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Biomechanical behavior of endodontically treated premolars using different preparation designs and CAD/CAM materials

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ABSTRACT

Objectives: To evaluate the effect of restoration design ('2.5-mm deep endocrown', '5-mm deep endocrown' or '5-mm deep post&crown') and CAD/CAM material type (composite or lithium disilicate glass-ceramic) on the load-to-failure of endodontically treated premolars in absence of any ferrule.
Methods: The crowns of 48 single-rooted premolars were cut and the roots were endodontically treated. Teeth were randomly divided into six groups (n = 8); teeth in each group were restored using one of the two tested materials with standardized CAD/CAM fabricated endocrowns (with either 2.5-mm or 5-mm deep intra-radicular extension) or conventional crowns (5-mm deep post&crown). After cementation using luting composite, the specimens were immersed in distilled water and subjected to 1,200,000 chewing cycles with a load of 50 N applied parallel to the long axis of the tooth (0°). After cyclic loading, a compressive load was applied at 45° to the tooth's long axis using a universal testing machine until failure. Load-to-failure was recorded (N) and the specimens were examined under a stereomicroscope with 3.5x magnification to determine the mode of failure.
Results: All specimens survived the 1,200,000 chewing cycles. A significant interaction between restoration design and CAD/CAM material was found using two-way ANOVA. In the '2.5-mm deep endocrown' groups, the composite achieved a significantly higher load-to-failure than the lithium disilicate glass-ceramic, while no differences between materials were found in the '5-mm deep endocrown' and '5-mm deep post&crown' groups. More unfavorable failures (root fractures) were observed for higher load-to-failure values.
Conclusions: Only following a '2.5-mm deep endocrown' design, composite appeared more favorable than lithium disilicate glass-ceramic as crown material; this may be explained by their difference in elastic modulus.
Clinical significance: Shallow endocrown preparations on premolars present less surface for adhesive luting and a difference in crown material becomes apparent in terms of load-to-failure. The use of a more flexible composite crown material appeared then a better option.

1. Introduction

The dental practitioner is often faced with a clinical dilemma when deciding how to restore endodontically treated premolars (ETPM) that suffered significant coronal loss. Due to poor structural integrity, those teeth have a higher risk of fracture and controversy exists with regard to the most suitable restoration technique [1].

In order to retain conventional crowns, the use of intra-root canal post&cores are standardly advocated to provide macro-retention [2]. Unlike metal posts that may weaken the root, fiber posts have an elastic modulus more similar to that of dentin; this characteristic is claimed to reduce the risk of catastrophic root

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fractures if the tooth is overloaded [3]. Furthermore, the development of effective adhesive luting composites promoted the distribution of occlusal stresses through the remaining tooth structure [4]. The 'endocrown' restoration was proposed by Pissis [5] in 1995 as an alternative crown for molars, depending on the availability of remaining tooth structure. The strategy consists of a single monobloc that comprises the entire crown and an intra-radicular extension that fits into the "endo-preparation". The preparation involves a circular equigingival butt-joint margin and a central cavity in the pulp chamber. All-ceramic endocrowns are retained by adhesive luting, and it is known that ceramics bonded to tooth structure induce a strengthening effect and an increase in fracture resistance [6]. Due to fewer clinical steps, no-post endocrowns seem also more practical in terms of time and costs [7].

The question that remains to be answered is the suitability of endocrowns to restore ETPM. The preliminary results of a clinical trial conducted by Bindl et al. [8] suggested endocrowns as a promising and efficient treatment method for crown reconstruction of molars and premolars. However, after four and a half years, the same authors considered endocrowns as inadequate for premolars [9]. They reported that this restorative approach was successful for 61 of the 70 restored molars (12% failure), while endocrowns on premolars underwent a higher failure incidence of 31% (5 out of 16 restorations). Loss of adhesion was the only failure reason for the premolars, thus indicating that the surface available for adhesive bonding may not have been large enough. Moreover, the unfavorable ratio between crown basis and crown height might cause a moment of force. Although suggested by Pissis [5] that the cavities must have 5-mm depth, Bindl et al. [8] reported that the depth of the central cavity was not standardized and ranged from 1 to 4 mm. It seems reasonable to hypothesize that the deeper the pulp-cavity preparation for an endocrown and the deeper the resultant intra-radicular extension, the greater the surface area for adhesive retention and the better the transmission of masticatory forces to the root [10]. Yet, there is a lack of data about the influence of the endocrown design on the biomechanical behavior of restored ETPM, and up till now, no studies have investigated the effect of the length of the intra-radicular extension. Another consideration is the use of newer and more flexible composite CAD/CAM milling blocks instead of ceramic ones that were originally described for the endocrown technique and used by Bindl et al. [9]. From a biomimetic perspective, these less brittle composite CAD/CAM blocks exhibit mechanical properties that more closely approximate those of human dentin [11]. Some *in vitro* studies showed a higher fracture resistance and more favorable fracture mode in molars [12–14]; in this way they were also suggested to have great potential for endocrowns. However, a recent study conducted by Gresnigt et al. [15] reported that endocrowns made of composite are more vulnerable under non-axial loading. Ultimately, no studies reported the application of these novel CAD/CAM materials to restore extensively decayed premolars.

Therefore, the objective of this *in vitro* study was to evaluate the effect of the restoration design ('2.5-mm deep endocrown', '5-mm deep endocrown' or '5-mm deep post&crown') and the CAD/CAM material type (composite or lithium disilicate glass-ceramic) on the load-to-failure of restored ETPM. The null hypotheses tested were that the restoration design and the CAD/CAM material type do not have a significant influence on the load-to-failure of restored ETPM.

2. Materials and methods

The brands, manufacturers, types, compositions and batch numbers of the materials used are listed in Table 1. Forty-eight sound and single-rooted premolars (gathered following the protocol approved by the Commission for Medical Ethics of KU Leuven under file number S57622), stored in 0.5% chloramine, were selected by visual inspection. All teeth had one radiographically visible root canal and similar dimensions at the cemento-enamel junction (CEJ; bucco-lingual: 7.2 ± 1.0 mm; mesio-distal: 5.0 ± 0.5 mm) and a root length of 13 ± 1.0 mm. Teeth with widely curved or atypically shaped roots were excluded.

The crowns of the teeth were removed by cutting at the level of the CEJ, using a water-cooled, low-speed diamond saw (Isomet

Table 1
Materials used for adhesive luting.

Brand	Manufacturer	Type	Composition	Batch no.
Cerasmart	GC, Tokyo, Japan	Resin composite CAD/CAM block	Silica (20 nm) and barium glass (300 nm) nanoparticles (71 wt.%), Bis-MEPP, UDMA and DMA polymers (29 wt.%)	1403101
IPS e.max CAD	Ivoclar Vivadent, Schaan Liechtenstein	Lithium disilicate glass-ceramic CAD/CAM block	SiO_2 (57–80%), Li_2O (11–19%), K_2O (0–13%), P_2O_5 (0–11%), ZrO_2 (0–8%), ZnO (0–8%) and other colouring oxides (0–12%)	T08295
Fiber Post	GC	1.6-mm diameter tapered fiber post	Methacrylates and glass fibers (11.85 μm diameter), fibers/matrix ratio: 57.83%	400001
Gradia Core + Self-etching Bond A + B	GC	Dual-curing composite for core build-up & post cementation	20–30% methacrylic acid ester, 70–75% fluoro-alumino-silicate glass, 1–5% silicon dioxide	1312201
Ceramic Primer II, GC	GC	Ceramic and composite bonding primer	90–100% ethanol, 1–5% 2,2′-ethylene dioxydiethyl dimethacrylate, 1–5% methacryloyloxydecyl dihydrogen phosphate, <1% (1-methylethylidene) bis[4,1-phenyleneoxy(2-hydroxy-3,1- propanediyl)] bismethacrylate	1401221
Monobond Plus	Ivoclar Vivadent	One component primer	Ethanol, 3-trimethoxysilsylproylmethacrylate, methacrylated phosphoric acid ester	S02028
Clearfil Esthetic Cement + ED Primer II A & B	Kuraray Noritake, Tokyo, Japan	Dual-curing composite cement	*Paste A:* bis-GMA, TEG-DMA, hydrophobic aromatic dimethacrylate, silanated barium glass filler, colloidal silica *Paste B:* bis-GMA, TEG-DMA, hydrophobic aromatic dimethacrylate, hydrophilic aliphatic dimethracrylate, silanated barium glass filler, silanated silica, colloidal silica, catalysts, dl-camphorquinone, pigments	590012
IPS Ceramic Etching Gel 5%	Ivoclar Vivadent	Ceramic etching gel	Aqueous solution of hydrofluoric acid (<5%)	S51072
Aluminum Oxide	Danville Materials, San Ramon, CA, USA	Particles for sandblasting	Aluminum oxide 27-μm particles	28482

1000, Buehler, Lake Bluff, IL, USA) (Fig. 1). No enamel was left on the remaining roots. They were endodontically treated following a standardized crown-down technique using a rotary files system (Pro-Taper, Dentsply-Maillefer, Konstanz, Germany; X-Smart-Endo-motor, Dentsply-Maillefer). The apical foramen was prepared to size 30 and the root canal was irrigated with 2.5% NaOCl solution after each instrument change. Root canals were dried with paper points and filled with an epoxy resin-based root-canal sealer (Top Seal, Dentsply-Maillefer) and tapered gutta-percha points using a hot continuous-wave condensation technique (System-B Heat Source, Sybron Endo, Amersfoort, The Netherlands). The root access was temporarily filled with composite (Clearfil AP-X, Kuraray Noritake, Tokyo, Japan) and all teeth were stored in distilled water at 37 °C during 24 h.

All roots were covered at the outside with an air-thinned layer (approximately 0.3-mm thick) of latex solution (Erkoskin, Erkodent, Pfalzgrafenweiler, Germany) to simulate the periodontal ligament (Fig. 1). Specimens were then positioned in a cylindrical plastic mold (20-mm high; 10.5-mm diameter) and embedded in methylmethacrylate resin (ClaroCit, Struers, Ballerup, Denmark) at 3 mm from the CEJ to simulate an acceptable biological width between the preparation finish lines and the alveolar bone. The teeth were randomly distributed in accordance with the three different preparation designs (Fig. 1):

- '2.5-mm deep endocrown': in each root, a standardized 2.5-mm deep central inlay-type cavity was prepared using a 5° tapered and 80-µm grit diamond bur (SBR5 Smooth Cut, GC) mounted in a high-speed air turbine (650, KaVo, Biberach, Germany), which was guided by a custom-made plexiglass matrix (MicroSpecimen Former, University of Iowa, Iowa City, IA, USA). The cavities were oval-shaped with a 2-mm mesial-distal width and a 4.5-mm buccal-palatal width at the top and dentin margins of at least 1-mm wide (Fig. 1). The internal cavo-surface line angle was rounded and the finish lines were polished using a 25-µm grit diamond bur (SBR5f Smooth Cut, GC) and abrasive discs (Sof-Lex 2382C and 2382F, 3 M ESPE).
- '5-mm deep endocrown': each root was prepared and finished in the same standardized manner as the previous group; however, the depth of the central inlay-type cavity was 5 mm
- '5-mm deep post&crown': post spaces were prepared at a 5-mm depth into the root canal with a 1.6-mm diameter using a low-speed tungsten bur (Drill Refill, GC, Tokyo, Japan). Each prepared root canal was rinsed with distilled water and dried with paper

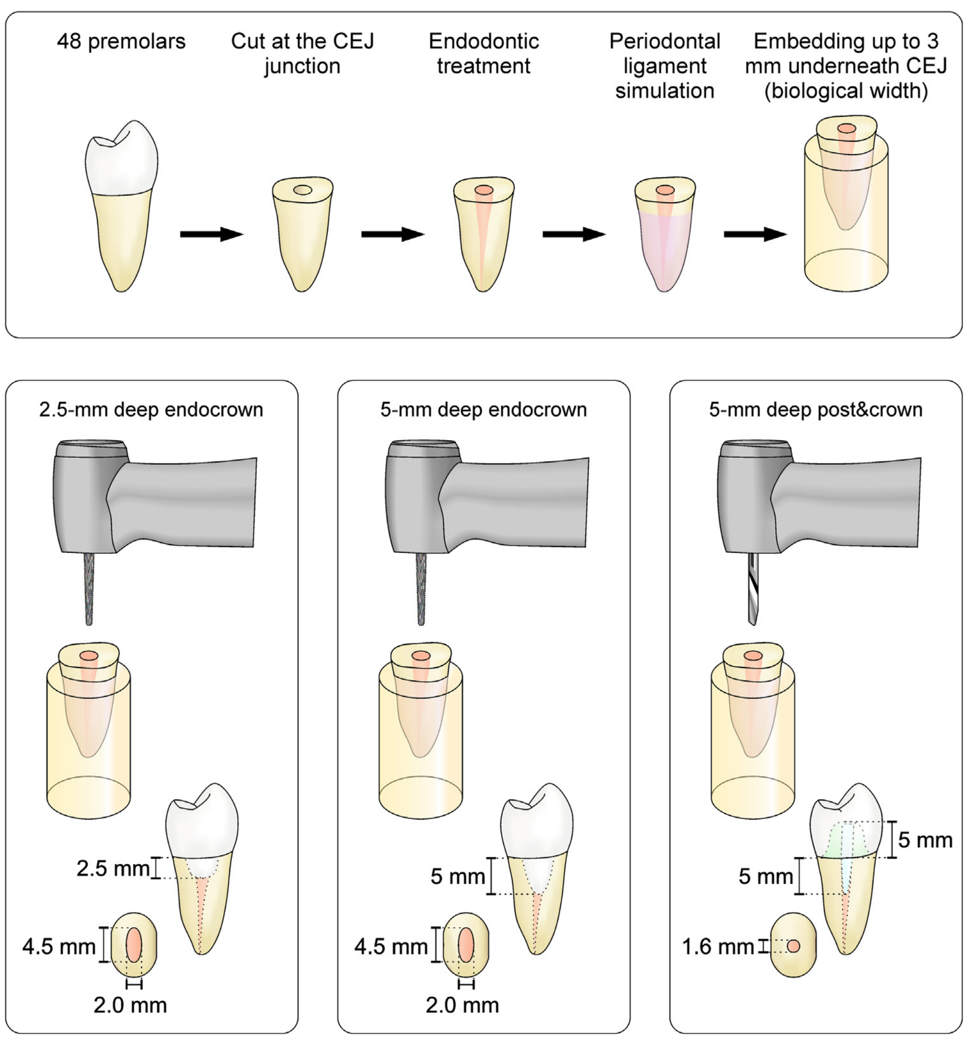

Fig. 1. Schematic explaining the study setup. The crowns of 48 sound premolars with similar dimensions were cut at the CEJ level. Next, the roots were endodontically treated, embedded in methylmethacrylate resin and prepared in accordance with the respective restoration design.

points. Translucent 4° tapered glass-fiber posts (GC Fiber Post – color code blue, GC) of 1.6-mm coronal and 0.7-mm apical diameters, were cut at 10-mm length from the most apical part, cleaned with alcohol and silanized during 60 s (Ceramic Primer II, GC). The post spaces were treated with a self-etch adhesive (Gradia Core Self-Etching Bond A + B, GC) for 5 s and after 30 s they were dried with medium air-pressure and light-cured for 10 s using a LED curing unit (Bluephase 20i, Ivoclar Vivadent, Schaan, Lichtenstein) with an approximate output of 1200 mW/cm^2, verified with a radiometer (Bluephase Meter, Ivoclar Vivadent). Posts were cemented using a dual-curing luting composite (Gradia Core, GC) and cured from the top of the posts for 15 s. Standardized cores were built with the same dual-curing composite material, which was dispensed into a custom-made transparent silicon matrix (2.4-mm mesio-distal x 4.4-mm bucco-lingual x 5-mm high; Memosil 2, Heraeus Kulzer, Hanau, Germany). Each post was fully covered by the matrix, which was centrally positioned by the same operator and dentin margins of at least 1 mm in width were ensured. After light-curing during 10 s from each surface (buccal, lingual, mesial, distal and occlusal), the matrix was removed and the core preparation was finished using a 5° tapered and 25-μm grit diamond bur (SBR5f Smooth Cut, GC) and abrasive discs (Sof-Lex 2382C and 2382F, 3 M ESPE, Seefeld, Germany).

A custom-made dental typodont allowed a standardized positioning of the methylmethacrylate cylinders, where teeth were previously fixed. A niche with dimensions identical to those of the cylinders (20-mm high; 10.5-mm diameter), located at the upper second premolar site was provided with a stop at the cervical area. Hence, a tight fit and exact positioning of each sample into the typodont, with the preparation margins of all specimens at the same level, was ensured. Digital optical impressions were taken with a powder-free chairside intraoral scanner (Cerec Omnicam, Sirona, Bensheim, Germany). The camera was rotated from the occlusal aspect to the buccal and lingual sides with an angle to the tooth long axis. Additionally, for the '5-mm deep endocrown' specimens, images of the internal surfaces of the preparations were properly acquired by using a wave motion of the camera in the mesio-distal and bucco-lingual directions. An intact lower jaw typodont was also scanned and used as antagonist for occlusal bite registration. Restorations were automatically designed by the Cerec AC CAD/CAM software (SW 4.3, Sirona) using the Biogeneric Variation of 0.20 (Fig. 2). The restoration-design parameters were: 50-μm spacer, 0-μm occlusal milling offset, 25-μm proximal contact strength, 25-μm occlusal contacts strength, 25-μm dynamic contacts strength, 1000-μm minimal radial thickness, 1000-μm minimal occlusal thickness and 500-μm margin thickness.

Specimens from each preparation design were divided in two groups and restorations were milled from a 14-size CAD/CAM block: composite (Cerasmart, GC) or lithium disilicate glass-ceramic (IPS e.max CAD, Ivoclar Vivadent). All restorations were milled at the same CAM unit (Cerec MC XL, Sirona) using the 'normal' milling mode, and immediately luted without use of provisional restorations. This resulted in 6 experimental groups (n = 8) according to the preparation design and the CAD/CAM block type.

The intaglio surface of each restoration was treated according to the manufacturer's instructions for the respective block material. The composite surface was sandblasted with 27-μm aluminum oxide particles (MicroEtcher CD, Danville Materials, San Ramon, CA, USA), perpendicular to the surface from a distance of 10 mm during 20 s with 0.28-MPa pressure. Remaining particles were removed using a gentle air-blow for 5 s. A silane solution (Ceramic Primer II, GC) was applied and allowed to dry for 60 s. The lithium disilicate glass-ceramic surface was etched with 5% hydrofluoric acid gel (IPS Ceramic Etching Gel (5% HF), Ivoclar Vivadent) for 20 s and then cleaned for 5 min in an ultrasonic bath. A silane coupling agent (Monobond Plus, Ivoclar Vivadent) was applied and allowed to dry for 60 s.

After cleaning the preparations with pumice slurry, followed by drying, the restorations were luted using a dual-curing cementation system (Clearfil Esthetic Cement, Kuraray Noritake). Equal amounts of the self-etch adhesive components were mixed (ED Primer II A & B, Kuraray Noritake), applied on the preparation surface and left for 30 s. The excess was wiped away using mild oil-free air. The two luting composite pastes (Clearfil Esthetic Cement Paste A & B, Kuraray Noritake) were dispensed from the automix syringe on the preparation surface and the inner restoration

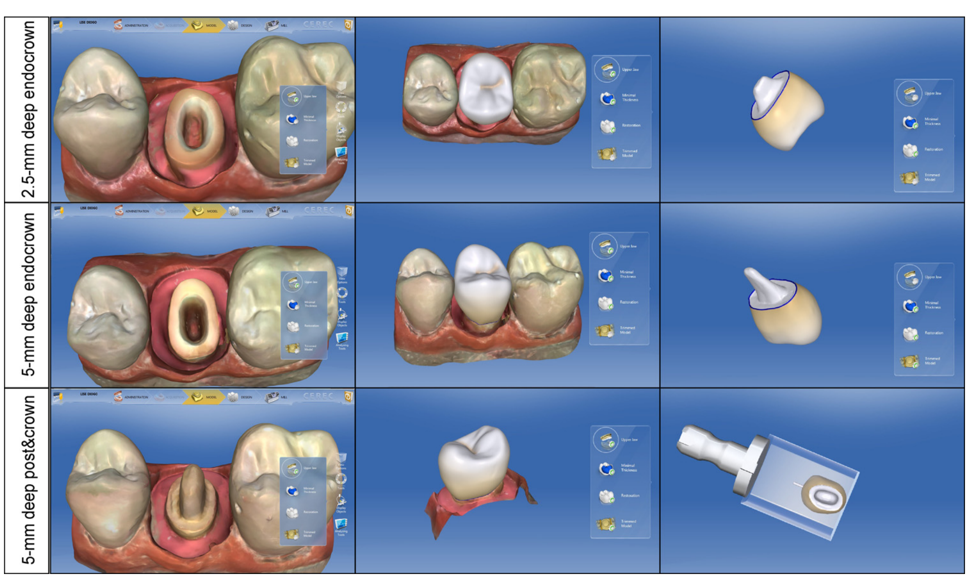

Fig. 2. Each specimen was placed in a custom-made typodont with adjacent teeth, digitally scanned and the restorations designed and milled using the Cerec 3 CAD/CAM system.

surface. All specimens were placed under a constant load of 1 kg maintained perpendicularly to the occlusal surface for 5 min. The restoration margins were covered with a glycerin gel (Liquid Strip, Ivoclar Vivadent) to prevent oxygen inhibition of polymerization, and light-cured for 20 s from each side using the same LED curing unit. The cementation lines of the restorations were finished with sandpaper polishing discs (Sof-Lex, 3 M ESPE).

After one-day storage in distilled water at 37 °C, the specimens were subjected to a fatigue aging of 1,200,000 cycles using a chewing simulator machine (SD Mechatronik, Chewing Simulator, Willytec, Munich, Germany). With the specimens positioned into chambers containing distilled water, a load of 50 N was applied with a 6-mm diameter ceramic ball-shaped stylus (Steatite, CeramTec, Plochingen, Germany) in the center of the occlusal surfaces. Load was applied parallel to the long axis of the teeth (0°) at a frequency of 1.6 Hz. The machine was equipped with infrared LVDT (Linear Variable Displacement Transducer) displacement-sensors connected to PC software and able to detect failures due to displacements of 100 μm.

Next, specimens were mounted in a fracture-test setup (5848 MicroTester, Instron, Norwood, MA, USA) with a 45° inclination (oblique to the long axis of the tooth) and loaded in compression until failure. The load was applied towards the inner slope of the buccal cusp using an antagonist 6-mm diameter stainless-steel ball at a crosshead speed of 0.5 mm/min. The maximum load-to-failure was recorded in Newton (N) and mean values were calculated per group. The failure mode was determined under a stereomicroscope with 3.5x magnification and categorized based on a 2-examiner agreement either as ”unfavorable” when a root fracture was observed (which in a clinical situation would require tooth extraction) or ”favorable” when the cause of failure was only de-bonding and/or cohesive fracture of the restoration.

The Shapiro-Wilk test was used to assess normal distribution of the data. As the load-to-failure data (N) were normally distributed ($p > 0.05$), groups were compared using two-way analysis of variance (two-way ANOVA) for the factors ‘restoration design’ and ‘CAD/CAM material type’, and *post-hoc* Tukey multiple comparisons at a significance level of $p < 0.05$. To make sure that the teeth were properly randomized regarding the dimensions, the Pearson's correlation was calculated. The relationship between load-to-failure and failure mode was analyzed using Student's *t*-test ($p < 0.05$). The data were analyzed with statistical softwares (SPSS 21.0, IBM Corp., Chicago, USA; R Core Team, Foundation for Statistical Computing, Vienna, Austria).

3. Results

All specimens survived the aging induced by the 1,200,000 cycles of chewing simulation without detectable damage. The load-to-failure results for the six experimental groups are shown in Fig. 3. When the means were pooled for restoration design, no significant differences were found ($p = 0.485$). Regarding the CAD/CAM material type, the mean results of both materials did not significantly differ from each other ($p = 0.772$). However, there was a significant interaction effect between the restoration design and the CAD/CAM material type ($p < 0.001$). A significantly higher load-to-failure was recorded for the ‘2.5-mm deep endocrown’ made of composite in comparison with those made out of lithium disilicate glass-ceramic. The composite showed a significantly lower load-to-failure for the ‘5-mm deep endocrown’ and ‘5-mm deep post&crown’ designs than for the ‘2.5-mm deep endocrown’. The lithium disilicate glass-ceramic revealed the opposite outcome, with the ‘2.5-mm deep endocrown’ resulting in a significantly lower load-to-failure than the ‘5-mm deep endocrown’.

When considering all groups together, significantly more unfavorable failures were observed for higher load-to-failure values (Student's *t*-test, $p \leq 0.0001$) (Fig. 4). The failure mode

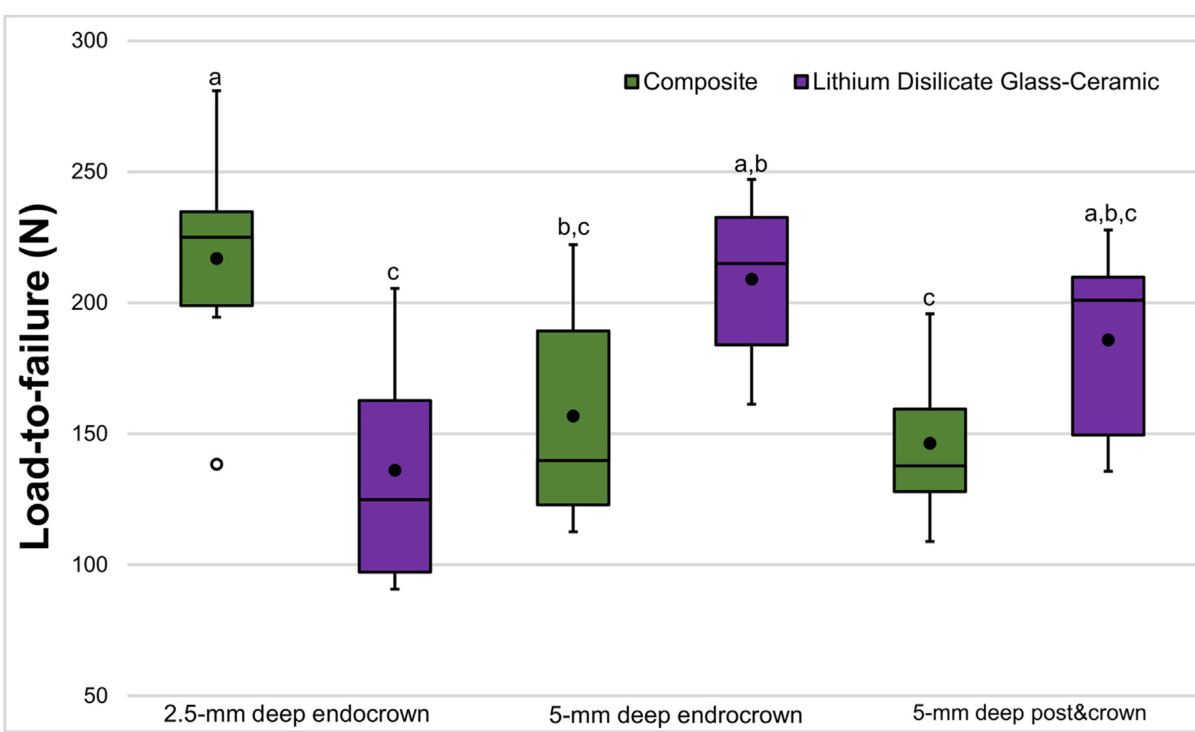

Fig. 3. Boxplots of the load-to-failure results. The box represents the spreading of the data between the first and third quartile. The central horizontal line and the black dot represent the median and mean, respectively. The whiskers extend to the minimum and maximum values measured, with the exception of the outlier that is represented with an open dot (°).Groups with the same capital letter are not significantly different (two-way ANOVA and Tukey's HSD, $p \leq 0.05$).

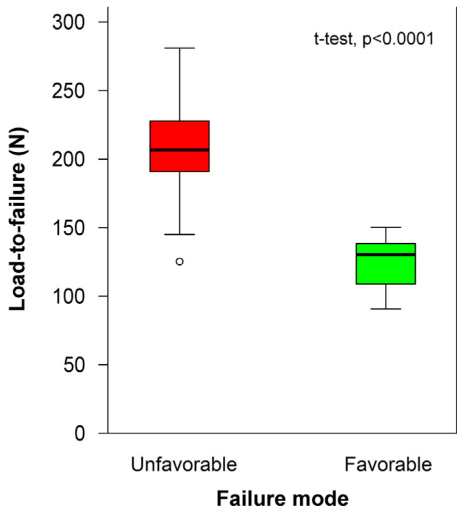

Fig. 4. Effect of the load on the failure mode (Student's *t*-test, $p \leq 0.0001$).

analysis showed a predominance of root fractures for the majority of the experimental groups; only two combinations of restoration design and CAD/CAM material ('2.5-mm deep endocrown' made of lithium disilicate glass-ceramic and '5-mm deep post&crown'; made of composite) yielded more de-bonding and/or displacements of the restorations without root fractures.

The different types of failures are shown in Fig. 5. Among the '2.5-mm deep endocrowns'; made of composite that presented root fractures, cohesive fracture of the intra-radicular extension of the restorations was observed in five specimens. The same 2.5-mm deep design made of lithium disilicate glass-ceramic induced de-bonding of all restorations and the only three root fractures occurred above the simulated alveolar bone. Fracture of the intra-radicular extension was observed in all '5-mm deep endocrowns'; made of composite; however, three specimens did not present root fractures. The same type of cohesive failure of the restorative material was observed in 6 out of 8 specimens made of lithium disilicate glass-ceramic; however, all the specimens of this group were classified as unfavorable due to the presence of root fractures. The '5-mm deep post&crown'; did not present cohesive failures within the restorative materials and de-bonding between the fiber post and the root canal was observed for the majority of specimens.

4. Discussion

With the intent of investigating the biomechanical behavior of ETPM restored with different restoration designs and CAD/CAM materials, the load-to-failure and failure mode under an oblique compressive load after fatigue aging were evaluated. Natural premolars with similar dimensions were selected in an effort to reduce confounding variability. There was no effect of the tooth dimensions on the obtained load-to-failure values ($r^2 = 0.0089$; $p = 0.2798$). Due to the fact that each specimen was inserted in the same custom-made typodont model with adjacent teeth and considering the occlusal bite reference provided by the antagonist model, the CAD/CAM system was able to reproduce samples that were nearly equal in coronal volume (distance between proximal contact areas: 6.8 mm; distance between buccal and lingual faces: 8.9 mm; height from the margin to the top of the buccal cusp: 7.5 mm; height from the margin to the top of the lingual cusp: 6.8 mm) and occlusal anatomy; standardization of the point of load application during testing was guaranteed.

No significant difference was found among the tested restoration designs and between the two CAD/CAM materials; thus, the null hypothesis cannot be rejected. Considering only the restoration design factor, no evidence was found that a deeper retention of 5 mm would improve the 45° load-to-failure of restored premolars. A shallow preparation could be interesting once it decreases the risk of accidental root perforation and avoids additional removal of sound tooth tissue that would weaken the tooth-root complex. However, even for the '2.5-mm deep endocrown' preparation

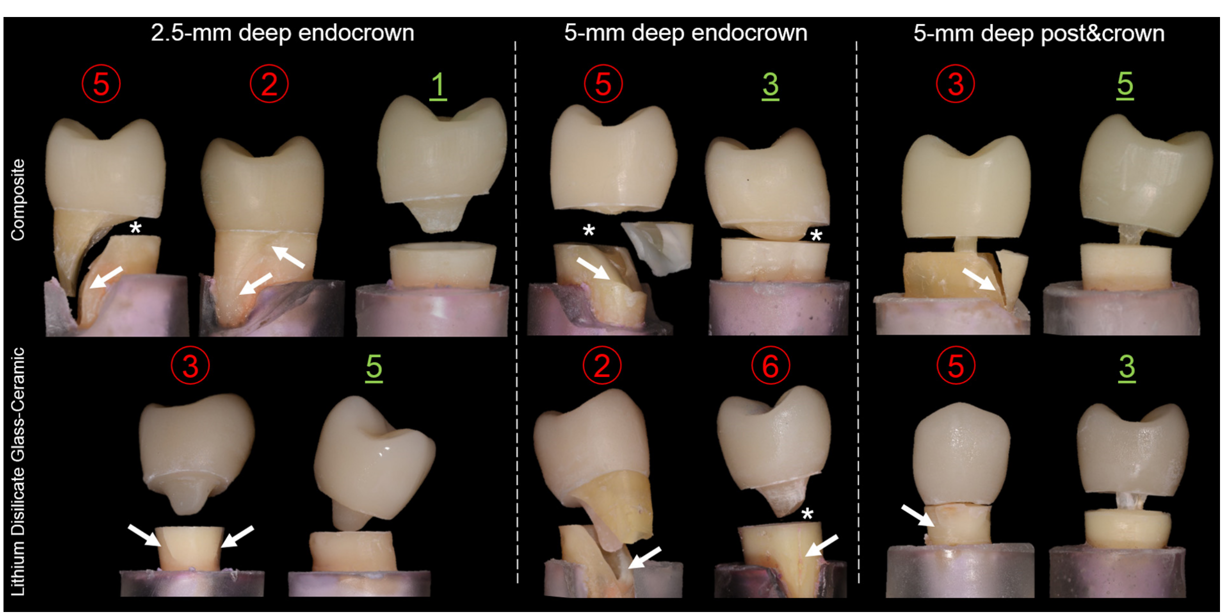

Fig. 5. Photographs of the failure modes for each experimental group. Circled and underlined numbers represent the number of unfavorable and favorable failures, respectively. Asterisk: cohesive failure of the restorative material. Arrow: root fracture (the embedding resin was partially removed in some specimens to visualize the fracture).

design, root fractures were observed on more than half of the specimens, what corroborates with the study of Forberger et al [16]. When considering only the CAD/CAM material type factor, no evidence was found that the choice either for lithium disilicate glass-ceramic (IPS e.max CAD, Ivoclar Vivadent) or the composite (Cerasmart, GC) would result in higher load-to-failure. So far, there are no studies comparing ceramic versus non-ceramic endocrowns on premolars; few studies using molars reported no significant difference on load-to-failure under axial loading [15], better performance for composite-based CAD/CAM materials under oblique loading[14] and lower load-to-failure under lateral loading [15]. The only study using anterior teeth reported a similar outcome regardless the restoration material employed [17].

A highly significant interaction effect between the restoration design and CAD/CAM material type was found; hence, the null hypothesis had to be rejected. When the ETPMs were restored using the '2.5-mm deep endocrown' approach, the composite (Cerasmart, GC) performed significantly better than the lithium disilicate glass-ceramic (IPS e.max CAD, Ivoclar Vivadent) in terms of load-to-failure ($p < 0.001$). While in the other deeper restoration designs ('5-mm deep endocrown' and '5-mm deep post&crown') the friction against the intra-radicular walls provided extra macro-mechanical retention[10], the retention following the '2.5-mm deep endocrown' design relied mainly on pure adhesion. In this situation, the whole interface is located very close to the rotation center of the moment of force created by the oblique load, considering that the extension of 2.5 mm was located above the simulated bone level represented by the embedding resin. More displacements of restorations due de-bonding at the luting interface were found with lithium disilicate glass-ceramic (5 out of 8) at lower oblique loads (136.1 ± 47.4 N) than with the composite (1 out of 8) at higher loads-to-failure (216.9 ± 41.2 N). However, this difference might not exclusively be related to the bond strength of both restorative materials to dentin, but also to their elastic modulus and consequent durability under shear stress. More brittle restorative materials tend to induce cohesive failure within the luting composite at lower load values, this due to an increased stress concentration at critical areas such as the edge of the luting interface [18]. Indeed, the composite (Cerasmart, GC) may have resulted in a more uniform stress distribution and higher load-to-failure, due to its lower modulus of elasticity (7.5 GPa), which is more in line with that of dentin (5.3–13.3 GPa), in contrast to the higher elastic modulus (95 GPa) of lithium disilicate glass-ceramic (IPS e.max CAD, Ivoclar Vivadent) [11]. This feature increases the ability of the cemented composite restoration to be more flexible under loading and to distribute stress more evenly [19]. On the other hand, more than half of '2.5-mm deep endocrown' specimens made of lithium disilicate glass-ceramic did not present root fractures (Fig. 5), which can be an advantage since de-bonded restorations could be re-luted after surface conditioning.

At 5-mm deep preparation designs, the type of CAD/CAM material did not influence the load-to-failure ($p = 0.097$ for the '5-mm deep endocrown'; $p = 0.213$ for the '5-mm deep post&crown'). A recent *in vitro* and finite element analysis study investigated the mechanical behavior of a 5-mm deep cavity preparation [20]. It was claimed that ETPM restored with post&crown or a 5-mm deep endocrown might present a similar probability to fail under normal occlusion, hereby corroborating the findings in this study. In previous studies, posts with an elastic modulus similar to that of dentin resulted in fewer root fractures than in case posts with a higher elastic modulus were employed [16,20,21]. In analogy with these findings, the higher incidence of root fractures recorded in our study with the '5-mm deep endocrowns' made of IPS e.max CAD (Ivoclar Vivadent) compared to those made of Cerasmart (GC) may have resulted from the stiffer lithium disilicate glass-ceramic versus the more resilient composite. Interestingly, the cohesive fracture of the composite intra-radicular extension at the cervical area did not induce root fractures. For both restorative materials, the cohesive fracture at the apical area of the intra-radicular extension was associated with unfavorable failures (Fig. 5).

The maximum load-to-failure in our study is lower than generally found in literature [16,21], which can be explained by (1) the severe aging protocol in the chewing simulator, (2) the 45° oblique load that created a large moment of force on the premolar, and (3) the absence of ferrule. None of the specimens failed during the 1,200,000 fatigue cycles, which suggests that the restorations can withstand the repetitive occlusal loads that teeth are normally subjected to during oral function [22]. However, this aging protocol might have stressed the tooth-restoration complex and consequently have resulted in a lower load-to-failure under the compressive test. The applied 45° load was more detrimental because the stress was not distributed along the long axis of the tooth, but was more concentrated at the cervical area [23,24]. This oblique direction simulates a very high single load-to-failure and enhances the fracture probability [25]. Different from other studies [26,27], no ferrule was created in any of the groups; hence, the worst-case scenario was simulated, since absence of ferrule is known to decrease the fracture resistance considerably and so the influence of the restoration design and CAD/CAM materials may have been more critical [28,29]. In fact, without a ferrule, post&core materials and post length are expected to exhibit a stronger influence on the stress distribution in the restored tooth [30]. Different dentin bonding strategies, such as for instance the application of immediate dentin sealing in a fully 'indirect' restorative workflow (in contrast to the 'semi-direct' restorative workflow employed in this study) [31], may influence the study outcome and should be investigated in further studies. Furthermore, the presence of remaining enamel on the preparation margins is beneficial for adhesion and might also have an influence on the premolar's load-to-failure [26,27]; thus, comparisons with our findings must be interpreted with caution. Randomized controlled clinical trials remain definitely needed to relate these findings to the clinical function.

5. Conclusions

The standardized conditions allow the following conclusions to be drawn for the restoration of ETPM in absence of any ferrule:

- The three restoration designs ('2.5-mm deep endocrown', '5-mm deep endocrown' and '5-mm deep post&crown') combined with both CAD/CAM material types (composite and lithium disilicate glass-ceramic) provided enough resistance to withstand the chewing aging;
- Under a single 45° oblique loading, the '2.5-mm deep endocrown' design could withstand a significantly higher load-to-failure, when made of composite, while the CAD/CAM material type was not significant for the '5-mm deep endocrown' and '5-mm deep post&crown' designs;
- Significantly more root fractures were observed for higher load-to-failure values.

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