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Effects of minimally invasive endodontic access cavity in molar teeth on polymerization, porosity and fracture resistance

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Minimally invasive access cavities have been proposed in the last decade to reduce tooth tissue loss during endodontic treatment and mitigate compromised fracture resistance of endodontically treated teeth. Fracture resistance of molars with different types of access cavity design may be affected by restorative materials and aging. Insufficient literature data exist on the effect of cavity design and type of restorative materials on restorative aspects such as material adaptation or photo-polymerization in restricted access cavities. This study analyses quality of polymerization, material adaptation and fracture resistance of molars with different types of access cavities restored with glass-ionomer, high-viscosity fiber-reinforced bulk-fill and nanofilled resin composite. Plastic molar teeth with truss (TREC) and traditional endodontic access cavity (TEC) were restored with nanofilled composite (Filtek Supreme), glass-ionomer Fuji IX and Filtek or fiber-reinforced everX Posterior and Filtek. Porosity was determined using microcomputer tomography and the degree of conversion of resin-based materials using micro-Raman spectroscopy. Human molars prepared and restored in the same way were used for fracture resistance testing at baseline and after thermocycling. The results demonstrate that high-viscosity fiber-reinforced composite was difficult to adapt in TREC cavity leading to greater porosity than Filtek or Fuji. TREC design did not affect composite polymerization and led to higher fracture resistance of restored molars compared to TEC but also more unrestorable fractures.

Keywords Access cavity, Resin composites, Glass ionomer, Fracture resistance, Degree of conversion, MicroCT

Minimally invasive access cavities have been proposed in the last decade to reduce tooth tissue loss during endodontic treatment and mitigate compromised fracture resistance of endodontically treated teeth¹. So far research ascertained the effects of minimally invasive access cavities on various aspects of endodontic treatment and fracture resistance of teeth^{2–9}. Two recent systematic reviews concluded that minimally invasive access cavities require specific clinical setting for optimal results, e.g. endodontic microscope, high illumination, thin and flexible instruments, prolonged and activated irrigation with high irrigant concentration, retrograde surgical tips for cleaning pulp horn areas and intracanal dressing with calcium hydroxide^{2,3}. Studies on the effects of minimally invasive access cavities on fracture resistance of endodontically treated teeth revealed inconsistent results with studies showing no difference^{2–9} or favouring minimally invasive access cavities^{10–14}.

Only recently have the restorative aspects of the procedure gained interest, indicating difficulties in material adaptation and remaining voids in restricted access cavities¹⁵. Even traditional access cavities have been associated with increased gaps and voids in temporary¹⁶ and definitive restorations¹⁷. So-called “truss” access

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cavities are minimally invasive access cavities that involve 2 or more small-sized cavities matching the diameter of root canal orifices². These are connected via remaining dentin, often referred to as existing dentinal bridge, which may hinder light penetration and may have adverse effects on polymerization and material adaptation in general.

Conservative approach in minimally invasive endodontic access cavities allows considerable portion of the crown to be preserved⁸. This gives preference to direct rather than indirect restorative options following endodontic treatment, particularly in pulpotomy cases when radicular pulp is expected to remain vital. Traditional full coverage restorations remain a common restorative option for endodontically-treated teeth. However, recent evidence indicates more conservative options should be taken into consideration, such as endocrowns if there is retention of at least 2 mm of the material in the pulp chamber¹⁸ or direct restorations with appropriate cuspal coverage^{18,19}. Literature lacks data when both minimally invasive endodontic access cavities and minimally invasive restorative approaches are employed to maximize the remaining tooth structure.

A variety of restorative materials are at the clinician's disposal for restoring such teeth. While universal resin-based composites are commonly the first choice, a combination of universal resin-based composites with fiber-reinforcement or a glass ionomer bulk core are also feasible options. With greater amount of dentin removal in endodontic access cavity preparation, fiber-reinforced composites may offer higher fracture resistance when compared with other resin-based composites²⁰.

Light attenuation is especially relevant in deeper cavities, when the light tip is at an increased distance from the material, leading to decreased conversion²¹. Angulation of the light tip would be required in minimally invasive endodontic cavities, with the remaining dentin above the pulp chamber allowing for direct contact with the restorative material. It was previously reported that angulation of the light tip has an adverse effect on polymerization of resin-based materials, adhesives²² and resin-based composite²³. Dental tissues further attenuate light from the light-curing unit²³. Insufficient light energy at the bottom of the resin-based composite results in suboptimal curing, which may lead to inferior mechanical characteristics^{24–28} and susceptibility for biofilm formation²³.

Insufficient literature data exist on the effect of cavity design and type of restorative materials on restorative aspects such as material adaptation or polymerization in restricted access cavities. Furthermore, there is limited information on the effect of restorative materials and aging on fracture resistance of teeth with different types of minimally invasive access cavities. In previous research, universal or bulk-fill resin-based composites were used as the sole restorative material, thereby excluding restorative material as an independent factor whilst the majority of studies either omitted aging (e.g. thermocycling) or included this step for all specimens^{13,14}. Additionally, no study has taken into consideration the possibility of a minimally invasive access cavity in a vital pulp therapy (full pulpotomy) case, leaving root canals untreated, which has been recommended as a viable option in permanent teeth^{29–32}.

The aim of this study was to determine the quality of polymerization and the porosity of restorative materials and fracture resistance of molars with different types of access cavities restored with glass-ionomer, high-viscosity fiber-reinforced bulk-fill and nanofilled resin composite. A further aim was to study the effect of thermocycling on fracture resistance of molars with mesio-occluso-distal (MOD) cavities and traditional or truss endodontic access cavities in a simulated vital pulp therapy (full pulpotomy) case. The design of the traditional endodontic access cavity included direct restoration with cuspal coverage whereas the truss design included direct restoration without cuspal coverage. The null hypotheses were that there are no statistically significant differences in the degree of conversion (DC) of restorative materials relative to cavity design (H_0 #1), in porosity of restorative materials relative to cavity design and restorative material (H_0 #2), in fracture resistance and types of fracture of molars relative to cavity design, restorative material and aging (H_0 #3).

Materials and methods

The study was approved by the University of Belgrade School of Dental Medicine Ethics Committee (Decision No. 36/10). All methods were performed in accordance with the relevant guidelines and regulations. Extracted teeth were collected from patients undergoing extraction for reasons unrelated to this study who provided written consent for their extracted teeth to be used for research purposes.

Pilot study for specimens – DC and porosity measurements

A pilot study was conducted to compare differences between human and plastic teeth for inclusion criteria for DC and porosity measurements. An MOD cavity was prepared in 3 plastic molars and 3 human third molars without cuspal reduction: occluso-cervical height was 4 mm, the distance between the buccal and oral walls were 4 mm and the gingival wall was 1 mm above the CEJ. The width of each of the gingival walls was 2 mm. A truss access endodontic cavity (TREC) was prepared by preserving part of the pulp chamber roof as a “bridge” connecting buccal and oral cavity walls with a thickness of 2 mm. The entire cavity was restored with Filtek (Table 1) applied in 2 mm thick increments, each light-cured for 40 s using an LED light-curing unit (Elipar Freelight, 3M). The light tip was supported by mesial cusps at 60° angle from the mesial direction, and by distal cusps at 60° angle from the distal direction.

The DC was determined as described in the main experiment (see under **Degree of conversion, porosity and fracture resistance testing**). Understanding the full width half maximum (FWHM) is vital for optimizing experimental design, interpreting spectroscopic data accurately and ensuring the precise analysis of complex mixtures. FWHM, is a statistical measure used to describe the width of a normal distribution. Specifically, it represents the width of a curve measured between the two points where the curve's value is half its maximum.

This preliminary analysis showed no significant difference in DC of resin composite in plastic or human teeth, when either peak intensity ($p=0.2051$; 95% confidence interval of difference -0.09840 to 0.02285) or full

Material	Manufacturer	Type	Composition
Filtek Supreme Code: Filtek	3 M ESPE St Paul, MN, USA	Nanocomposite	<i>Matrix:</i> bis-phenol A diglycidylmethacrylate (bis-GMA), triethylene glycol dimethacrylate (TEG-DMA), urethane dimethacrylate (UDMA), bisphenol A polyethylene glycol diether dimethacrylate <i>Filler:</i> silica nanofillers (5–75 nm) zirconia/silica nanoclusters (0.6–1.4 μm) <i>Filler content:</i> 78.5% (w/w) 59% (v/v)
everX Posterior Code: everX	GC EUROPE N.V., Leuven, Belgium	Fiber-Reinforced Composite	<i>Matrix:</i> Bis-GMA, PMMA, TEGDMA <i>Filler content:</i> 74.2 wt%, 53.6 vol% Short E-glass fiber filler, barium glass
Fuji IX GP Code: Fuji	GC Tokyo, JAPAN	GIC	Polyacrylic acid, fluoroaluminosilicate glass, polybasic carboxylic acid. Particle size: 10 μm. (70–80%)
Single Bond Universal Code: SBU	3 M ESPE, St Paul, MN, USA	Universal adhesive	Bisphenol a diglycidylether dimethacrylate (BisGMA), 2-propenoic acid, 2-methyl-, reaction products with 1,10-decanediol and phosphorous oxide (P ₂ O ₅), ethanol, water, 2-propenoic acid, 2-methyl-3-(trimethoxysilyl) propyl ester, reaction products with vitreous silica copolymer of acrylic and itaconic acid, camphorquinone, dimethylaminobenzoate(-4) (dimethylamino)ethyl methacrylate

Table 1. Details on the materials used in this study.* * Information obtained from the respective manufacturer's technical manual.

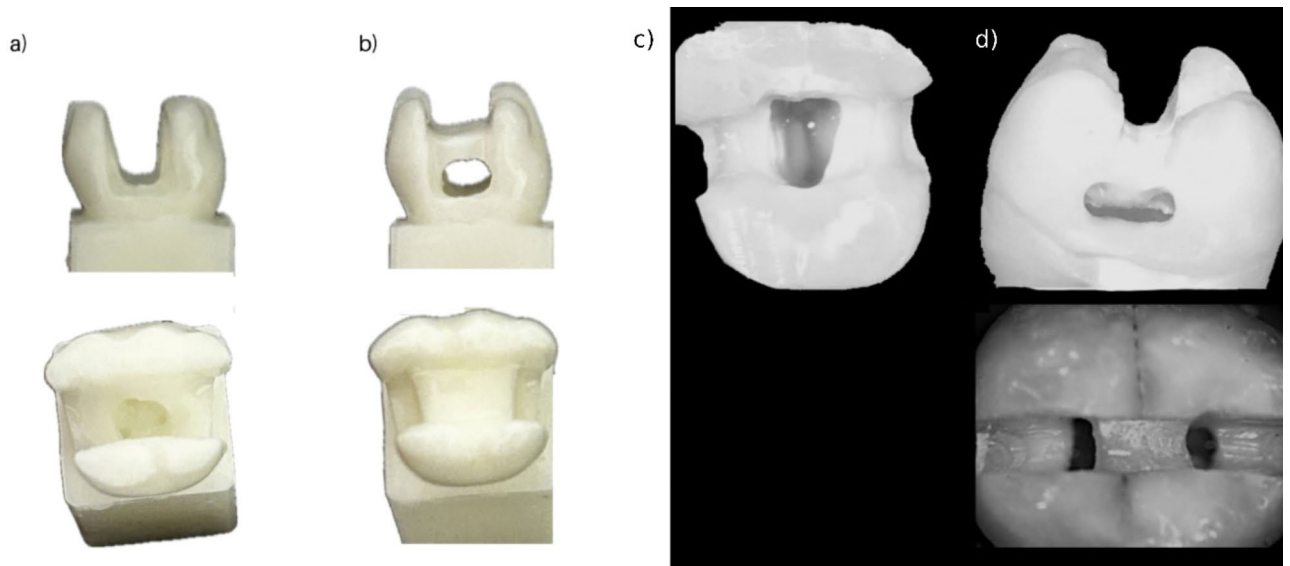


Fig. 1. Representative images of samples with prepared TEC plastic tooth (a), TREC plastic tooth (b), TEC human tooth (c) and TREC human tooth (d).

width half maximum ($p = 0.4237$; 95% CI -0.08756 to 0.03867) was used to measure DC. Therefore, plastic teeth were used to prepare specimens with standardized dimensions avoiding variety in natural teeth.

Specimen preparation – plastic teeth

An MOD cavity with traditional endodontic access (TEC) and a truss access cavity (TREC) achieved from a mesial and distal direction leaving a dentinal “bridge” over the pulp chamber were prepared a diamond bur FG 856 (Komet Italia Srl, Milan, Italy) mounted on a highspeed handpiece with water cooling and with a tungsten carbide round drill of an appropriate diameter.

TEC MOD group: An MOD cavity was prepared with 4 mm distance between the buccal and oral wall, 4 mm in mesio-distal direction and the gingival wall 1 mm above the cemento-enamel junction (CEJ). Non-functional cusps were reduced by 1 mm, and functional cusps were reduced by 1.5 mm. The roof of the pulp chamber was removed, and straight-line access into the coronal third of the root canal was established (Fig. 1a).

TREC MOD group: An MOD cavity was prepared as above but without cuspal reduction: occluso-cervical height was 4 mm, the distance between the buccal and oral walls was 4 mm and the gingival wall was 1 mm above the CEJ. The width of each of the gingival walls was 2 mm. TREC was prepared by preserving part of the pulp chamber roof as a “bridge” connecting buccal and oral cavity walls with a thickness of 2 mm (Fig. 1b). Details on the materials used in this study are provided in Table 1.

The following groups of resin-based materials were prepared for DC measurements ($n = 10$ teeth/group):

Group 1: everX + Filtek.

Group 2: Filtek only.

plastic teeth were prepared to microcomputed tomography (microCT) measurements of material porosity. Groups for microCT measurements ($n = 6$ teeth/group):

Group 1: everX + Filtek.

Group 2: Filtek only.

Group 3: Fuji + Filtek.

In Groups 1 and 2, SBU adhesive was applied to the entire cavity in each 3D printed tooth and light-cured for 20 s (Elipar Freelight, 3 M ESPE). Elipar is a monowave, high-intensity LED (Light Emitting Diode) light-curing unit with an emitted light spectrum of 440–490 nm and an irradiance of 1280 mW/cm² as measured by Bluephase Meter II (Ivoclar Vivadent). In Group 1, everX was placed as a base in the pulp chamber only, without filling of gingival margin and light-cured for 20 s using the same light-curing unit followed by incremental restoration with Filtek, which was also used for vertical closure in the proximal box as an axial wall. In TREC design, the light tip was supported by mesial cusps at 60° angle from the mesial direction, and by distal cusps at 60° angle from the distal direction. In TEC design, light-curing was done from occlusal direction by placing the light tip against the cusps for stability and standardized distance (8 mm tip-to-material distance). In Group 2, the entire cavity was restored with Filtek applied in 2 mm thick increments, each light-cured for 40 s using the same light-curing unit. In Group 3, Fuji was applied as a base, followed by incremental restoration with Filtek as previously described.

Specimen preparation – natural teeth

For fracture resistance, human extracted teeth were used. Following extraction, teeth were cleaned of debris and refrigerated in 0.2% thymol at +4 °C.

The research included a total of 120 extracted sound, intact, mature human maxillary and mandibular molars ($n=40$ teeth/ per material). The inclusion criteria were: (1) recently extracted teeth, within 6 months post-extraction; (2) teeth with similar shape and size, to minimize the effect of variable sizes and shapes and (3) teeth with no fractures, cracks and caries. Teeth were randomly divided into six subgroups of 20 teeth (10 traditional endodontic access cavity - TEC and 10 truss endodontic access cavity - TREC). Teeth were stored in chloramine-T at 4 degrees C.

Group 1 Immediately loaded samples restored with Filtek only;

Group 2 Immediately loaded specimens restored with everX + Filtek;

Group 3 Immediately loaded samples restored with Fuji + Filtek;

Group 4 Thermocycled samples restored with Filtek only;

Group 5 Thermocycled samples restored with everX + Filtek;

Group 6 Thermocycled samples restored with Fuji + Filtek;

A single operator prepared the endodontic access cavities, root canal detection and restoration procedures. Access cavities were prepared using a diamond bur FG 856 (Komet Italia Srl, Milan, Italy) mounted on a highspeed handpiece with water cooling and with a tungsten carbide round drill of an appropriate diameter. A new diamond and tungsten carbide bur was used for each group. Root canal orifices were detected with a #10 K-file (Dentsply Sirona Endodontics). The treatment of the pulp chamber was performed with a barbed broach to extirpate pulp. Then rinsed using 2.5% NaOCl.

TEC MOD group: An MOD cavity was prepared with 4 mm distance between the buccal and oral wall and the gingival wall 1 mm above the CEJ. Non-functional cusps were reduced by 1 mm, and functional cusps were reduced by 1.5 mm. The roof of the pulp chamber was removed, and straight-line access into the coronal third of the root canal was established (Fig. 1c).

TREC MOD group: An MOD cavity was prepared as above but without cuspal reduction: occluso-cervical height was 4 mm, the distance between the buccal and oral walls were 4 mm and the gingival wall was 1 mm above the CEJ. TREC was prepared by preserving part of the pulp chamber roof as a “bridge” connecting buccal and oral cavity walls (Fig. 1d).

In groups 1 and 4, enamel and dentin were etched with 37% phosphoric acid for 30 s and 15 s, respectively, rinsed and lightly air-dried followed by SBU adhesive application and light-curing for 20 s (Elipar Freelight, 3 M ESPE). In TREC design, the light tip was supported by mesial cusps at 60° angle from the mesial direction, and by distal cusps at 60° angle from the distal direction. In TEC design, light-curing was done from occlusal direction by placing the light tip against the cusps for stability and standardized distance. Irradiance of the light-curing unit ($1280\pm 140\text{mW/cm}^2$) was monitored with a radiometer (BlueMeter II, Ivoclar Vivadent). The entire cavity was restored with Filtek applied in 2 mm thick increments, each light-cured for 40 s using the same light-curing unit. In groups 2 and 4, SBU adhesive was applied following the same total-etch procedure and light-cured for 20 s. everX was placed as a base and light-cured for 20 s using the same light-curing unit followed by incremental restoration with Filtek as previously described. In groups 3 and 6, the smear layer was removed with 10% polyacrylic acid for 20 s. Cavities were rinsed with water/air spray, gently air dried and Fuji was applied as a base, followed by incremental restoration with Filtek as previously described.

Specimen preparation - storage

Following preparation, all samples were stored in distilled water in an incubator at 37 °C for 48 h between restoration and loading test. Groups 1–3 were tested immediately after storage and labeled as “immediately loaded samples”. Groups 4–6, “thermocycled samples”, were subjected to 10 000 thermal cycles between 5 °C and 55 °C with a dwell time of 30 s and transfer time of 5 s in a thermocycler (TermocycleR v1.0) and then loaded. According to ISO 11,405, the use of 500 thermal cycles between 5 °C and 55 °C is considered to be suitable to

simulate short-term aging of dental materials³³. In addition, Gale and Darvell³⁴ proposed that 10,000 cycles might represent approximately 1 year of in vivo functioning, with 20 to 50 cycles considered equivalent to a single day. Therefore, we decided to continue thermal cycling to 10,000 cycles to examine the results.

Degree of conversion, porosity and fracture resistance testing

Specimens for DC were sectioned using a slow-speed diamond saw (Isomet 4000, Buehler, Lake Bluff, IL, USA) mesio-distally in the region of the central fissure, creating roughly equal halves. The manufacturer recommended sectioning coolant was used, appropriately diluted with cold water. Cut specimens were stored dry in a light-proof container in an incubator at 37 °C for 24 h. After 24 h Raman spectra were recorded on a DXR Raman Microscope (Thermo Scientific, Waltham, MA, USA), using a diode-pumped solid-state laser with an excitation wavelength 532 nm at 3 locations (mesial, medial and distal in the middle of the occluso-lingival direction). The condition for all Raman measurements were the same: laser power of 10.0 mW on the sample, exposure time of 10 s, 10 exposures per spectrum, a grating with 900 lines/mm and a 50 µm pinhole spectrograph aperture. The laser beam was focused on the sample using an objective magnification 10x. Measurements were done in triplicates for each specimen. Raman spectra were analysed in OMNIC software (Thermo Scientific) and the DC was calculated using the formula:

$$DC = (1 - R_{cured}/R_{uncured}) \times 100$$

where R is the ratio of 1639 cm^{-1} and 1609 cm^{-1} band heights in cured and uncured material, which is used as reference. The 1639 cm^{-1} and 1609 cm^{-1} bands in a Raman spectrum correspond to vibrations of aliphatic C=C bonds and aromatic C=C bonds, respectively.

For porosity analysis, the specimens were scanned using SkyScan1272 micro-CT (Bruker, Belgium) under the following scanning parameters: voltage of 90 kV, current of 111 µA, exposure time of 2030 ms, camera binning of 2 K, resolution of 8.96 µm, and Cu filter of 0.11 mm. Reconstruction was conducted in NRecon software (Bruker, Belgium). The volume of interest (VOI) was delineated manually on reconstructed images, and a global threshold was chosen for each material ensuring that it optimally distinguished pores from the rest of the material. Specifically, the selected threshold values were 98/255 for everX Posterior and 85/255 for Fuji IX and Filtek Supreme because these values best identified pores in a given material, with minimal under- or overestimation of their size (Fig. 2). CTAn software (Bruker, Belgium) was used for 3D quantitative analysis, and the following parameters were determined: open porosity (Po.op, %)—which indicates the ratio of the volume of the open pores (pores located between the material and the tooth, or pores located within the material but reaching the boundary between the material and the tooth) to the total VOI; closed porosity (Po.cl, %)—which indicates the ratio of the volume of the closed pores (pores fully contained within the material) to the total material volume; total porosity (Po.tot, %)—which indicates the ratio of the total pore volume to the total VOI.

For fracture resistance testing, teeth were embedded with the roots 3 mm apical to the CEJ in customized steel cylinders rings fabricated with self-curing resin (SR Ivolen; Ivoclar Vivadent, Schaan, Liechtenstein) without simulating the periodontal ligament and loaded in the Universal testing machine Shimadzu AGS-X 100kN (Shimadzu Corp. Kyoto, Japan) at their central fossa so that the force was transmitted to the internal surfaces of the cusps, at a 30° angle from the long axis of the tooth. In the review literature for fracture testing 30 degrees is commonly used^{2–14}. A continuous compressive force was applied with a 5-mm spherical steel crosshead speed of 0.5 mm/min. The loads at fracture were recorded in Newton (N) by the software *Trapezium-X* software (Shimadzu Corp. Kyoto, Japan). The fractured specimens were examined under a magnifying glass x2 to determine the fracture levels. Fracture patterns were classified as “restorable” when the failures were above the CEJ and “unrestorable” when the failures were extending below the level of the CEJ³⁵.

Statistical analysis

Data were analyzed using SPSS version 22 (SPSS Inc., IL, USA) – degree of conversion, porosity and fracture resistance testing. Mean and SD and 95% Confidence Interval (CI) were used for description of numerical data. Categorical data were expressed as percentages. Categorical variables were compared using Chi-Square Test (χ^2). Numerical continuous variables were tested with a One-sample Kolmogorov-Smirnov test to determine if their distribution was normal. Independent Samples T test was used for normally distributed data. One-way ANOVA was applied to analyse parametric data for three and more groups. Non-parametric data were analyzed using Mann-Whitney U test for comparison of two groups, while Kruskal-Wallis test was used for three and more groups. Multiple linear regression analysis was performed to determine the predictive factors affecting fracture resistance. The significance level was established at 5% ($p < 0.05$).

G*Power 3.1.9.4. software for Windows (Heinrich Heine-Universität, Dusseldorf, Germany) used for calculate samples size for three outcomes. Based on data from a pilot study the difference between the two mean values was compared for an alpha-type error of 0.05 and power beta for the study was 80% ($d_z = 0.6478$). 39 samples per material group were required for observing significant differences. Forty teeth per each material group were included due to the possibility of dropouts during the study.

In order to calculate the sample size for DC, data from pilot study were used (Filtek vs. everX + Filtek). The sample size was 9 teeth to test the difference of the two arithmetic means for a significance level of 0.05 and a statistical strength of 80% ($d_z = 1.4427$). We included 10 teeth per material group because of dropouts.

Sample size for porosity was calculated based on data from the pilot study. A sufficient number of observation units to test the difference of 3 arithmetic means for a statistical significance level of 0.05 and a statistical power of 0.80 (ANOVA fixed effects, one way, $d_z = 0.8200$) is a total of 18.

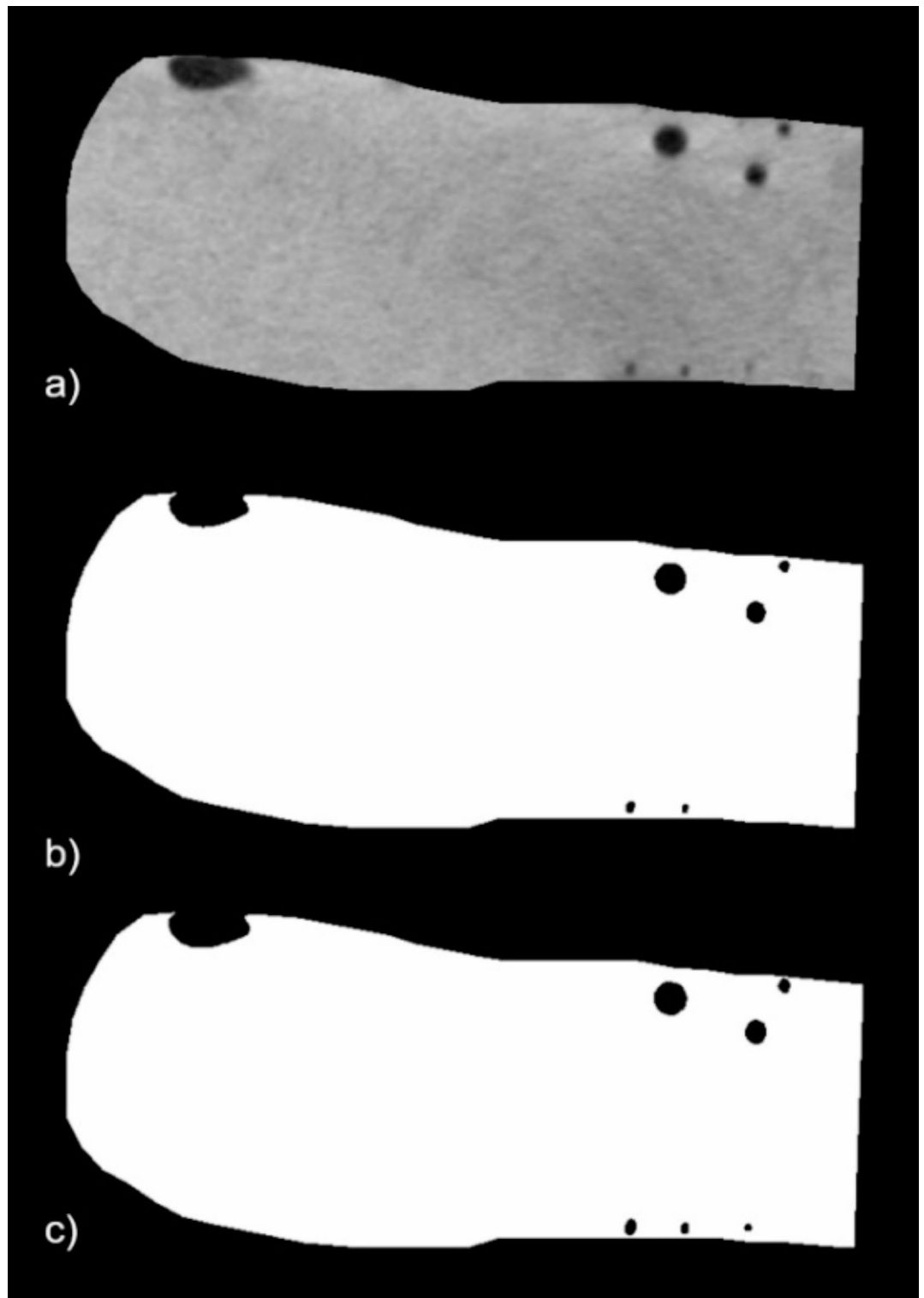


Fig. 2. Choosing optimal threshold values for microCT evaluation of everX: A representative single reconstructed slice from microCT imaging (a), threshold = 85 underestimated pores size and number (b), whereas threshold = 98 best identified pores in the material (c).

Results

Degree of conversion (DC)

There was no statistically significant factor interaction in DC analysis ($p=0.101$). Significantly higher DC was detected in Filtek than everX in both access cavities ($p<0.001$; 95% CI of difference 6.1637 to 12.3163). Conversely, no significant differences in DC were found between different types of access cavity (TREC vs.

Cavity access method						
	Tec			Trec		
	Distal	Medial	Mesial	Distal	Mesial	Medial
everX + Filtek	56.20 ± 2.95 ^{B, a}	55.00 ± 2.45 ^{B, a}	57.80 ± 2.17 ^{B, a}	55.40 ± 2.19 ^{B, a}	55.20 ± 3.19 ^{B, a}	57.20 ± 1.09 ^{B, a}
Filtek	65.60 ± 2.79 ^{A, a}	69.00 ± 9.45 ^{A, a}	66.20 ± 12.79 ^{A, a}	65.00 ± 5.34 ^{A, a}	61.80 ± 10.38 ^{A, a}	64.20 ± 5.76 ^{A, a}

Table 2. Mean and SD of DC for factors material, access cavity and locations. The same lower case letters indicate no statistically significant differences in rows ($p > 0.05$). The same upper case letters indicate no statistically significant differences in columns ($p > 0.05$).

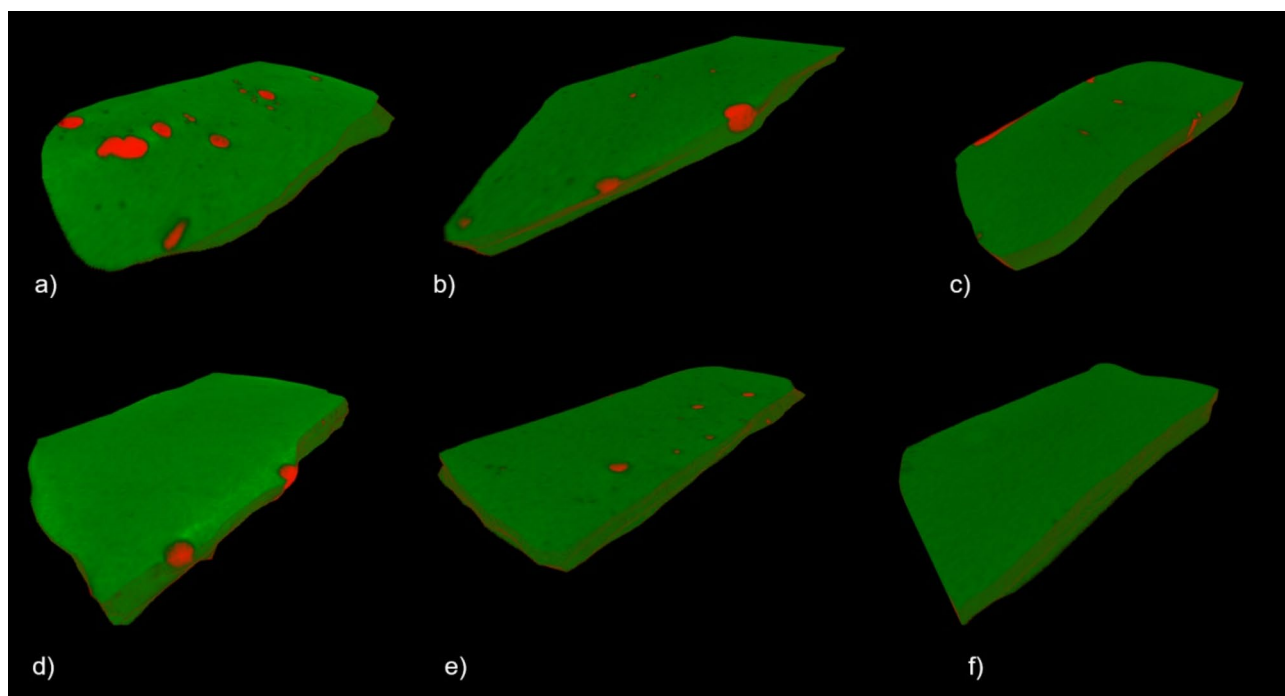


Fig. 3. Representative three-dimensional microCT reconstructions of restorative material (green) and pores (red) (below the „bridge” in TREC, and the same location section in TEC) in TRECs restored with everX (a), Fuji (b), and Filtek (c), and TECs restored with everX (d), Fuji (e), and Filtek (f).

TEC) in each composite ($p = 0.254$; 95% CI of difference -2.580 to 9.380). No significant differences in DC were found between locations (mesial vs. medial vs. distal) for each restorative materials and access cavity ($p = 0.994$). (Table 2)

Total, open and closed porosity

For total porosity analyses showed that there no statistically significant differences between materials ($p = 0.250$). Significantly higher percentage of total porosity was found in everX when placed in TREC than TEC ($p = 0.050$, 95% CI of difference 1.6716 to 4.6684).

For open porosity, follow-up analyses showed that there were no statistically significant differences between materials ($p = 0.220$). Higher percentage of open porosity was found in the everX group when placed in TREC than TEC but without significantly difference. ($p = 0.061$). Significantly lower open porosity was observed in Fuji when placed in TREC compared to TEC ($p = 0.050$, 95% CI of difference -0.0034 to 0.3434).

For closed porosity analyses between materials showed significantly higher percentage of closed porosity in Fuji in TEC ($p = 0.027$, 95% CI of difference 0.2573 to 0.8027) and everX showed higher percentage of closed porosity in TREC but without significant difference ($p = 0.061$). Significantly higher closed porosity was observed in everX when placed in TREC compared to TEC ($p = 0.046$, 95% CI of difference -0.2664 to 2.2664). (Figs. 3 and 4 and Tables 3 and 4). **Additional reconstruction of microCT images is presented as Supplementary material.**

Fracture resistance of restored molars

When each factor was individually assessed, the following results were observed: TREC groups showed statistically higher fracture resistance than TEC groups ($p = 0.001$, TREC 95% CI mean 1419.81 to 1665.76 , TEC 95% CI mean 1136.87 to 1309.10) (Fig. 5a). Significant differences were observed between restorative materials

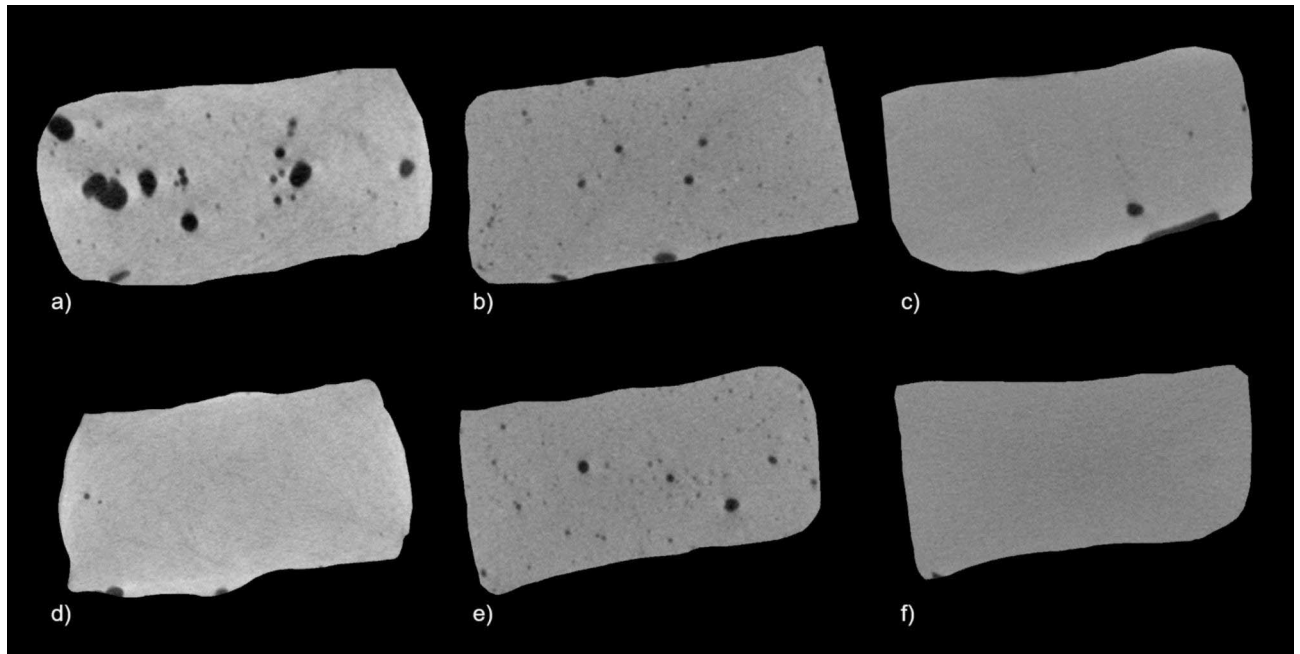


Fig. 4. Representative two-dimensional microCT slices of restorative material (gray) and pores (black) (below the „bridge” in TREC, and the same location section in TEC) in TREC restored with everX (a), Fuji (b), and Filtek (c), and TECs restored with everX (d), Fuji (e), and Filtek (f).

	Total porosity(%)		Open porosity(%)		Closed porosity(%)	
	Cavity access method					
	Tec	Trec	Tec	Trec	Tec	Trec
Filtek	0.46 ± 0.15 ^{A, a}	0.62 ± 0.74 ^{A, a}	0.38 ± 0.19 ^{A, a}	0.50 ± 0.67 ^{A, a}	0.10 ± 0.03 ^{A, a}	0.09 ± 0.09 ^{A, a}
everX + Filtek	0.59 ± 0.83 ^{A, a}	3.76 ± 0.43 ^{B, b}	0.58 ± 0.83 ^{A, a}	2.76 ± 1.28 ^{B, b}	0.01 ± 0.01 ^{A, a}	1.02 ± 0.79 ^{B, b}
Fuji + Filtek	0.67 ± 0.22 ^{A, a}	0.81 ± 0.18 ^{A, a}	0.09 ± 0.09 ^{A, a}	0.26 ± 0.06 ^{A, a}	0.55 ± 0.17 ^{B, a}	0.55 ± 0.13 ^{A, a}

Table 3. Mean and SD of porosity(%) dependence of material and access cavity. The same upper case letters indicate no statistically significant differences in rows ($p > 0.05$). The same lower case letters indicate no statistically significant differences in columns ($p > 0.05$).

TEC vs. TREC								
Total porosity			Open porosity			Closed porosity		
Material	P value	95% CI diff.	Material	P value	95% CI diff.	Material	P value	95% CI diff.
EverX	0.050	1.6716 to 4.6684	EverX	0.200	0.2654 to 4.6204	EverX	0.046	-0.2664 to 2.2664
Filtek	0.513	-1.0503 to 1.3703	Filtek	0.827	-0.9963 to 1.2363	Filtek	1.000	-0.1521 to 0.1521
Fuji	0.275	-0.3157 to 0.5957	Fuji	0.050	-0.0034 to 0.3434	Fuji	0.827	-0.3231 to 0.3631

Table 4. Material-wise comparison of different cavity access groups (p value).

($p = 0.001$). everX + Filtek and Fuji + Filtek groups showed higher fracture resistance than Filtek ($p = 0.001$, everX + Filtek 95% CI mean 1366.82 to 1647.23, Fuji + Filtek 95% CI mean 1321.72 to 1647.23, Filtek 95% CI mean 1061.97 to 1647.23) whilst no difference was observed between everX + Filtek and Fuji + Filtek ($p = 0.704$) (Fig. 5b). Immediately loaded samples showed significantly higher fracture resistance than thermocycled samples ($p = 0.011$, Immediately loaded 95% CI mean 1369.03 to 1579.37, Thermocycled 95% CI mean 1174.03 to 1579.37) (Fig. 5c).

TREC group (55% unrestorable, 45% restorable) had significantly more unrestorable than restorable fractures than TEC (25% unrestorable, 75% restorable) ($p = 0.002$). No differences in the fracture type were observed relative to material ($p = 0.066$) or aging ($p = 0.35$) (Filtek: 55% unrestorable, 45% restorable; everX + Filtek: 30% unrestorable, 70% restorable; Fuji + Filtek: 35% unrestorable, 65% restorable). The percentage of restorable

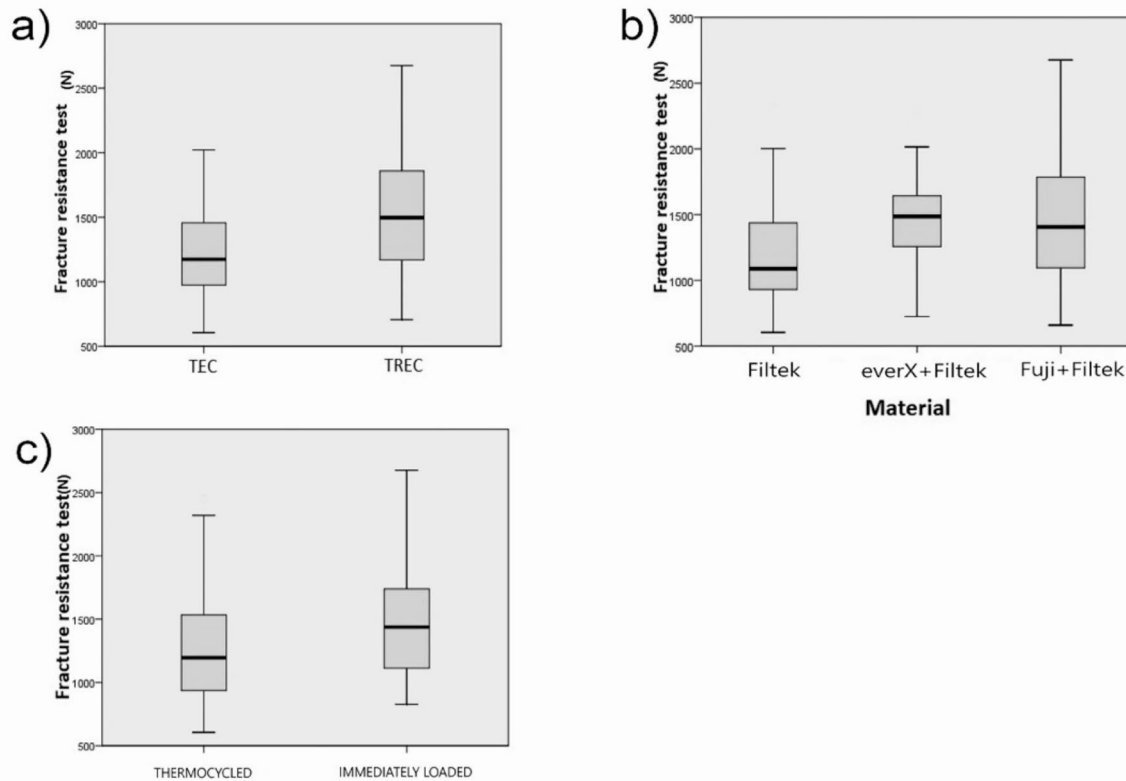


Fig. 5. Box and Whisker plots for fracture resistance: TEC and TREC access cavity (a), restorative material (b) and aging (c). Each box displays the upper and lower quartile, the horizontal line inside the box shows median, and whiskers show upper and lower extreme values.

	Tec		Trec	
	Unrestorable (%)	Restorable (%)	Unrestorable (%)	Restorable (%)
Filtek only	50.0 ^{a, A}	50.0 ^{a, A}	60.0 ^{a, A}	40.0 ^{a, B}
everX + Filtek	20.0 ^{c, A}	80.0 ^{b, B}	40.0 ^{a, A}	60.0 ^{a, B}
Fuji + Filtek	10.0 ^{c, A}	90.0 ^{b, B}	65.0 ^{a, A}	35.0 ^{a, B}
Thermocycled	20.0 [†]	80.0 ^{**}	53.3 [#]	46.7 [#]
Immediately loaded	33.3 [*]	66.7 ^{**}	56.7 [#]	43.3 [#]

Table 5. Percentage of unrestorable and restorable fractures relative to restorative material, access cavity and aging. The same lower case letters indicate no statistically significant differences in columns ($p > 0.05$) whilst the same upper case letters indicate no statistically significant differences in rows within TEC or TREC for factor “material” ($p > 0.05$). The same symbols indicate no statistically significant differences in both rows and columns within TEC or TEC for factor “aging” ($p > 0.05$).

fractures was higher than unrestorable in both groups (thermocycled: 35% unrestorable, 65% restorable; immediately loaded: 45% unrestorable, 55% restorable).

There was no statistically significant difference in the type of fracture in relation to aging (thermocycling) in TEC cavities ($p = 0.243$). Both groups (immediately loaded and thermocycled) had a higher percentage of restorable than unrestorable fractures. everX + Filtek and Fuji + Filtek groups had a significantly higher percentage of restorable fractures than the Filtek group ($p = 0.012$) (Table 5).

TREC groups restored with Fuji + Filtek showed significantly higher fracture resistance compared to Filtek only ($p = 0.001$, 95% CI of difference -740.69 to -29.31) whilst no significant difference was observed between Filtek and everX + Filtek and no significant difference was observed between everX + Filtek and Fuji + Filtek ($p = 0.168$, 95% CI of difference -599.82 to 111.54). There was no significant difference in fracture resistance between immediately loaded and thermocycled TREC groups ($p = 0.267$, 95% CI of difference -382.872 to 108.139).

Cavity access method				
	Tec	Trec	95% CI mean	P value
Filtek	1009 ± 235 ^{a, A}	1367 ± 444 ^{a, A}	1061.97 to 1314.48	0.077
everX + Filtek	1444 ± 227 ^{a, A}	1508 ± 430 ^{a, A}	1366.82 to 1585.08	0.168
Fuji + Filtek	1216 ± 372 ^{a, A}	1753 ± 492 ^{b, B}	1321.72 to 1647.23	0.001
Thermocycled	1109 ± 305 ^{*, A}	1474 ± 509 ^{**, B}	898.22 to 1319.48	0.004
Immediately loaded	1337 ± 326 ^{*, A}	1611 ± 438 ^{**, A}	1116.59 to 1418.61	0.007

Table 6. Forces in Newton (N) measured at fracture for all tested groups (mean ± standard deviation). Significant values are in bold. The same upper case letters indicate no statistically significant differences in rows ($p > 0.05$) whilst the same lower case letters indicate no statistically significant differences in columns for factor “material” ($p > 0.05$). The same symbols indicate no statistically significant differences in both rows and columns within TEC or TREC for factor “aging” ($p > 0.05$).

Material	Access Cavity	Fracture resistance test (N) thermocycled	Fracture resistance test (N) immediately loaded	95% CI mean	P value	95% CI diff.
Filtek only	TEC	929 ± 216 ^{A, a}	1089 ± 236 ^{A, a}	974.21 to 1258.07	0.132	-372.86 to 53.06
	TREC	1289 ± 556 ^{A, a}	1446 ± 305 ^{A, a}	1190.11 to 1686.29	0.442	-578.73 to 263.53
everX + Filtek	TEC	1428 ± 226 ^{A, a}	1459 ± 239 ^{A, a}	1266.51 to 1629.77	0.774	-249.04 to 188.44
	TREC	1430 ± 456 ^{A, a}	1587 ± 415 ^{A, a}	1105.79 to 1883.81	0.429	-565.35 to 250.75
Fuji + Filtek	TEC	970 ± 173 ^{A, a}	1462 ± 356 ^{B, a}	975.11 to 1718.63	0.001	-757.06 to -229.94
	TREC	1704 ± 473 ^{A, b}	1801 ± 453 ^{A, a}	1365.88 to 2041.92	0.671	-569.36 to 374.96

Table 7. Mean and SD of fracture resistance test relative to restorative material, access cavity and aging. Significant values are in bold. The same upper case letters indicate no statistically significant differences in rows ($p > 0.05$). The same lower case letters indicate no statistically significant differences in columns within each group ($p > 0.05$).

There was no statistically significant difference in the type of fracture in relation to aging (thermocycling) in TREC cavities ($p = 0.795$). Both groups (immediately loaded and thermocycled) had a slightly higher percentage of unrestorable than restorable fractures (Table 5). There was no statistically significant difference in the type of fracture in relation to the type of material used to restore the TREC cavities ($p = 0.243$). everX + Filtek group had a higher percentage of restorable fractures, while Filtek and Fuji + Filtek groups had a higher percentage of unrestorable fractures (Table 5).

Further analysis within factors revealed significantly higher fracture resistance between several groups as indicated in Table 6. TREC restored with Fuji + Filtek showed higher fracture resistance than TEC restored with the same material ($p = 0.001$) as did TREC groups compared to TEC groups after thermocycling ($p = 0.004$). Immediately loaded TREC samples had significantly higher fracture resistance than thermocycled samples with TEC access cavity ($p = 0.007$).

Immediately loaded TEC samples with Fuji + Filtek had significantly higher fracture resistance than thermocycled samples with TEC access cavity ($p = 0.001$). There were no significant differences between other tested groups (Table 7).

A multilinear regression model ($R^2 = 0.327$, $F = 11.102$, $p < 0.001$) revealed the following factors as statistically significant predictors for fracture load: access cavity type ($\beta = 0.289$, 95% CI [0.082–0.285], $p < 0.001$), whereby TREC samples had higher fracture resistance compared to TEC; type of fracture ($\beta = 0.198$, 95% CI [0.023–0.235], $p = 0.018$), where the fracture line below the level of the CEJ related to higher values of fracture resistance; aging/thermocycling ($\beta = 0.228$, 95% CI [0.048–0.242], $p = 0.004$), where immediate load affects increased resistance test values; material type everX + Filtek ($\beta = 0.402$, 95% CI [0.150–0.393], $p < 0.001$) and Fuji + Filtek ($\beta = 0.352$, 95% CI [0.118–0.358], $p < 0.001$) resulted in higher fracture resistance compared to Filtek only. This regression model explains 33% of the effect of the factors on the outcome. The model is significant, but the small R^2 indicates that other factors should be considered when explaining the outcomes.

Discussion

In the present study, the differences in DC between resin-based composites were not related to cavity design, thus $H_0 \#1$ was upheld. There were significant differences in porosity between restorative materials and cavity design, thus, $H_0 \#2$ was rejected. Similarly, significant differences were observed in fracture resistance relative to material type, cavity design and aging, therefore $H_0 \#3$ was rejected. The null hypothesis related to the types

of fractures was rejected for access cavity design and restorative materials, as significantly more unrestorable fractures were observed in TREC than TEC group whilst everX + Filtek and Fuji + Filtek had more restorable fractures than Filtek in TEC cavities.

Achieving TREC design under clinical conditions requires magnification, high illumination, clinical experience and proper radiographic assessment in the treatment-planning stage to avoid missed canals. Endodontic static guides are useful to avoid gauging and perforation as this approach was recently shown to be effective in the management of calcified canals, also requiring precise and reduced-sized endodontic access³⁶. Agitated and prolonged irrigation and retrograde surgical tips are required with TREC design to achieve complete removal of pulp tissue^{2,3}.

Fiber-reinforced bulk-fill composite everX showed significantly different lower DC than nanofilled Filtek Supreme. This may be explained by the presence of glass fibers of much greater size in everX than nanosized fillers in Filtek which may have affected the growing polymer differently leading to limited cross-linkage and higher percentage of pending C=C double bonds. A previous study reported on the significantly lower DC of everX compared to non-glass fiber-containing composites, mean DC values at 4 mm ranged largely from 57.95 to 6.82%³⁷. Despite different curing conditions (no distance and perpendicular angle) from the present study, the range of DC was comparable between these studies³⁷. A similar range of DC was reported for Xenius, which is a predecessor of everX Posterior, TEC Bulk, Xenius, and SonicFill, bulk-filled as 4-mm-thick specimens, showed bottom-to-top hardness ratios above 80%²⁶. No literature data was found for comparison on the DC of everX when the light-tip was held at an angle as was done in the present study. The DC of nanofilled Filtek Supreme was around 60%, which was similar to a previous study in which a halogen light-curing unit was used to deliver a comparable radiant exposure as was delivered in the present study (24–25 J/cm²)³⁸.

The main clinically relevant finding related to the quality of polymerization is that the conservative access cavity design (TREC) with the dentinal “bridge” overlying the restorative material did not have a significant effect on monomer-to-polymer conversion in either resin composite. This means that a high-intensity, light-curing unit held at an angle to allow as much as possible material exposure to the incoming light was able to deliver sufficient light energy density, i.e. radiant exposure, to achieve similar DC throughout the specimen. In case of an MOD cavity, multiple exposures, one from mesial and another from distal, achieved similar DC across the composite restoration as indicated by multiple measurements at different locations in the present study. This curing protocol is dictated by the TREC cavity design due to the presence of the dentinal “bridge” hindering light penetration from the occlusal. In the case of the TEC cavity design, the usual occlusal positioning of the light tip perpendicular to the surface of the restoration at minimal distance is recommended for optimal curing³⁹. The present finding should not be generalized and further research is warranted to include a variety of light-curing units. Furthermore, literature does not offer data on other curing scenarios (e.g. different curing light, distances, angulation) when restoring teeth with minimally invasive endodontic cavities.

Porosity in a material may be localized either internally (closed porosity) or at the tooth-material interface (open porosity). Both types are relevant, however, for different reasons. While closed porosity increases stresses and deformability⁴⁰, open porosity may facilitate bacterial leakage. The present study found that high-viscosity, fiber-reinforced composite everX was particularly susceptible to porosity in conservative TREC cavity design. About three quarters of the total porosity in the everX group were found to be open porosity where one quarter were closed porosity. This finding is expected, as the limited space in a conservative cavity design makes adaptation of everX more difficult. High viscosity of everX and the presence of glass fibers prevent intimate contact of the material and cavity walls, particularly in the area of the remaining dentinal “bridge”. Moreover, air is more easily entrapped despite a single increment being placed, as is the recommendation for bulk-fill composites with 4–5 mm depth of cure.

Conversely, Fuji IX showed mainly closed porosity which may be due to the fact that the material is applied in one increment and viscosity was adequate to facilitate material adaptation against the cavity walls. Internal material pores may be residues of the manufacturer process⁴¹. Similarly, predominant closed porosity was reported for the same material, Fuji IX, placed in a different indication, as a retrograde root filling⁴², confirming that the application in an even more confined space does not increase open porosity.

Nanofilled resin composite Filtek performed generally better than Fuji IX and fiber-reinforced everX in terms of lower porosity irrespective of the cavity design. It should be noted that the analysis was focused on the area of the pulp chamber, and so care should be taken during incremental layering as porosities could be present between Filtek increments.

TREC cavity design was associated with a higher material porosity than TEC in high-viscosity everX, but not for glass-ionomer Fuji or nanofilled composite Filtek. A recent study reported increased porosity in TREC cavity design, even when a bulk-fill composite without glass-fibers was placed in a single increment¹⁵. Similar to the present study, porosity existed in universal composites and in TEC cavity design, albeit to a smaller extent¹⁵. Flowable bulk-fill resin composites, such as everX flow may be a better choice, however, further research is required to ascertain the porosity in this case.

TREC cavity design was associated with a higher fracture resistance of restored molars compared to TEC. This finding can be explained by the presence of the central dentinal “bridge” joining the buccal and oral remaining walls, thereby providing resistance to cusp displacement under occlusal forces and stress concentration in the cervical region. Conversely, TEC preparation was associated with reduced fracture resistance of teeth as a result of the removal of strategic internal architecture at the center of the tooth (complete deroofting of the pulp chamber). This was previously reported for TREC in endodontically treated teeth¹⁵, while the present study focused on a pulpotomy case.

Restorative material was found to be a significant factor determining fracture resistance of restored molars with different access cavities. There was a significant decrease in fracture resistance in the Filtek group compared to the Fuji + Filtek group. Lower fracture resistance in the Filtek group may be associated with higher interfacial

stresses compared to glass-ionomer-composite bonded restorations⁴³. In general, the strength of conventional glass-ionomer was dominated by polymer matrix with unreacted residual glass fillers acting as a reinforcing phase⁴⁴. Glass-ionomer base was shown to decrease the propensity of shrinkage-induced cracks in large MOD cavities restored with universal composites, thereby increasing restoration survival rate and resulting in restorable fracture types⁴⁵. A greater percentage of restorable fracture types was also seen in the present study in TEC groups with Fuji IX placed as a base.

The present results also showed lower fracture resistance of Filtek compared to everX + Filtek restored teeth. Glass-fiber reinforcing restorative material (everX Posterior) could improve fracture resistance of endodontically treated teeth⁴⁶, especially when placed in oblique layers⁴⁷. Higher fracture resistance was recently reported for MOD cavities in vital teeth restored with everX and a Filtek universal composite compared to Filtek only restoration⁴⁸. The present study confirms the same for TEC and TREC cavities albeit the difference reached statistical significance only in TEC design. Glass fibers in everX were associated with improved mechanical properties compared to universal composite and an ability to arrest crack propagation⁴⁹ which could account for the high fracture resistance of restored teeth. This is despite slightly lower filler volume in everX (53.6%) compared to Filtek (59%), as filler volume was closely related to flexural strength and flexural modulus^{50,51}. An adverse effect of glass fibers may be increased percentage of unrestorable failures, as recently reported in large MOD cavities in typodont teeth⁵². This result was not observed in the present study in natural teeth with either TEC or TREC access design, the difference being related to differences in mechanical properties of plastic and natural teeth.

The present study associated more restorable fractures with the TEC than TREC design, contrary to previous studies^{13,53}. That might be explained by cusp reduction in TEC but not in TREC design, which likely resulted in more favorable crack propagation. In TEC design, reduced cusps were included in cavity preparation and covered by restorative material. According to the parallelogram principle for force distribution and vector analysis, a combination of incoming force angulation, the existing restoration and remaining cavity design resulted in a vertical rather than oblique outward-oriented direction of occlusal forces. In TREC design, cusps were not reduced to allow maximum tissue preservation, however, the remaining dentinal “bridge” in TREC may not be sufficient to mitigate unfavorable force distribution, resulting in more unfavorable fractures. The present results pose a clinical dilemma: while the TREC design displayed higher fracture resistance, it also led to more catastrophic non-repairable fractures. This indicates that further studies, especially using finite element analysis, are required to study stress concentration in minimally invasive access cavity design, and broadening research to include other restorative materials.

Our results indicate that aging (thermocycling) significantly decreased fracture resistance of the tested teeth. Significant decrease in fracture resistance as a result of thermocycling of endodontically treated teeth was recently reported in other studies^{13,14}. Decrease in fracture resistance after thermocycling may be associated with different coefficients of thermal expansion of restorative materials and enamel/dentin leading to interfacial stresses which likely amplify the effect of occlusal loading. The outcomes from this study also suggest that the thermal and mechanical properties of a restorative material can have a considerable effect on the selection of restorative materials by dental clinicians over conventional restorative materials^{54,55}. TREC design appears to have a somewhat protective effect due to the remaining dentinal “bridge” between buccal and oral cavity walls and retained cusps.

The present results should be viewed considering several limitations of this study. It is acknowledged that the use of natural teeth, with all of the variety encountered, is more clinically relevant. However, it was previously shown that small variations in light curing, such as distance and thickness of the remaining tooth structure may have significant effect on the outcome^{39,56}. A pilot study comparing the DC of resin composites in natural and plastic teeth found no significant differences, thereby justifying the use of plastic teeth. Plastic teeth allowed complete standardization of specimens and cavities and reduced the required number of extracted human teeth. The fracture resistance was tested on human teeth using static compressive loading in a universal testing machine because of its availability. Tooth variability was unavoidable, however, this was mitigated by selecting teeth of similar size and shape and with the same operator performing all cavity preparation. Another limitation is that the pulp chamber was restored with restorative materials as described in the Materials and Methods, without the use of pulp capping material. This approach does not entirely follow the protocol for a pulpotomy case in which a pulp capping material should be used in the pulp chamber. This was done for standardization, to avoid further variability in the study design and because a previous literature review showed that pulp capping materials do not affect fracture resistance⁵⁷. Although dynamic load would be more useful to simulate functional forces, this was not available, and fracture resistance was instead tested with static force. Similar approach was taken in other studies^{2–13}. The identification of pores was limited by the pixel size, meaning that we were not able to reliably detect and quantify pores with diameters below the nominal resolution used for micro-CT imaging. It is possible that there may be some variations in gray levels even within the same material, but we believe that these are relatively minor. However, to be able to perform comparative analysis, we had to select a single threshold for each material, ensuring that it optimally detected pores and their sizes as much as possible with this method.

Conclusions

Under the conditions of this study the quality of photo-polymerization was material-dependent and was not influenced by differences in access cavity design, i.e. the presence of a dentinal “bridge” in the TREC cavity design did not have an adverse effect on the DC of resin-based composites. Unlike TEC, minimally invasive TREC was associated with increased porosity of high-viscosity fiber-reinforced composite everX Posterior. Glass-ionomer (Fuji IX) and nanofilled composite Filtek Supreme showed better adaptability and similar porosity, irrespective of access cavity design. TREC design, coupled with non-cuspal coverage direct restoration, resulted in significantly higher fracture resistance of restored molars but also more unrestorable fractures than

TEC design with cuspal coverage direct restoration. Fiber-reinforced composite everX Posterior placed as a base under a nanofilled composite (Filtek Supreme) improved fracture resistance of molars with TEC whilst conventional glass-ionomer Fuji IX improved fracture resistance of molars with TREC. Thermocycling generally decreased fracture resistance of restored molars albeit to a lesser extent in minimally invasive TREC. When all present data are taken together, fiber-reinforced composite everX Posterior can be recommended for restoring molars with TEC cavity design but not TREC. Glass-ionomer Fuji IX appears to be a better choice for restoring TREC as a base material than fiber-reinforced everX Posterior and nanofilled composite Filtek.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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References

- Silva, E. et al. Impact of contracted endodontic cavities on fracture resistance of endodontically treated teeth: a systematic review of in vitro studies. *Clin. Oral Investig* **22**, 109–118 (2018).
- Silva, E. J. N. L. et al. Current status on minimal access cavity preparations: a critical analysis and a proposal for a universal nomenclature. *Int. Endod J.* **53**, 12 (2020).
- Chan, M. Y. C., Cheung, V., Lee, A. H. C. & Zhang, C. A literature review of minimally invasive endodontic access cavities - past, present and future. *Eur. Endod J.* **7**(1), 1–10 (2022).
- Chlup, Z., Zizka, R., Kania, J. & Pribyl, M. Fracture behaviour of teeth with conventional and mini-invasive access cavity designs. *J. Eur. Ceram. Soc.* **37**, 14 (2017).
- Niranjan, N. T. & Rajkumar, J. Impact of access cavity design and root canal taper on fracture resistance of permanent mandibular molars: an in-vitro study. *J. Clin. Diagn. Res.* **16**(4), ZC45–ZC50 (2022).
- Ivanoff, C. S. et al. Fracture resistance of mandibular premolars with contracted or traditional endodontic access cavities and class ii temporary composite restorations. *Endodontic Pract. Today* **11**, 07–14 (2017).
- Rover, G. et al. Influence of access cavity design on root canal detection, instrumentation efficacy, and fracture resistance assessed in maxillary molars. *J. Endod* **43**(10), 1657–1662 (2017).
- Moore, B., Verdelis, K., Kishen, A., Dao, T. & Friedman, S. Impacts of contracted endodontic cavities on instrumentation efficacy and biomechanical responses in maxillary molars. *J. Endod* **42**(12), 1779–1783 (2016).
- Corsentino, G. et al. Influence of access cavity preparation and remaining tooth substance on fracture strength of endodontically treated teeth. *J. Endod* **44**(9), 1416–1421 (2018).
- Maske, A., Weschenfelder, V. M., Soares Grecca Vilella, F., Burnett Junior, L. H. & de Melo, T. A. F. Influence of access cavity design on fracture strength of endodontically treated lower molars. *Aust Endod J.* **47**(1), 5–10 (2021).
- Krishan, R. et al. Impacts of conservative endodontic cavity on root canal instrumentation efficacy and resistance to fracture assessed in incisors, premolars, and molars. *J. Endod* **40**(8), 1160–1166 (2014).
- Plotino, G. et al. Fracture strength of endodontically treated teeth with different access cavity designs. *J. Endod* **43**(6), 995–1000 (2017).
- Santosh, S. S., Ballal, S. & Natanasabapathy, V. Influence of minimally invasive access cavity designs on the fracture resistance of endodontically treated mandibular molars subjected to thermocycling and dynamic loading. *J. Endod* **47**(9), 1496–1500 (2021).
- Saberi, E. A., Pirhaji, A. & Zabetiyan, F. Effects of endodontic access cavity design and thermocycling on fracture strength of endodontically treated teeth. *Clin. Cosmet. Investig Dent.* **12**, 149–156 (2020).
- Prado, H. S. et al. Impact of access cavities on root canal preparation, restorative protocol quality, and fracture resistance of teeth. *Braz Oral Res.* **37**, e096 (2023).
- Alkadi, M. et al. Assessment of the effect of spacer material on gap and void formation in an endodontic temporary restoration using micro-computed tomography. *Sci. Rep.* **13**, 4354 (2023).
- Körner, P. et al. A laboratory pilot study on voids in flowable bulk-fill composite restorations in bovine class-II and endodontic access cavities after sonic vibration. *Sci. Rep.* **13**, 18557 (2023).
- Mannocci, F., Bhuva, B., Roig, M., Zarow, M. & Bitter, K. European society of endodontology position statement: the restoration of root filled teeth. *Int. Endod J.* **54**(11), 1974–1981 (2021).
- Josic, U. et al. Clinical longevity of direct and indirect posterior resin composite restorations: an updated systematic review and meta-analysis. *Dent. Mater.* **39**(12), 1085–1094 (2023).
- Bilgi, P., Shah, N., Patel, P. & Vaid, D. Comparison of fracture resistance of endodontically treated teeth restored with nanohybrid, silorane, and fiber reinforced composite: an in vitro study. *J. Conservative Dentistry* **19**(4), 364–367 (2016).
- Al Nahedh, H., Al-Senan, D. F. & Alayad, A. S. The effect of different light-curing units and tip distances on the polymerization efficiency of bulk-fill materials. *Oper. Dent.* **47**(4), E197–E210 (2022).
- Komlenic, V. & Miletic, V. Effects of the light tip position on the degree of conversion and dentin bond strength of a universal adhesive. *Srp. Arh. Celok. Lek.* **149**, 149–154 (2021).
- Maktabi, H. et al. Improper light curing of bulkfill composite drives surface changes and increases s. mutans biofilm growth as a pathway for higher risk of recurrent caries around restorations. *Dent. J. (Basel)* **9**(8), 83 (2021).
- Uusitalo, E., Varrela, J., Lassila, L. & Vallittu, P. Transmission of curing light through moist, air-dried, and edta treated dentine and enamel. *Biomed. Res. Int.* **2016**, 5713962 (2016).
- Catelan, A. et al. Impact of the distance of light curing on the degree of conversion and microhardness of a composite resin. *Acta Odontol. Scand.* **73**(4), 298–301 (2015).
- Miletic, V., Pongprueksa, P., De Munck, J., Brooks, N. R. & Van Meerbeek, B. Curing characteristics of flowable and sculptable bulk-fill composites. *Clin. Oral Investig* **21**(4), 1201–1212 (2017).
- Price, R. B. et al. Correlation between the beam profile from a curing light and the microhardness of four resins. *Dent. Mater.* **30**(12), 1345–1357 (2014).
- Sartori, N., Knezevic, A., Peruchi, L. D., Phark, J. H. & Duarte, S. Jr. Effects of light attenuation through dental tissues on cure depth of composite resins. *Acta Stomatol. Croat* **53**(2), 95–105 (2019).
- Duncan, H. F. et al. European society of endodontology position statement: management of deep caries and the exposed pulp. *Int. Endod J.* **52**(7), 923–934 (2019).
- Asgary, S., Roghanizadeh, L., Eghbal, M. J. & Akbarzadeh Baghban, A. Managing failed vital pulp therapies in mature permanent teeth in a retrospective cohort study, with success and survival rates of managing protocols. *Sci. Rep.* **14**(1), 11621 (2024).
- Tong, H. J. et al. Deep dentine caries management of immature permanent posterior teeth with vital pulp: a systematic review and meta-analysis. *J. Dent.* **124**, 104214 (2022).

32. Leibow, W. B. & Springer, L. The other side of endodontics: vital pulp therapy on mature permanent teeth. *Compend Contin Educ Dent.* **45**(6), e1–e4 (2024).
33. International Organization for Standardization. *ISO/TS 11405 Dentistry -- Testing of adhesion to tooth structure* 3rd edn (International Organization for Standardization, 2015).
34. Gale, M. S. & Darvell, B. W. Thermal cycling procedures for laboratory testing of dental restorations. *J. Dent.* **27**, 89–99 (1999).
35. Taha, N. A., Palamara, J. E. & Messer, H. H. Fracture strength and fracture patterns of root filled teeth restored with direct resin restorations. *J. Dent.* **39**, 527–535 (2011).
36. Fornara, R. et al. Management of Calcified Canals with a New Type of Endodontic Static Guide: A Case Report. *Dent J (Basel)*. **3**;12(6):166. (2024).
37. Goracci, C. et al. Polymerization efficiency and flexural strength of low-stress restorative composites. *Dent. Mater.* **30**(6), 688–694 (2014).
38. Cuevas-Suárez, C. E. et al. Effect of radiant exposure and uv accelerated aging on physico-chemical and mechanical properties of composite resins. *J. Appl. Oral Sci.* **27**, e20180075 (2019).
39. Price, R. The Dental Curing Light. in *Dental Composite Materials for Direct Restorations*. 1st ed. (ed Miletic, V.) 43–62. (Springer International, (2018).
40. Zeleniakienė, D., Kleveckas, T., Liukaitis, J. & Marazas, G. The influence of porosity on stress and strain state of porous polymer materials. *Mater. Sci.* **9**(4), 358–362 (2003).
41. Rodrigues, D. B., Martinelli, M. & Nascimento, A. Mechanical strength and wear of dental glass-ionomer and resin composites affected by porosity and chemical composition. *J. Bio- Tribo-Corros* **1**(24), (2015).
42. Biočanin, V. et al. Marginal gaps between 2 calcium silicate and glass ionomer cements and apical root dentin. *J. Endod* **44**(5), 816–821 (2018).
43. Naoum, S. J. et al. Reducing composite restoration polymerization shrinkage stress through resin modified glass-ionomer based adhesives. *Aust Dent. J.* **60**(4), 490–496 (2015).
44. Alhalawani, A. M. F., Curran, D. J., Boyd, D. & Towler, M. R. The role of poly(acrylic acid) in conventional glass polyalkenoate cements. *J. Polym. Eng.* **36**(3), 221–237 (2016).
45. Magne, P., Silva, S. & Andrada Md, Maia, H. Fatigue resistance and crack propensity of novel super-closed sandwich composite resin restorations in large mod defects. *Int. J. Esthet Dent.* **11**(1), 82–97 (2016).
46. Garlapati, T. G., Krithikadatta, J. & Natanasabapathy, V. Fracture resistance of endodontically treated teeth restored with short fiber composite used as a core material-an in vitro study. *J. Prosthodont. Res.* **61**(4), 464–470 (2017).
47. Frater, M., Forster, A., Kereszturi, M., Braunitzer, G. & Nagy, K. In vitro fracture resistance of molar teeth restored with a short fibre-reinforced composite material. *J. Dent.* **42**(9), 1143–1150 (2014).
48. Albar, N. & Khayat, W. Fracture load of mesio-occluso-distal composite restorations performed with different reinforcement techniques: an in vitro study. *Polym. (Basel)* **15**(6), 1358 (2023).
49. Bijelic-Donova, J., Garoushi, S., Lassila, L. V., Keulemans, F. & Vallittu, P. K. Mechanical and structural characterization of discontinuous fiber-reinforced dental resin composite. *J. Dent.* **52**, 70–78 (2016).
50. Ilie, N., Bucuta, S. & Draenert, M. Bulk-fill resin-based composites: an in vitro assessment of their mechanical performance. *Oper. Dent.* **38**(6), 618–625 (2013).
51. Garoushi, S., Sailynoja, E., Vallittu, P. K. & Lassila, L. Physical properties and depth of cure of a new short fiber reinforced composite. *Dent. Mater.* **29**(8), 835–841 (2013).
52. Magne, P., Carvalho, M. A. & Milani, T. Shrinkage-induced cuspal deformation and strength of three different short fiber-reinforced composite resins. *J. Esthet Restor. Dent.* **35**(1), 56–63 (2023).
53. Ozyurek, T., Ulker, O., Demiryurek, E. O. & Yilmaz, F. The effects of endodontic access cavity preparation design on the fracture strength of endodontically treated teeth: traditional versus conservative preparation. *J. Endod* **44**(5), 800–805 (2018).
54. Thadathil Varghese, J., Babaei, B., Farrar, P., Prentice, L. & Prusty, B. G. Influence of thermal and thermomechanical stimuli on a molar tooth treated with resin-based restorative dental composites. *Dent. Mater.* **38**(5), 811–823 (2022).
55. Raju, R., Rajan, G., Farrar, P. & Prusty, B. G. Dimensional stability of short fibre reinforced flowable dental composites. *Sci. Rep.* **11**(1), 4697 (2021).
56. Pacheco, R. R. et al. Comparison of blue and infrared light transmission through dental tissues and restorative materials. *Oper. Dent.* **49**(3), 300–310 (2024).
57. Kucukyilmaz, E., Yasa, B., Akcay, M., Savas, S. & Kavrik, F. Effects of pulp capping materials on fracture resistance of class ii composite restorations. *Eur. J. Dent.* **9**(2), 218–223 (2015).

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Author contributions

Conceptualization and Methodology [NN, VOG, VM, MM], Investigation [NN, IT, MM, DYB], Data analysis [NN, IT, DBB, JKP, PM], Figure preparation [NN, PM], Writing original draft [NN, VM], Writing review and editing [VOG, DBB, JKP, PM, MDj, DYB].

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Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

The study was approved by the School Ethics Committee (Decision No. 36/10).

Additional information

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