-fiber-reinforced post. All teeth were prepared to receive bonded glass ceramic crowns (Empress CAD luted with Variolink II) and were subjected to accelerated fatigue testing. Cyclic isometric loading was applied to the palatal cusp at an angle of 30° and a frequency of 5 Hz, beginning with a load of 200 N (×5000 cycles) and followed by stages of 400, 600, 800, 1000, 1200, and 1400 N at a maximum of 30,000 cycles each. Specimens were loaded until failure or to a maximum of 185,000 cycles. Groups were compared using the life-table survival analysis (log rank test at p=0.05). Average fracture loads and number of sur-

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vived cycles were compared with one-way analysis of variance (Scheffé post hoc at p=0.05).

Results: None of the tested specimen withstood all 185,000 load cycles. There was a significant difference in mean fracture load, survived cycles, and survival; the HPP group (fracture load 975.27N±182.74) was significantly higher than the TEC (716.87N±133.43; p=0.001) and TECP (745.67±156.34; p=0.001) groups, and the TEC and TECP groups showed no difference (p=0.884). Specimens in the TECP group were affected by an initial failure phenomenon (wide gap at the margin between the buildup/crown assembly and the root).

Conclusions: Semidirect core buildup made from high-performance polymer enhanced the performance of all-ceramic leucite-reinforced glass ceramic crowns compared with direct light-curing composite resin buildups. The use of a fiber-reinforced post system did not influence the fatigue strength of all-ceramic crowns.

INTRODUCTION

The reconstruction of severely broken-down and endodontically treated teeth is a challenge in daily practice. Although it is agreed that restorative treatment is critical to the long-term success of endodontic treatment, the possible reconstruction materials and techniques are still being debated.[1]

Meanwhile, it is widely accepted, that the clinically relevant physical properties of dentin are not necessarily affected by the loss of vitality.[2,3] Instead, the risk of fracture of endodontically treated teeth is known to result from structural defects related to decay or tooth preparation requirements (eg, caries removal and endodontic access).[4,5] Additional removal of intact dentin will occur during root canal therapy and preparation for post placement. This will further weaken the tooth and reduce its fracture strength.[6] In spite of the aforementioned issues and the fact that the use of posts does not necessarily reinforce nonvital teeth, direct posts are still frequently used to retain adhesive core buildups.

Optimization of the biomechanical behavior of restored teeth is possible through the preservation of sound cervical tooth structure, which is crucial to create a ferrule effect.[7] Currently, a minimum ferrule of 1.0 mm is deemed necessary to stabilize the restored tooth.[8] In cases where no ferrule effect can be obtained, it was concluded that inserting a fiber post might improve the retention and fatigue resistance of the restoration.[9] However, there is a lack of data to support this claim.

Composite resins, either light polymerized or dual cured, are commonly used as materials for direct buildups. Light-cure buildup materials have several advantages over dual-cure materials. First, they can be bonded, layered, and shaped to ideal form. Second, they present optimal mechanical properties and color stability.[10-12] More recently, dentists and dental technicians, thanks to the development of computer-aided design/computer-aided manufacturing (CAD/CAM) technology, have access to high-performance polymers (HPPs). The polymerization of these materials under controlled and standardized industrial conditions, with optimized pressure and temperature parameters, leads to improved mechanical properties of the resulting restoration compared with manual fabrication.[13,16] Because of their favorable properties, CAD/CAM HPP materials may also have an advantage when it comes to the reconstruction of root-canal-treated molars. Because of their density and homogeneity, along with their dentin-like elastic modulus, it would be reasonable to consider them as a shrink-free core buildup material under bonded ceramic crowns. This concept closely mimics the biomechanical behavior of a natural tooth (biomimetics approach), in which the shock-absorbing dentin (e-modulus ~14 GPa) is covered by stiff and wear-resistant enamel (80 GPa) that preserves shape and function.[17]

The aim of the study was to investigate the restoration of broken-down endodontically treated molars with no ferrule effect using glass ceramic crowns over three different core buildups: an HPP CAD/CAM core buildup, a direct core buildup from light-curing composite with the use of a fiber-reinforced post, and a direct core buildup from light-curing composite without the use of a fiber-reinforced post. The first null hypothesis was that the HPP CAD/CAM core buildup would not lead to different fatigue strength of all-ceramic crowns compared with conventional direct core buildup methods. The second null hypothesis was that the use of a fiber-reinforced post system would not influence the fatigue strength of all-ceramic crowns.

METHODS AND MATERIALS

Upon approval from the Ethical Review Committee of the University of Southern California, Los Angeles (proposal HS-13-00162), and the Ludwig Maximilian University of Munich, Germany, 45 maxillary third molars were collected.

Table 1: *Overview of Properties of Material Used for Core Buildups*

Parameter	Experimental HPP	Tetric EvoCeram
Matrix	Dimethacrylates	Bis-GMA, UDMA, ethoxylated Bis-EMA
Matrix (weight %)	22.0	16.8
Filler	Barium glass fillers (15%), ytterbium trifluoride (9%), mixed oxides (44%), silicium oxide (3), copolymer (7%)	Barium glass fillers, ytterbium trifluoride, mixed oxides
Filler content (weight %)	78	48.5
Prepolymer (weight %)	not available	34.0
Flexural strength (MPa)	167	120
Flexural modulus (MPa)	11,400	10,000
Compressive strength (MPa)	not available	250
Vickers hardness (MPa)	915	580
Water absorption 7 days ($\mu g/mm^3$)	28	21.2

Abbreviations: Bis-EMA, ethoxylated bisphenol A glycol dimethacrylate ; Bis-GMA, bisphenol A glycol dimethacrylate; HPP, high-performance polymer; UDMA, urethane dimethacrylate.

In order to evenly distribute the teeth according to size and shape, all specimens (N=45) were organized in groups of three (triplets with similar buccolingual and mesiodistal size and height) and subsequently reassigned randomly to groups that received 1) a CAD/CAM core buildup from HPP (the HPP group), 2) a direct core buildup from the universal composite Tetric EvoCeram (Ivoclar Vivadent, Schaan, Liechtenstein) (the TEC group), or 3) a direct core buildup from the universal composite Tetric EvoCeram in combination with a post (the TECP group) (n=15 each). Each tooth was mounted using a special positioning jig with acrylic resin (Palapress Vario Light Pink, Heraeus Kulzer, Hanau, Germany) embedding the root up to 2.0 mm below the cementoenamel junction. Standardized defects were generated by removing the clinical crown horizontally down to 1 mm above the cementoenamel junction using rotating diamond cutting instruments. The remaining ceiling of the pulp chamber was removed, and root canals were cleaned and shaped using the stepback technique (maximum file 35) and then partially filled and covered by glass ionomer cement (Ketac Molar, 3M ESPE, Seefeld Germany) up to 1.5 mm below the level of the occlusal reduction. According to Schumacher and others,[18] a maxillary first molar has an overall average length of 19.5 mm (±1.8 mm) with an average crown length of 6.2 mm (±0.8 mm) and an average root length of 13.3 mm (±1.7 mm). Therefore the teeth were reconstructed on one average height between 8.5 and 9.0 mm measured from the acrylic resin to the cusps of the crowns.

Teeth from the HPP group received a CAD/CAM fabricated indirect core buildup milled from an experimental HPP material (Ivoclar Vivadent, Schaan, Liechtenstein). Teeth from the TEC group were restored with a conventional direct buildup using the light-curing composite Tetric EvoCeram. In the TECP group, a glass-fiber-reinforced post (FRC Postec Plus system, Ivoclar Vivadent) system was applied before the core buildup, which was also carried out using Tetric EvoCeram light-curing composite. The properties of the two resin materials are presented in Table 1. The following detailed procedures were carried out to create different core buildups.

HPP Group: CAD/CAM Core-Buildup With Experimental HPP Material

Immediate dentin sealing (IDS) was applied: dentin was etched for 10-15 seconds using 37% phosphoric acid (Total etch, Ivoclar Vivadent) before the adhesive system (Syntac, Ivoclar Vivadent) was applied according to the manufacturer's recommendations, except for the fact that Heliobond (Ivoclar Vivadent) was applied in a thick layer without air thinning (requirement of the IDS technique; Figure 1a). Heliobond was then polymerized for 20 seconds and covered with glycerin jelly (Liquid strip, Ivoclar Vivadent) with an additional 20 seconds of light exposure to minimize the oxygen-inhibited layer and

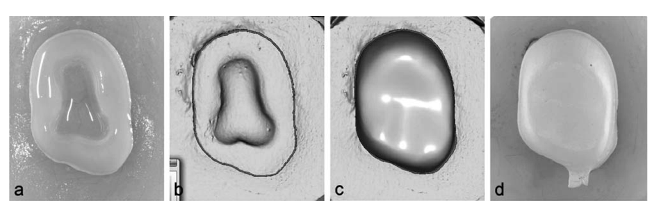

Figure 1. *Fabrication process of CAD/CAM buildup from HPP. (a): Tooth surface after IDS. (b): Data set of scanned tooth. (c): CAD of buildup. (d): Milled HPP buildup after adhesive luting to the tooth.*

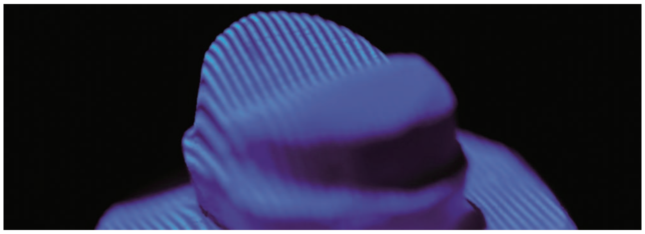

Figure 2. *Digitalization of a prepared tooth using the Cerec AC bluecam.*

secure the thickness of the resin coating.[19,20] A curing lamp (Bluephase, Ivoclar Vivadent) with a light intensity of 1200 mW/cm^2 and a light spectrum between 385 and 515 nm was used.

Specimens were then scanned with a CEREC AC Bluecam (Sirona Dental Systems, Bensheim, Germany), and core buildups with a simplified anatomy were designed (CEREC Software 3.60, Sirona Dental Systems, Figure 1b,c) and milled from an experimental HPP block (CEREC 3 compact milling unit, Sirona Dental Systems). In preparation for adhesive luting procedures, the fitting surface of the milled HPP core buildups was air-abraded (27 μm aluminum oxide, 0.5 bar, 10 seconds, 10-mm distance) then cleaned with phosphoric acid for 10 seconds and in an ultrasonic bath in distilled water for 2 minutes. A silane-containing coupling agent (Monobond Plus, Ivoclar Vivadent) was applied to the fitting surface and dried in an oven (DI-500, Coltene, Altstätten, Switzerland) at 212°F for 60 seconds, followed by wetting with adhesive resin (Heliobond) and air-thinning but not light-curing. On the tooth side, the IDS surface was refreshed by airborne-particle abrasion (27-μm aluminum oxide, 0.5 bar, 10 seconds, 10-mm distance), followed by 30 seconds of etching with phosphoric acid. Then adhesive resin (Heliobond) was applied and air-thinned but not light-cured. The core buildup was then luted using a dual-cure composite resin cement (Variolink II, Ivoclar Vivadent, Figure 1d). After careful elimination of excessive unpolymerized composite resin, each surface was light-cured for 60 seconds (20 seconds per surface, three times). All margins were covered with an air-blocking barrier (Liquid strip) for the last polymerization cycle.

The TEC Group: Core-Buildup With Light-Cure Composite Resin Material (Tetric EvoCeram)

After 10-15 seconds of dentin and 30 seconds of enamel etching with 37% phosphoric acid (Total etch) the Syntac adhesive system was applied according to the manufacturer's recommendations. Composite resin (Tetric EvoCeram) was applied incrementally, each layer (total 4-5 layers) with a maximum thickness of 1.5 mm, and polymerized for 60 seconds (buccal, occlusal, lingual for 20 seconds each).

The TECP Group: Core Buildup With Light-Cure Composite Resin (Tetric EvoCeram) and FRC Post (FRC Postec Plus)

A glass-fiber reinforced post (FRC Postec Plus system) was placed in the palatal root in accordance with the manufacturer's recommendations. The post space was prepared (about 10 mm deep measured from the defect surface) with the FRC Postec Plus Reamers at 1000-5000*g* for a post size 1 (white; 0.7 mm). The post was tried in, and checked for proper fit, then cut 3 mm above the defect surface and cleaned with phosphoric acid etching gel (Total etch) for 60 seconds, rinsed with water, and dried before applying silane (Monobond Plus) for 60 seconds. The manufacturer of the post system recommends the application of Multilink-Automix (Ivoclar Vivadent) in combination with the FRC Postec as a system. Primer A and B were mixed at a 1:1 ratio and applied for 15 seconds into the root canal and on the prepared tooth surface by scrubbing with light pressure. The excesses were removed with a strong stream of air and paper points. Multilink Automix was applied to the post, and the post was rotated to its final position. The excess Multilink Automix was strategically dispensed over the prepared and primed surface of the tooth and light-cured for 20 seconds. The light-curing composite resin (Tetric EvoCeram) was then applied incrementally in a similar fashion as in the TEC group.

Preparation for Glass Ceramic Crowns

All 45 teeth with the different core buildups were prepared to receive a standardized full anatomic glass ceramic crown: occlusal clearance of 2.0 mm, circumferential reduction of 1.0 mm with an axial convergence taper of 12°, preparation height of 7 mm from the level of the embedding resin to the cusp tips, and 5.0 mm at the central groove.

Manufacturing of Glass Ceramic Crowns

A standardized full anatomic crown in the form of a simplified maxillary molar with three cusps was designed using the CEREC system (Figures 2 and 3). The CEREC database was used, and adjustments were made for each individual tooth (Figures 4 and 5) in order to obtain specific dimensions of the crowns: 1.5 mm at central groove, 2.0 mm at cusp

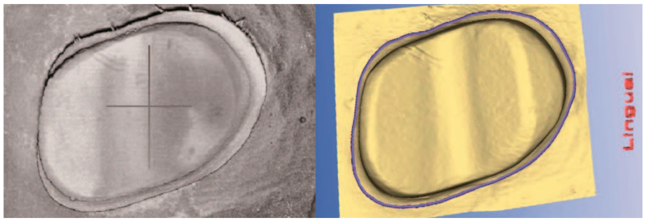

Figure 3. *(Left): Digitalization of a prepared tooth using the Cerec AC blucam. (Right): CAD data set of preparation with determined preparation line.*

tips and 1.0 mm of circumferential thickness. Restorations were milled from leucite-reinforced glass ceramic blocks (EmpressCAD, Ivoclar Vivadent), and all measurements were verified manually using a caliper and confirmed visually by uniform translucency across specimens (Figure 6).

Adhesive Luting of the Glass Ceramic Crowns

The fitting surface of the milled glass ceramic crown was etched with hydrofluoric acid (<5%) (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 60 seconds, cleaned with phosphoric acid for 10 seconds (Total etch) and in an ultrasonic bath for 2 minutes. Silane was applied (Monobond Plus) and heat-dried for 60 seconds. Immediately before cementation, the adhesive resin (Heliobond) was applied to the crown and air-thinned but not light-cured. The tooth was conditioned by air abrasion of the core buildup (27 μm aluminum oxide; 0.5 bar, 10 seconds, 1 cm distance), followed by 30 seconds of phosphoric etching to clean the surface and etch the enamel areas. Adhesive resin (Heliobond) was applied to all surfaces and air-thinned but not light-cured. All crowns were cemented using a dual-cure composite cementation system (Variolink II). After careful elimination of the excess unpolymerized composite resin, the vestibular, occlusal, and palatal surfaces of the crown were polymerized for 60 seconds (20 seconds per surface, three times). All margins were covered with an air-blocking barrier (Liquid strip) for the last polymerization cycle. Each specimen was stored in distilled water at ambient temperature for at least 24 hours before testing.

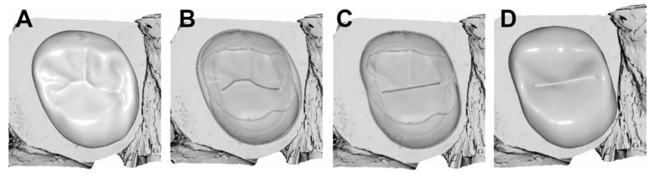

Figure 5. *CAD of crowns using standardized parameters within the Cerec software 3.60. (a): Design suggestion by the software. (b and c): Modifications of the design using the edit mode. (d): Outline of crown with standardized parameters.*

Loading Procedure and Configuration

Masticatory forces were simulated using closed-loop servohydraulics (Mini Bionix II, MTS Systems, Eden Prairie, MN, USA). The masticatory cycle was simulated by an isometric contraction (load control) applied through an artificial composite resin cusp (Z100, 3M ESPE) in the shape of a semicylinder (2.5-mm radius). The low stiffness and toothlike wear of the composite resin cylinder allows realistic simulation of tooth contacts through wear facets distributing the load without reaching the compressive limit of the tissues or restorative materials.

All specimens were placed in the load chamber at 30° angulation and situated with a positioning device (sliding table) to create a single contact between the semicylinder and the palatal cusp. The loading point was equidistant to the cusp tip and central groove (Figure 7). The load chamber was filled with distilled water to submerge the specimens during testing. Cyclic load was applied at a frequency of 5 Hz, starting with a warm-up load of 200 N for 5000 cycles (preconditioning stage), followed by stages of 400, 600, 800, 1000, and 1200 and 1400 N at a maximum of 30,000 cycles each. Specimens were loaded until fracture or to a maximum of 185,000 cycles.

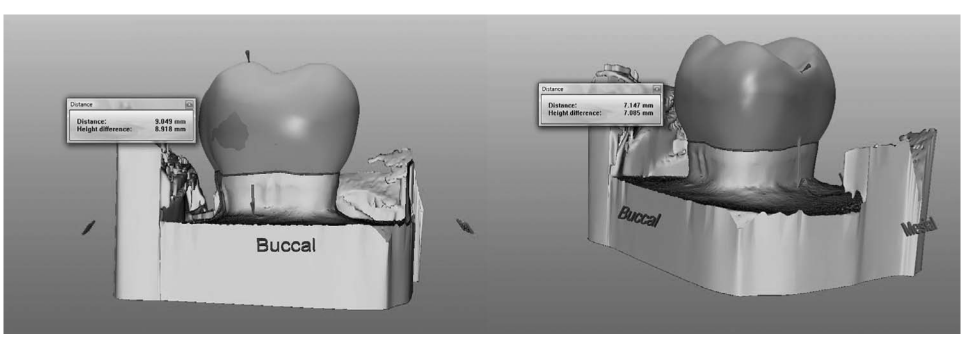

Figure 4. *Standardization of crown design using the Cerec software. Height of cusp tips and marginal ridges could be measured within the software.*

Figure 6. *Translucency confirming homogenous material thickness within specimens.*

Analysis

The fracture load was determined by the load step at which the machine stopped (triggered by the displacement-based, failure-detect module of the testing software). The number of endured cycles and the failure mode were recorded. After a three-examiner agreement under optical microscopy (Leica MZ 125, Leica Microsystems, Wetzlar, Germany) and transillumination, a distinction was made among three fracture modes, considering the reparability of the tooth: catastrophic, that is, tooth/root fracture that would require tooth extraction; possibly reparable, that is, cohesive/adhesive failure with fragment and minor damage, chip or crack, of underlying tooth structure; or reparable fracture, that is, cohesive or adhesive failure of restoration only (Figure 8).

The fatigue resistance of the three groups was compared using the life-table survival analysis. At each time interval (defined by each load step), the number of specimens starting the interval intact and the number of specimens fracturing during the interval were counted. This allowed the calculation of survival probability (%) at each load step. The influence of the different core buildups on the fracture strength was analyzed using the log-rank test at a significance level of 0.05. Differences were localized using pairwise post hoc comparisons with the same test at a significance level of 0.017 (Bonferroni correction for three comparisons). Additionally, the fracture load and number of cycles at which the specimen failed was compared using one-way analysis of variance (ANOVA) followed by Scheffé post hoc procedure at a significance level of 0.05.

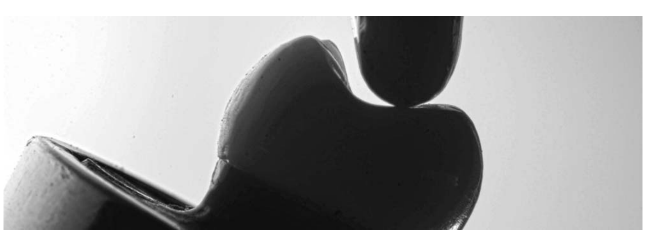

Figure 7. *Specimen in load chamber with the loading point equidistant between cusp tip and central groove.*

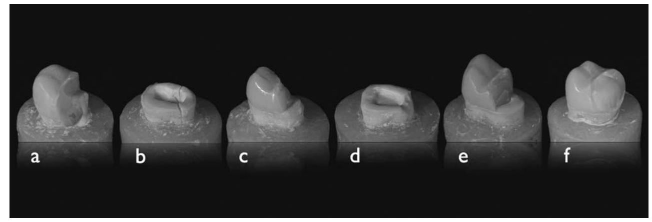

Figure 8. *All specimens were analyzed and classified in one of the three failure modes: (a,b): Catastrophic, that is, tooth/root fracture that would require tooth extraction. (c,d): Possibly reparable, that is, cohesive/adhesive failure with fragment and minor damage, chip, or crack of the underlying tooth structure. (e,f): Reparable fracture, that is, cohesive or cohesive/adhesive fracture of restoration only.*

RESULTS

None of the tested specimens withstood all 185,000 load cycles. Only one specimen from group A (HPP), with a core buildup from the experimental CAD/CAM HPP, fractured during the last interval of 1400 N. As all specimens fractured, the mean fracture load could be calculated. One-way ANOVA and Scheffé post hoc revealed that the mean fracture load for the HPP group with 975.27 $\pm$ 182.74 N was significantly higher than that for the TEC group (716.87$\pm$133.43 N; p=0.001) and the TECP group (745.67$\pm$156.34 N; p=0.001), while the TEC and TECP groups showed no difference (p=0.884). The same results were found when the number of survived cycles was statistically compared (HPP group to TEC group: p=0.001; HPP group to TECP group: p=0.001; TEC group to TECP group: p=0.994). Figure 9 shows the mean values of mean fracture loads and average number of survived cycles and their standard deviations, respectively.

During cyclic loading, initial failures were detected in 26.7% (4/15) specimens of the TECP group. Failure of the specimen was preceded by the cyclic opening of a wide gap at the margin between the buildup/crown assembly and the root. The gap was always located at the opposing side of the post. Such occurrence was never found in the other groups.

Because clinical detection of such failures appears to be questionable, the analysis of survival was conducted for total failure (TECP) as well as considering initial failure (TECPi). The life-table survival graphs for all groups, including analysis of initial failure are displayed in Figure 10. The log-rank test showed significantly higher survival for the HPP group compared with the TEC (p=0.001)

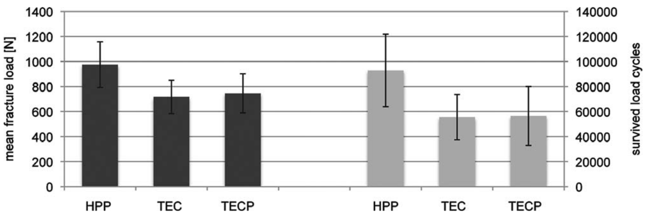

Figure 9. *Mean fracture loads and number of survived load cycles for groups HPP, TEC, and TECP.*

and TECP (p=0.001) groups. No difference could be found between the TEC and TECP groups (p=0.688). Also, when considering the initial failure, the log-rank test showed significantly higher survival for the HPP group compared with the TECPi group (p=0.001). However, no difference was found between the TEC and TECPi groups (p=0.453).

Analysis of Failure Mode

After three-examiner agreement, the HPP and TECP groups showed the highest rate of catastrophic failures (each 80% vs 53,3% in the TEC group). Possible fractures of the roots were made visible by transillumination in order to classify the specimen correctly (Figure 11). Figure 12 gives the number of specimens and percentage of each specific fracture mode for each group.

DISCUSSION

This study evaluated the performance of leucite-reinforced glass ceramic crowns for the rehabilitation of severely broken-down endodontically treated molars with no ferrule effect. A core buildup from an experimental HPP was compared with direct light-curing composite resin core buildups with and

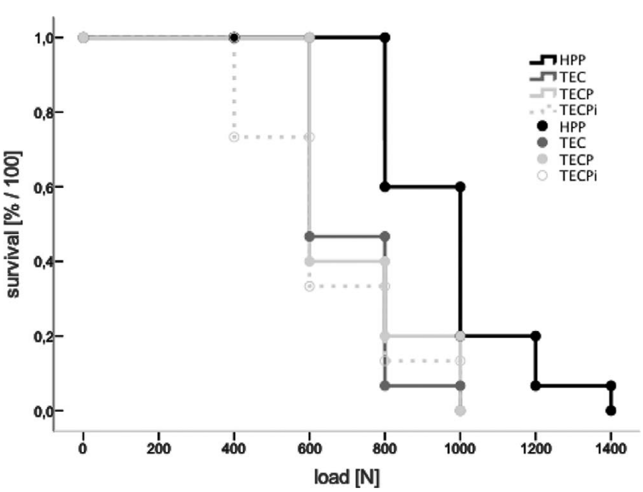

Figure 10. *Life table of survival for groups HPP, TEC, and TECP.*

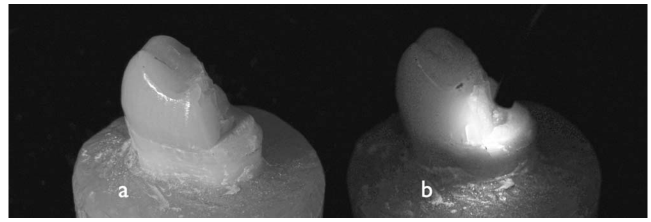

Figure 11. *Specimens were examined using a white-light lamp to make possible cracks visible (same specimen as in Figure 10c, possibly restorable).*

without the application of a fiber-reinforced post system. The first null hypothesis, stating that different core buildups influence the survival rate and fracture load of the restorations, was rejected because HPP was associated with significantly higher fracture loads and survival rates compared with the TEC and TECP groups. Because the TEC and TECP groups were associated with similar survival rates and fracture resistance of all-ceramic crowns, the second null hypothesis, stating the absence of effect of fiber-reinforced posts, was accepted.

In the present study, a closed-loop servohydraulic control system in combination with a stepped load protocol was applied to create a testing method, which allows a physiologic representation of mastication.[21] This stepped load protocol represents a compromise between the conventional load-to-failure protocol and the time-consuming low-load fatigue test. Based on original studies by Fennis and others,[22] this test strategy seems to provide a better simulation of clinical conditions than static load tests. The presented protocol appears to be the best compromise between available *in vitro* fatigue testing methods and clinical reality.

The application of cyclic loads, increasing the load in 200-N steps up to 1400 N and a frequency of 5 Hz using a similar testing machine was already described elsewhere.[23] However, during pilot tests for

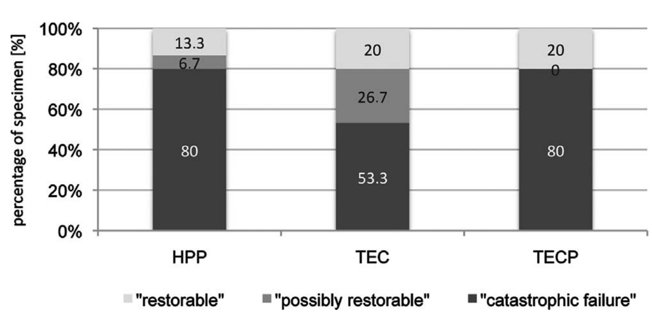

Figure 12. *Percentage of observed fracture mode of specimens for groups HPP, TEC, and TECP.*

the present study, no specimen failed when the load was applied axially and distributed on three opposing cusps of the crown. Therefore, the authors decided to maintain the loading sequence and values but to modify the angle of force to 30° and to concentrate its application to the working cusp using a composite resin cylinder (Z100, 3M ESPE) as an antagonist.[24] This measure increases the stress to the restoration and simulates an extreme load configuration (nonworking contact).

Healthy humans exhibit maximal isometric bite forces in the molar region ranging between 597 N (women) and 847 N (men), but they can also reach up to 900 N.[25] Even higher forces can occur by an accidental bite on a hard foreign body found in a food bolus (eg, stone in a bean/salad, cherry pit). Although it is difficult to draw direct correlations between the load ranges applied in this study and their significance *in vivo*, a study by Sakaguchi and others,[26] using a similar machine, correlated 250,000 cycles at only 13.6 N with 1 year of clinical service. Because of the application of far higher forces in this study, it can be expected that an accelerated life cycle of the restored tooth may have been simulated.

Although *in vitro* studies only partially mimic clinical reality, their chief advantage over clinical studies is the possibility to almost eliminate confounding variables and further enable the testing of samples with well-defined biomechanical status.[27] Because of the high standardization level that can be attained at all preparation steps and restorative steps, the remaining confounding variables are limited to the age, size, and shape of extracted teeth. Therefore, only upper third molars with comparable outer size and geometry of crowns and roots were selected from a larger selection and distributed evenly into each experimental group using the innovative randomly reassigned triplets method (see beginning of the Methods and Materials section). However the different internal and external dimensions of the teeth still has to be considered as a limitation of studies in which natural teeth are used.

Further, after standardized preparation of the different core buildups, standardized crowns were designed using CAD/CAM technology, enabling the use of the same database (maxillary third molar) for each specimen. Adjustments in the edit mode of the software allowed us to create a simplified crown design with highly reproducible anatomy, cuspal inclines, grooves, and a strictly similar thickness parameter for each specimen. All the aforementioned facilitated the loading of the specimen in a strictly identical configuration.

High strength coronal coverage can make the underlying core hypofunctional. Because the overlay of the crown should not be too strong to avoid masking the effect of the core buildups, leucite-reinforced glass ceramic Empress CAD was used. On the other hand, the combination of the experimental HPP (flexural modulus: 11.4 GPa; source: Research and Development-Ivoclar Vivadent) covered with the brittle glass ceramic (flexural modulus: 62 GPa) closely mimics the mechanical properties of a natural tooth, in which the comparably soft dentin (14 GPa) with a shock-absorption property is covered by hard, brittle enamel (80 GPa) that protects the tooth from premature wear.

The combination of shock-absorbing properties of the core buildup and protective crown coverage appears to be the major advantage of this approach. This approach closely mimics the structure and biomechanical behavior of a natural tooth, in contrast to the concepts of endocrowns from polymers or ceramics, where dentists have to choose one of the aforementioned properties. All elements (crown, buildup, and tooth) have to form a cohesive assembly requiring a capable adhesive system and cement, which ideally mimics the properties of the dentinoenamel junction.

The superior performance of the HPP core buildup in this study may have various reasons. First, by using a milled HPP block, polymerization shrinkage will only be limited to the cementation gap instead of the whole buildup itself (Tetric groups).[28] This might be of particular advantage in situations where a negative c-factor (eg, configuration of the pulp chamber) combined with the extreme volume of the buildup may lead to significant shrinkage stresses within the tooth.[29]

The insertion of a fiber post did not seem to influence the load-bearing capacity and survival probability of the restorations (TEC vs TECP groups). This aligns with data on endodontically treated molars with two-wall and one-wall cavities restored with indirect onlay composite resin restorations, in which insertion of a fiber post did not increase the fracture resistance.[30] A unique finding for the TECP group, however, was that in 4 (26.7%) of the specimens initial failure (displayed in Figure 10 as TECPi) could be observed during load cycling. A wide gap at the margin between the buildup/crown assembly and the root could be observed, which intensified over time until total failure. This indicates an adhesive failure at the core buildup/tooth interface, possibly due to the weakness of the self-adhesive system that was used for cementation of the post and core buildup. Such initial failures did not occur when a classic dentin adhesive was used (HPP and TEC groups). This raises questions about whether the manufacturer's recommendation to extend the use of the adhesive system of the post over the entire prepared surface should be modified. A more favorable approach would be to limit the application of the adhesive system of the post to the root canal itself and use a classic adhesive system on the remaining dentin surface to which the core material will be bonded. This renders the already time-consuming procedure of post insertion and buildup even more complicated, material intensive, and error prone without real benefits from a biomechanical standpoint. The post even caused an increased rate of catastrophic failures when comparing the TEC and TECP groups.

As those initial failures only occur under load (cyclic opening of the gap), they would not necessarily be detected clinically by the dentist during regular checkups and may lead to a pump effect, facilitating bacterial infiltration with dramatic clinical consequences.

Another advantage of the HPP core buildup over direct methods is the possibility of applying the immediate dentin sealing (IDS) technique. This means bonding and adhesive are directly applied after preparation to the freshly cut dentin to seal the dentin surfaces. Before adhesive luting, the sealed surface is conditioned by sandblasting, and the bonding can be applied. This technique has been shown to optimize bond strength and protects the preparations and root canals from bacterial infiltration.[31] The effective performance of the IDS procedure was demonstrated by the absence of adhesive failures in the HPP group. On the other hand, the strong adhesion may have facilitated cohesive failures within the remaining tooth substance (80% of nonreparable catastrophic failures). A similar amount of catastrophic failures was found for the TECP group; however, the specimen failed at significantly lower loads and showed unfavorable initial failures. Only in the TEC group, where no post was used, the amount of catastrophic failures was reduced to 53%. This means that the smallest number of unrestorable failures were found with direct core buildups from the light-curing composite without a fiber-reinforced post. In these re-restorable cases it would be possible for the dentist to make a new buildup instead of losing the natural tooth. However, the loads under which the failures occurred were significantly lower. Therefore, the performance of the HPP buildups can be considered superior compared with the other groups; even when the same number of catastrophic failures occurred, those failures happened significantly later and therefore at a significantly higher load.

Regarding these results under extreme circumstances (30° angulation, load on one cusp), the application of indirect CAD/CAM fabricated buildups might be an alternative to known direct methods for core buildups. Also, it demonstrates the potential to replace the application of a fiber-post system. However, further studies should investigate the so-called ideal bond strength, which is strong enough to ensure the long-term clinical success but weak enough to protect the remaining tooth structure in case of fracture under high loads.

From a clinical standpoint, a bacteria-proof sealing of the tooth by a buildup should be achieved immediately after successfully completed endodontic treatment.[32,33]

Novel clinical approaches may result from the findings of the present study. The HPP material may be milled with full anatomy (like an endcrown) and serve as a long-term provisional approach to seal and build up the tooth directly after root canal treatment. After successful recovery of the surrounding tissues and confirmation of endodontic status and prognosis, the polymer restoration could serve as either the definitive restoration or as a core buildup under an all-ceramic crown. As currently only limited data are available regarding the wear behavior of HPPs in occlusion,[34] this study evaluates the behavior of an experimental HPP material as a core buildup under a leucite-reinforced glass ceramic crown. The presented novel concept using HPPs for a long-term provisional and core buildup, respectively, is facilitated by the use of chairside CAD/CAM systems.

CONCLUSION

Within the limitations of this *in vitro* study, when restoring endodontically treated molars without ferrule, the following can be concluded:

1. Indirect CAD/CAM-fabricated core buildup from HPP might offer the potential to enhance the load-bearing capacity and survival of all-ceramic leucite-reinforced glass ceramic crowns.
2. Insertion of a fiber-reinforced post did not enhance the load-bearing capacity and survival of all-ceramic leucite-reinforced glass ceramic crowns on direct core buildups from light-curing composite.

3. The smallest number of unrestorable failures was found with direct core buildups from light-curing composite without a fiber-reinforced post.

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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 of the University of Southern California and Ludwig-Maximilians University, in Munich, Germany.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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REFERENCES

1. Ree M, & Schwartz RS (2010) The endo-restorative interface: Current concepts *Dental Clinics of North America* **54(2)** 345-374.
2. Fusayama T, & Maeda T (1969) Effect of pulpectomy on dentin hardness *Journal of Dental Research* **48(3)** 452-460.
3. Reeh ES, Messer HH, & Douglas WH (1989) Reduction in tooth stiffness as a result of endodontic and restorative procedures *Journal of Endodontics* **15(11)** 512-516.
4. Papa J, Cain C, & Messer HH (1994) Moisture content of vital vs. endodontically treated teeth *Endodontics & Dental Traumatology* **10(2)** 91-93.
5. Sedgley CM, & Messer HH (1992) Are endodontically treated teeth more brittle? *Journal of Endodontics* **18(7)** 332-335.
6. Sidoli GE, King PA, & Setchell DJ (1997) An in vitro evaluation of a carbon fiber-based post and core system *Journal of Prosthetic Dentistry* **78(1)** 5-9.
7. Dietschi D, Duc O, Krejci I, & Sadan A (2007) Biomechanical considerations for the restoration of endodontically treated teeth: A systematic review of the literature—part 1. Composition and micro- and macrostructure alterations *Quintessence International* **38(9)** 733-743.
8. Sorensen JA, & Engelmann MJ (1990) Ferrule design and fracture resistance of endodontically treated teeth *Journal of Prosthetic Dentistry* **63(5)** 529-536.
9. Zicari F, Van Meerbeck B, Scotti R, & Naert I (2013) Effect of ferrule and post placement on fracture resistance of endodontically treated teeth after fatigue loading *Journal of Dentistry* **41(3)** 207-215.
10. Vouvoudi EC, & Sideridou ID (2013) Effect of food/oral-simulating liquids on dynamic mechanical thermal properties of dental nanohybrid light-cured resin composites *Dental Materials* **29(8)** 824-850 DOI: Pii: S0109-5461(13)00110-3.10.1016/j.dental.3013.04.2013.
11. Ilie N, Rencz A, & Hickel R (2013) Investigations towards nano-hybrid resin based composites. *Clinical Oral Investigations* **17**(1) 185-193.
12. Stawarczyk B, Sener B, Trottmann A, Roos M, Ozcan M, & Hämmerle CH (2012) Discoloration of manually fabricated resins and industrially fabricated CAD/CAM blocks versus glass-ceramic: Effect of storage media, duration, and subsequent polishing *Dental Materials Journal* **31(3)** 377-383.
13. Alt V, Hannig M, Wostmann B, & Balkenhol M (2011) Fracture strength of temporary fixed partial dentures: CAD/CAM versus directly fabricated restorations *Dental Materials* **27(4)** 339-347.
14. Goncu Basaran E, Ayna E, Vallittu PK, & Lassila LV (2011) Load-bearing capacity of handmade and computer-aided design-computer-aided manufacturing-fabricated three-unit fixed dental prostheses of particulate filler composite *Acta Odontologica Scandinavica* **69(3)** 144-150.
15. Stawarczyk B, Ender A, Trottmann A, Özcan M, Fischer J, & Hämmerle CH (2012) Load-bearing capacity of CAD/CAM milled polymeric three-unit fixed dental prostheses: Effect of aging regimens *Clinical Oral Investigations* **16(6)** 1669-1677.
16. Magne P, & Knezevic A (2009) Influence of overlay restorative materials and load cusps on the fatigue resistance of endodontically treated molars. *Quintessence International* **40(9)** 729-737.
17. Magne P, & Belser U (2002) Understanding the intact tooth and the biomimetic principle In: Magne P, Belser U (eds) *Bonded Porcelain Restorations in the Anterior Dentition: A Biomimetic Approach* Quintessence Publishing Co, Berlin, Germany 23-56.
18. Schumacher GH (1997) Dentes permanentes. In: *Anatomie für Zahnmediziner: Lehrbuch und Atlas* **3rd edition** Hörbig, Heidelberg, Germany 330-349.
19. Magne P, & Nielsen B (2009) Interactions between impression materials and immediate dentin sealing *Journal of Prosthetic Dentistry* **102(5)** 298-305.
20. Stavridakis MM, Krejci I, & Magne P (2005) Immediate dentin sealing of onlay preparations: Thickness of pre-cured dentin bonding agent and effect of surface cleaning *Operative Dentistry* **30(6)** 747-757.
21. DeLong R, & Douglas WH (1991) An artificial oral environment for testing dental materials *IEEE Transactions in Biomedical Engineering* **38(4)** 339-345.
22. Fennis WV, Kuijs RH, Kreulen CM, Verdonschot N, & Creugers NH (2004) Fatigue resistance of teeth restored with cuspal-coverage composite restorations *International Journal of Prosthodontics* **17(3)** 313-317.
23. Magne P, & Knezevic A (2009) Simulated fatigue resistance of composite resin versus porcelain CAD/

CAM overlay restorations on endodontically treated molars *Quintessence International* **40(4)** 125-133.

24. Magne P, Boff LL, Oderich E, & Cardoso AC (2010) Computer-aided-design/camputer-aided-manufactured adhesive restoration of molars with a compromised cusp: Effect of fiber-reinforced immediate dentin sealing and cups overlap on fatigue strength *Journal of Esthetic and Restorative Dentistry* **24(2)** 135-146.

25. Waltimo A, & Könönen M. (1993) A novel bite force recorder and maximal isometric bite force values for healthy young adults *Journal of Dental Research* **101(3)** 171-175.

26. Sakaguchi RI, Douglas WH, DeLong R, & Pintado MR (1986) The wear of a posterior composite in an artificial mouth. A clinical correlation *Dental Materials* **2** 235-240.

27. Dietschi D, Duc O, Krejci I, & Sadan A (2008) Biomechanical considerations for the restoration of endodontically treated teeth: A systematic review of the literature, part 2 (Evaluation of fatigue behavior, interfaces, and in vivo studies) *Quintessence International* **39(2)** 117-129.

28. Koplin C, Jaeger R, & Hahn P (2009) A material model for internal stress of dental composites caused by the curing process *Dental Materials* **25(3)** 331-338.

29. Davidson CL, & Feilzer AJ (1997) Polymerization shrinkage and polymerization shrinkage stress in polymer-based restoratives *Journal of Dentistry* **25(6)** 435-440.

30. Scotti N, Borga FAC, Alovisi M, Rota R, Pasqualini D, & Berutti E (2012) Is fracture resistance of endodontically treated mandibular molars restored with indirect onlay composite restorations influenced by fibre post insertion? *Journal of Dentistry* **40(10)** 814-820.

31. Magne P, Kim TH, & Cascione D (2005) Immediate dentin sealing improves bond strength of indirect restorations *Journal of Prosthetic Dentistry* **94(6)** 511-519.

32. Fox K, & Gutteridge DL (1997) An in vitro study of coronal microleakage in root-canal-treated teeth restored by the post and core-technique *International Endodontology Journal* **30(6)** 361-368.

33. Magura ME, Kafrawy AH, Brown CE Jr, & Newton CW (1991) Human saliva coronal microleakage in obturated root canals—an in vitro study *Journal of Endodontics* **17(7)** 324-331.

34. Kunzelmann KH, Jelen B, Mehl A, & Hickel R (2001) Wear evaluation of MZ100 compared to ceramic CAD/CAM materials *International Journal of Computerized Dentistry* **4(3)** 171-184.