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Cuspal displacement, marginal adaptation, and nanoleakage in maxillary premolars restored with a novel auto-cured bulk-fill composite versus a light-cured bulk-fill composite: an in-vitro study

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Abstract

Background STELA is a newly introduced auto-cured bulk-fill composite proposed as an alternative to amalgam. It does not require light activation and provides an unlimited depth of cure, in addition to acceptable esthetic and mechanical properties.

Objectives To evaluate cuspal displacement, marginal adaptation, and nanoleakage in mesio-occluso-distal (MOD) Class II preparations of maxillary premolars restored with an auto-cured bulk-fill composite compared with a light-cured bulk-fill composite.

Materials and methods Sixty maxillary human premolars extracted for orthodontic purposes were randomly assigned to two groups ($n=30$) according to the bulk-fill composite used. Standardized MOD Class II preparations were made and restored using either Group 1: STELA Capsule (SDI, Australia) or Group 2: Tetric N-Ceram Bulk Fill (Ivoclar Vivadent, Liechtenstein). Each group was subdivided into three subgroups ($n=10$) based on the test performed. In Subgroup 1, cuspal displacement was recorded after post-cavity preparation and at (5 min, 24 h) post-restoration using a digital microscope. The remaining restored specimens underwent thermocycling and mechanical loading. Subsequently, marginal adaptation (Subgroup 2) was examined using scanning electron microscopy. Nanoleakage (Subgroup 3) was evaluated using silver nitrate tracing. Statistical analysis was performed using the independent-samples t-test and Fisher's exact test ($P \leq 0.05$).

Results STELA Capsule demonstrated significantly lower cuspal displacement at both 5 min and 24 h post-restoration compared with Tetric N-Ceram Bulk Fill ($P < 0.001$). Following thermocycling and mechanical loading,

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STELA Capsule also exhibited better marginal adaptation ($P = 0.033$) and reduced nanoleakage ($P < 0.001$) compared with the Tetric N-Ceram Bulk Fill.

Conclusions The STELA composite with its dedicated primer showed favorable laboratory outcomes compared with Tetric N-Ceram Bulk Fill used with Tetric N-Bond. This restorative protocol can serve as a viable clinical alternative to light-cured bulk-fill composites, particularly for restoring MOD Class II preparations in maxillary premolars.

Clinical relevance The novel auto-cured bulk-fill composite with its dedicated primer demonstrated excellent performance in reinforcing weakened premolars. It exhibited superior results in reducing cuspal displacement, improving marginal adaptation, and minimizing nanoleakage compared to a light-cured bulk-fill composite, indicating its potential for clinical use.

Keywords Cuspal displacement, Marginal adaptation, Nanoleakage, Maxillary premolars, Auto-cured bulk-fill composite, STELA

Background

Cuspal compliance, the inverse of rigidity, represents the change in dimension per unit of applied force. When cuspal compliance is high, polymerization shrinkage of resin composites can generate contraction stresses at the composite–adhesive interface [1]. These stresses may lead to two main clinical concerns. First, residual stresses within the restoration can pull the cusps inward, reducing the intercuspal distance (ICD) and resulting in cuspal displacement. This displacement may alter occlusal contacts, promote enamel cracking, and increase the risk of cusp fracture under functional loading [2]. Second, shrinkage-induced stresses may disrupt the adhesive interface, leading to gap formation that can contribute to postoperative sensitivity, marginal discoloration, and secondary caries development [3].

Durable marginal integrity is critical for the long-term success of restorative therapy. The quality of the adhesive interface between the restoration and the tooth structure is known as marginal adaptation. Improved marginal adaptation minimizes gap formation, thereby reducing the risk of secondary caries and postoperative sensitivity [3]. Nanoleakage refers to nanoscale porosities within the hybrid layer at the dentin–resin interface, where incomplete resin infiltration leaves voids along exposed collagen fibrils or within demineralized dentin [4, 5]. Therefore, achieving a durable adhesive bond is critical to minimize fluid diffusion, molecular movement, and bacterial ingress. It should also strengthen the remaining tooth structure through effective stress distribution across the tooth–restoration complex [5].

A new generation of auto-cured bulk-fill composite, STELA (SDI, Bayswater, Victoria, Australia), has recently been introduced. According to the manufacturer, STELA contains bisphenol-A (BPA)-free monomers, ionglass filler, and surface-modified amorphous silica [5, 6]. As a chemically activated material, it does not require light-curing and is described as having an unrestricted depth of cure. When used in combination with its dedicated primer, the polymerization reaction is accelerated, which may enhance bonding to dentin and reduce postoperative discomfort [7]. The primer is formulated without tertiary amines, which have been associated with discoloration of resin restorations over time. Additionally, STELA incorporates calcium, strontium, and fluoride ions intended to support bioactive behavior [8]. In a recent clinical trial [9] that assessed 165 posterior restorations, both STELA delivery systems (automix and capsule) were associated with lower rates of postoperative sensitivity and less shade mismatch compared with a light-cured composite. Similarly, a recent randomized controlled trial [10] compared the one-year clinical performance of Class II restorations using three types of bulk-fill composites: auto-, dual-, and light-cured. All three types of restorations showed a 100% survival rate after 12 months. Overall, the auto- and dual-cured composites demonstrated comparable short-term functional and biological performance to the light-cured composite, although the esthetic outcomes varied depending on the material used. Another recent study [11] compared the performance of STELA auto-cured bulk-fill composite with two conventional light-cured composites. The results demonstrated that after storage in distilled water at 37 °C for 24 h and 28 days, STELA exhibited significantly higher compressive strength than the two conventional light-cured composites. Scanning electron microscopy (SEM) analysis revealed the presence of cubic crystalline structures on the surface of STELA following immersion in phosphate-buffered saline (PBS) and saliva for 28 days, indicating a degree of bioactivity. No such changes were observed in the conventional light-cured composites. Additionally, wettability testing showed that STELA had the lowest contact angle compared to the conventional light-cured composites, suggesting better hydrophilicity. Varghese et al. (2024) [12] compared the STELA auto-cured composite with several commercially available dual-cured restorative materials and found that the STELA auto-cured composite exhibited higher flexural strength, compressive strength, fracture toughness, and microhardness. The authors suggested that STELA possesses excellent

mechanical properties suitable for posterior stress-bearing restorations. An important aspect of auto-cured bulk-fill composites is their ability to generate minimal polymerization shrinkage stress. The prolonged pre-gel phase and gradual curing reaction mitigate stress at the bonded interfaces and diminish gap formation [13].

Laboratory thermomechanical aging devices can provide insight into the durability of restorative materials under simulated intraoral conditions. Repeated masticatory loading generates mechanical stresses that accumulate at the composite–adhesive interface, contributing to fatigue, microcrack development, and eventual interfacial debonding. Temperature fluctuations induce cycles of contraction and expansion within both the restoration and tooth structure, which may facilitate hydrolytic degradation and further weaken the bonded interface [14].

Despite its growing clinical use, limited scientific data are available regarding the performance of this novel auto-cured bulk-fill composite. Therefore, evaluating its behavior in standardized cavity preparations is warranted. The objectives of this study were: (1) to measure cuspal displacement after post-cavity preparation and at (5 min, 24 h) post-restoration; (2) to evaluate marginal adaptation; and (3) to assess nanoleakage following thermocycling and mechanical loading (TCML) in mesio-occluso-distal (MOD) Class II preparations of maxillary premolars restored with an auto-cured bulk-fill composite compared with a light-cured bulk-fill composite. The null hypotheses were that there would be no significant differences between the two materials regarding (1) cuspal displacement, (2) marginal adaptation, and (3) nanoleakage.

Table 1 Chemical formulations of the restorative materials and adhesives used in this study

Material (Abbreviation/ Shade)	Manufacturer (Lot No.)	Chemical Formulation		Filler Loading
STELA Capsule bulk-fill composite (STL-C/ Universal Chroma)	SDI, Victoria, Australia (1235340)	**Base** Fluoro-alumino-silicate glass (4 µm)	**Catalyst** UDMA, GDMA, fumed silica, ytterbium fluoride, 10-MDP, calcium aluminate, initiators, stabilizers, pigments	76.8 wt% 55.4 vol%
STELA Primer	SDI, Victoria, Australia (1221210 A)	10-MDP, DUDMA, MEK, 4-META, acrylic monomer, water, initiators, stabilizers		N/A
Tetric N-Ceram Bulk Fill Compule (TNC-B/ IVA)	Ivoclar Vivadent, Liechtenstein (Z05ZRF)	**Filler Content** Barium-aluminosilicate glass (0.4–0.7 µm), Isofiller, ytterbium fluoride, spherical mixed oxide, prepolymer fillers and Ivocerin curing booster	**Organic Matrix** Bis-GMA, Bis-EMA, UDMA.	75–77 wt% 53–55 vol%
Tetric N-Bond Universal (U)	Ivoclar Vivadent, Liechtenstein (Z05ZLH)	10-MDP, HEMA, Bis-GMA, D3MA, MCAP, ethanol, water, highly dispersed silicon dioxide, and curing booster (CQ)		N/A

UDMA urethane dimethacrylate, *GDMA* glycerol-dimethacrylate, *10-MDP* 10-methacryloyloxydecyl dihydrogen phosphate, *DUDMA* diurethane dimethacrylate, *MEK* methyl ethyl ketone, *4-META* 4-methacryloxyethyl trimellitic anhydride, *Bis-GMA* bisphenol-A-glycidyl methacrylate, *Bis-EMA* bisphenol ethyl methacrylate, *HEMA* 2-hydroxyethyl methacrylate, *D3MA* decandiol dimethacrylate, *MCAP* methacrylate carboxylic acid polymer, *CQ* camphorquinone

Materials and methods

Restorative materials

The chemical formulations of the restorative materials and adhesive systems used in this study are summarized in Table 1. The precise composition and initiator systems of the STELA auto-cured bulk-fill composite and STELA Primer are protected by a patent [15].

Ethical committee approval

The study protocol was reviewed and approved by the Research Ethics Committee of the Faculty of Oral and Dental Medicine at Nahda University (protocol number: 001-7-25-1). All procedures adhered to institutional guidelines governing the use of extracted human teeth for research purposes. This in vitro study used sound extracted teeth collected from anonymous patients who provided informed consent for the use of their teeth in research. No identifying information was gathered from any individuals. The informed consent process was a routine procedure, as the patients were receiving dental treatment at an educational hospital.

Sample size calculation

Based on the findings of a pilot study carried out on three specimens from each group, in which marginal adaptation scores served as the main outcome. In the STL-C group, one specimen (0.33) obtained a score of 0, while two specimens (0.67) obtained a score of 1. In contrast, all specimens in the TNC-B group obtained a score of 1. With a power of 80% and 1 degree of freedom, the effect size (w) was 0.702, and the minimum predicted sample size was 16 specimens, using an alpha (α) level of 5% and a beta (β) level of 20%. The sample size was increased to a total of 20 specimens (10 specimens per group) to compensate for a potential dropout rate of 25% due to

possible pulp exposure during tooth preparation or specimen loss after aging. G*Power version 3.1.9.2 was used to compute the sample size.

Teeth selection

Sixty maxillary premolars extracted for orthodontic purposes were collected from the Oral and Maxillofacial Surgery Clinic, Faculty of Oral and Dental Medicine, Nahda University. The donors were systemically healthy adults within the age range of 18–36 years. All selected teeth were free of caries, cracks, previous restorations, and developmental or structural defects [16, 17].

Disinfection, cleaning, and storage of extracted teeth

Immediately after atraumatic extraction, the premolars were disinfected in a 0.5% chloramine-T solution [3]. Extracted premolars with calculus deposits or surface stains were cleaned using an ultrasonic scaler and polished with eugenol-free pumice. The teeth were then stored in sterile saline at 4 °C to inhibit bacterial growth before use [18, 19]. The buccopalatal and mesiodistal dimensions of each premolar were measured using a digital caliper (Mitutoyo, Japan) to ensure dimensional standardization. Only maxillary premolars with an occluso-cervical distance between 8.0 and 8.5 mm were included in the study to minimize anatomical variability [20]. The cementoenamel junction (CEJ) was first marked with an indelible pen, and the distance from the cusp tip to the marked CEJ was measured using a digital caliper (Mitutoyo, Japan) [21]. Only teeth with a maximum dimensional variation of ± 0.5 mm were included [3, 22].

Study design

Sixty selected teeth were randomly assigned to two groups ($n = 30$) based on the bulk-fill composite material used. Group 1: STL-C auto-cured bulk-fill composite; Group 2: TNC-B light-cured resin composite. Each group was further subdivided into three subgroups ($n = 10$) according to the outcome measure assessed. In Subgroup 1, cuspal displacement was recorded post-cavity preparation and at (5 min, 24 h) post-restoration using a digital microscope. The remaining restored specimens underwent 250,000 mechanical cycles between 5 °C and 55 °C. Following aging, Subgroup 2 was examined for marginal adaptation at the enamel–resin interface using SEM. Subgroup 3 was evaluated for nanoleakage at the dentin–resin interface using a silver nitrate tracer.

Randomization and allocation

The extracted teeth were randomly allocated to either the auto-cured or light-cured bulk-fill composite groups using a computer-generated randomization table created in Microsoft Excel. Each tooth was given a unique identification code (ID) to ensure allocation concealment and reduce selection bias. Blinding the operator was not feasible due to differences in the restorative protocols between the two materials. However, all evaluators responsible for assessing cuspal displacement, marginal adaptation, and nanoleakage were blinded to minimize assessment bias [23].

Mold designing and tooth mounting

Each premolar was embedded in warm wax up to 2 mm below the CEJ to simulate the periodontal region. After the wax solidified, the tooth–wax assembly was placed in a cylindrical plastic mold and surrounded by auto-cured acrylic resin to replicate the characteristics of alveolar bone. Once the resin had partially polymerized, the teeth were removed, and the residual wax was eliminated using a warm water bath [24]. A light-body silicone material was then injected into the mold, and each tooth was repositioned parallel to its long axis and carefully pressed into place to expel excess silicone. This technique created a uniform silicone layer approximately 0.2–0.3 mm thick around the root surface, effectively simulating the periodontal ligament [25].

MOD Class II preparations

The mounted teeth were secured in a tooth preparation device (BEGO, Bremen, Germany) to ensure proper alignment during preparation. MOD Class II preparations were performed using a high-speed, straight fissure carbide bur with a rounded end (#1158, SS White, NJ, USA) under air–water cooling. A new bur was used after every five preparations to maintain cutting efficiency. The intended preparation outline was marked on the occlusal surface with a permanent marker (Sharpie, Sanford, USA) to ensure central positioning and preserve balanced dentinal support for both buccal and palatal cusps [26].

Standardized MOD Class II preparations (Fig. 1) were created by a single operator. The buccopalatal width was set at 4 mm with parallel buccal and palatal walls. The depth of the pulpal floor was standardized at 4 mm, measured from the palatal cusp tip. A rubber stopper was placed 4 mm from the bur tip to prevent further dentin cutting. The gingival margins were located above the CEJ with no gingival seats. Final cavity dimensions were verified using a digital caliper (Mitutoyo, Japan). All internal line angles were rounded, and no bevels were prepared at the cavosurface margins. Any tooth with pulp exposure was excluded from subsequent statistical analysis [26, 27].

Application of restorative materials

A matrix band (Automatrix, Bioggio, Switzerland) was placed around each premolar. All restorative materials were manipulated according to the manufacturers'

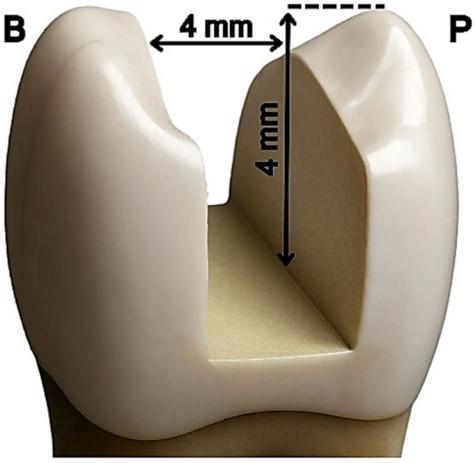

Fig. 1 Schematic diagram (proximal view) illustrating the standardized dimensions of the MOD Class II preparations

instructions. For the STL-C group, two drops of STELA primer were dispensed into a plastic mixing well and vigorously scrubbed onto all internal cavity walls and margins using a disposable brush. The STELA primer was left undisturbed for 5 s and then gently air-dried for 2–3 s. Each STELA restoration was prepared by activating the capsule through plunger depression, followed by mixing for 10 s in a triturator (TPC Advanced Technology, USA). The mixed capsule was loaded into an applicator (GC, Japan), and the composite was injected into the prepared cavity in a single bulk increment. The cavity was slightly overfilled and sculpted, after which the material was allowed to auto-polymerize for 4 min to achieve complete setting.

For the TNC-B group, all prepared enamel and dentin surfaces were treated with Tetric N-Bond Universal using a microbrush. The saturated microbrush was actively rubbed over the surface for 20 s, and excess adhesive material was removed with a new microbrush. The solvent was evaporated by air-drying for 5 s until no fluid movement was visible, followed by light-curing for 10 s. The TNC-B composite was then injected into the prepared cavities using a compule gun in a single increment. Photoactivation was performed with a light-emitting diode (LED) curing device (Bluephase N, Ivoclar Vivadent) for 10 s, with the light tip maintained over the center of the occlusal surface. Light output was routinely verified with a radiometer (Bluephase Meter II, Ivoclar Vivadent) to ensure an intensity of at least 1000 mW/cm² [27]. After removal of the matrix band, additional curing was performed from both the buccal and palatal directions. Final contouring was achieved using coarse and fine diamond burs, followed by polishing with 1200-grit silicon carbide (SiC) sheets [12].

Measurement of cuspal displacement

Calculations of cuspal displacement (Subgroup 1) were performed using a digital measurescope (UM-2 Nikon 10×, Tokyo, Japan) with an accuracy of 0.001 mm. A custom-made polymethyl methacrylate (PMMA) sheet was used to maintain the horizontal alignment of each specimen during repeated measurements [26]. Two reference markers were created by bonding short segments of orthodontic wire as close as possible to the buccal and palatal cusp tips of each premolar prior to tooth preparation [17]. After the measurescope was switched on, the specimen on the observation table was examined through the eyepiece using the main adjustment control until the short segments of orthodontic wire on the cusp tips became clearly visible. The fine adjustment control was then used to move the measurescope observation table until the targeting reticle was centered on the short segment of orthodontic wire at the buccal cusp tip. The reset button on the digital readout unit was pressed to set the initial reading to zero. The fine adjustment control was then used again to center the targeting reticle on the short segment of orthodontic wire at the palatal cusp tip. The linear distance (μm) between the short segments of orthodontic wires on both cusp tips was automatically displayed on the digital readout unit and recorded as the baseline measurement (post-cavity preparation). Subsequent measurements were obtained at 5 min and 24 h post-restoration, with the specimens stored in water at room temperature (23 ± 1 °C) between measurements. The difference between the baseline measurement and the final result at each time-point was used to determine cuspal displacement for each tooth. All procedures were conducted by the same assessor, and a second assessor verified the reproducibility of the measurements [26].

Thermocycling and mechanical loading (TCML)

Specimens in Subgroups 2 and 3 were subjected to 250,000 mechanical cycles in a computer-controlled Robota chewing simulator. The applied load was 50 N, with a frequency of 1.7 Hz and a lateral movement of 0.8 mm. Thermocycling was performed between water baths maintained at 5 °C and 55 °C, with a dwell time of 30 s in each bath [28–30]. After completing the TCML protocol, the specimens were removed from their resin blocks and thoroughly air-dried.

Evaluation of marginal adaptation

Marginal adaptation at the enamel–resin interface (Subgroup 2) was assessed after cleaning the gingival margins with 10% orthophosphoric acid for 5 s to eliminate any debris present. The specimens from each group were then mounted on aluminum stubs using carbon adhesive tape (SPI Supplies, West Chester, USA) and sputter-coated with gold. The mounted and coated specimens

Table 2 Comparison of the cuspal displacement (μm) between the two bulk-fill composite groups at 5 min and 24 h post-restoration

Time	STL-C ($n=10$)		TNC-B ($n=10$)		*P*-value	Effect size (d)
	Mean	SD	Mean	SD		
5 min	4.96	0.21	29.4	1.02	< 0.001*	33.09
24 h	2.13	0.83	14.79	1.81	< 0.001*	8.99

* Statistically significant difference with $P \leq 0.05$. Independent-samples t-test. μm: microns; *n*: sample size per group; *SD* standard deviation

Table 3 Comparison of the marginal adaptation scores between the two bulk-fill composite groups after TCML

Marginal adaptation score	STL-C ($n=10$)		TNC-B ($n=10$)		*P*-value	Effect size (odds ratio)
	n	%	*n*	%		
Score 0	5	50	0	0	0.033*	3
Score 1	5	50	10	100		
Score 2	0	0	0	0		

* Statistically significant difference with $P \leq 0.05$. Fisher's exact test. *n*: sample size per group; *n*: frequencies; %: percentages

were placed in the chamber of the SEM (JSM-5600LV, Tokyo, Japan). The gingival margin of the proximal area was examined at 200× magnification. Two reference sites—one on the tooth and the other on the composite—were used to identify five distinct gap locations along the gingival margin of the enamel–resin interface. The distances (μm) between these sites were measured [31]. The overall margin was then examined, and the maximum marginal gap was measured. Marginal adaptation was scored according to a previous report [32], based on the maximum width of the marginal gaps as follows; score 0; no detectable gap, score 1; maximum gap width < 30 μm, and score 2; maximum gap width > 30 μm.

Evaluation of nanoleakage

The entire surface of each restored tooth in Subgroup 3 was coated with acid-resistant varnish (Flormar MATTE, Kocaeli, Turkey), leaving a 1 mm window around the adhesive interface and the area within 1 mm surrounding the proximal margins of the restoration. A second coat was applied only after the first had fully dried [33]. The restored teeth were then immersed in 50% ammoniacal silver nitrate ($AgNO_3$) in complete darkness for 24 h at 25 °C, followed by thorough rinsing with distilled water. Subsequently, they were transferred to a photographic developing solution (Kodak, USA) and exposed to fluorescent light for 8 h to reduce silver ions to metallic silver grains [34]. After being thoroughly rinsed with water, the restored teeth were sectioned longitudinally in a mesiodistal direction through the center of the restoration using a low-speed, water-cooled diamond saw (IsoMet, Buehler Ltd., USA). The objective was to obtain dentin–resin sticks with an approximate cross-sectional area of 1 × 1 mm [33]. All sections were then embedded in epoxy resin (Buehler) and polished using a lapping device (Metaserv, Buehler, USA) with 600- and 1200-grit SiC papers under running water to minimize electron scattering [34]. Nanoleakage patterns were first examined in backscattered electron mode using an environmental scanning electron microscopy (ESEM) (FEI Quanta 200 ESEM, France) at 2000× magnification by a single blinded calibrated examiner [35]. This was followed by an analysis of the weight% of $AgNO_3$ penetration (wt%) at the resin-dentin interface using energy-dispersive X-ray analysis (EDAX) [34].

Table 4 Comparison of the $AgNO_3$ penetration (wt%) between the two bulk-fill composite groups after TCML

STL-C ($n=10$)		TNC-B ($n=10$)		*P*-value	Effect size (d)
Mean	SD	Mean	SD		
0.99	0.26	7.79	1.33	< 0.001*	7.099

* Statistically significant difference with $P \leq 0.05$. Independent-samples t-test. wt%: weight%, *n*: sample size per group, *SD* standard deviation

Statistical analysis

Data were assessed for normality using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Marginal adaptation scores showed a nonparametric (nonnormal) distribution, whereas cuspal displacement and nanoleakage values showed parametric (normal) distributions. Homogeneity of variance was assessed using Levene's test, which yielded statistically nonsignificant results, indicating homogeneity of variance between the groups. Data were reported as means along with their corresponding standard deviations (SD). Comparisons of cuspal displacement and nanoleakage values (wt%) between the two groups were performed using the independent-samples t-test. Marginal adaptation scores were analyzed using Fisher's exact test. Statistical analyses were conducted using IBM SPSS Statistics for Windows, Version 23.0 (IBM, Armonk, NY).

Results

All specimens successfully withstood TCML, with no specimen loss in either group. The mean cuspal displacement values (μm) for both groups are presented in Table 2. Marginal adaptation scores and nanoleakage values (wt%) after TCML are summarized in Tables 3 and 4, respectively.

Cuspal displacement

The STL-C group exhibited significantly lower mean cuspal displacement than the TNC-B group at both 5 min (4.96 µm vs. 29.4 µm) and 24 h (2.13 µm vs. 14.79 µm) post-restoration (Table 2).

Marginal adaptation

Following TCML, the STL-C group demonstrated the highest prevalence of specimens with no detectable gaps at the gingival margins (score 0: 50%). In contrast, the TNC-B group exhibited the highest prevalence of marginal gaps < 30 µm (score 1: 100%), followed by the STL-C group (score 1: 50%) (Table 3). The mean marginal enamel gap in the STL-C group was 3.35 µm, whereas the TNC-B group showed a considerably larger mean gap of 22.26 µm (Fig. 2a–b).

Nanoleakage

Following TCML, the STL-C group showed significantly lower $AgNO_3$ penetration (wt%) than the TNC-B group (0.99% vs. 7.79%, respectively) (Table 4). Mild silver deposition localized to the base of the hybrid layer was observed in STL-C-restored specimens, whereas specimens restored with TNC-B exhibited intense silver uptake with extensive deposition at the base of the hybrid layer (Fig. 3a–b).

Discussion

Cuspal displacement, marginal adaptation, and nanoleakage are recognized as critical parameters influencing the long-term performance of resin-based dental restorations [3]. This study makes a unique contribution to the dental literature by simultaneously assessing cuspal displacement, marginal adaptation, and nanoleakage using a novel auto-cured bulk-fill composite. Understanding the behavior of this novel restorative material in large MOD cavities is critical because it has direct implications for restorative decision-making in dental treatment [4].

The null hypotheses were rejected, as significant differences were observed between the two restorative protocols examined (STL-C versus TNC-B) in terms of cuspal displacement, marginal adaptation, and nanoleakage. It is important to acknowledge that different adhesive systems were used for the two bulk-fill composites, which may have influenced the results. However, each bulk-fill composite was applied with its respective adhesive system, as recommended by the manufacturers. While in vitro studies cannot fully replicate the biomechanical complexity of the oral environment, they offer controlled conditions that provide valuable preliminary insights into material behavior prior to clinical application [3].

Maxillary premolars were selected because of their comparable occlusal anatomy and crown dimensions, as well as the presence of only two cusps. These characteristics facilitated the accurate placement of reference points on the buccal and palatal cusp tips, allowing precise monitoring of cuspal displacement before and after the placement of composite restorations. The teeth were further standardized by selecting those with comparable buccopalatal widths using a digital caliper, allowing a maximum dimensional variation of ± 0.5 mm [3, 22]. MOD Class II preparations lacking marginal ridges were used in this study to intentionally weaken the tooth structure, favor cuspal displacement, and imitate clinical

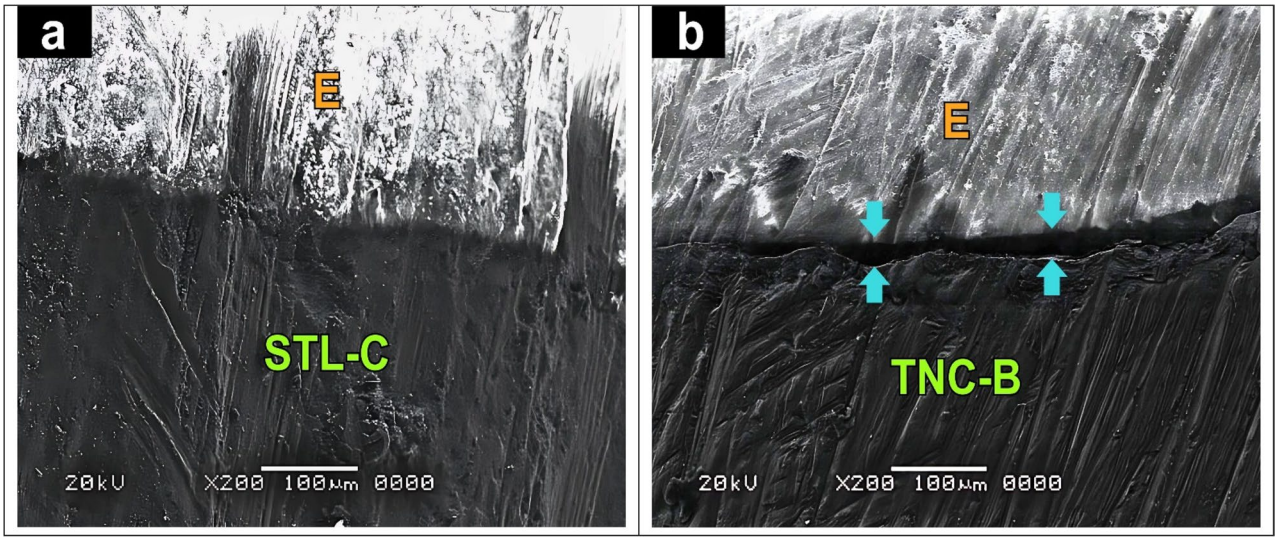

Fig. 2 Representative SEM photomicrographs of marginal adaptation for the two bulk-fill composite groups after TCML (at the gingival margins, under 200× magnification, in over area of 100 µm). **a** Continuous margin in the proximal enamel of specimens restored with STL-C (score 0). **b** Non-continuous margin in the proximal enamel of specimens restored with TNC-B (score 1). The symbols on the SEM micrographs indicate the following: (E) enamel and (arrows) gaps

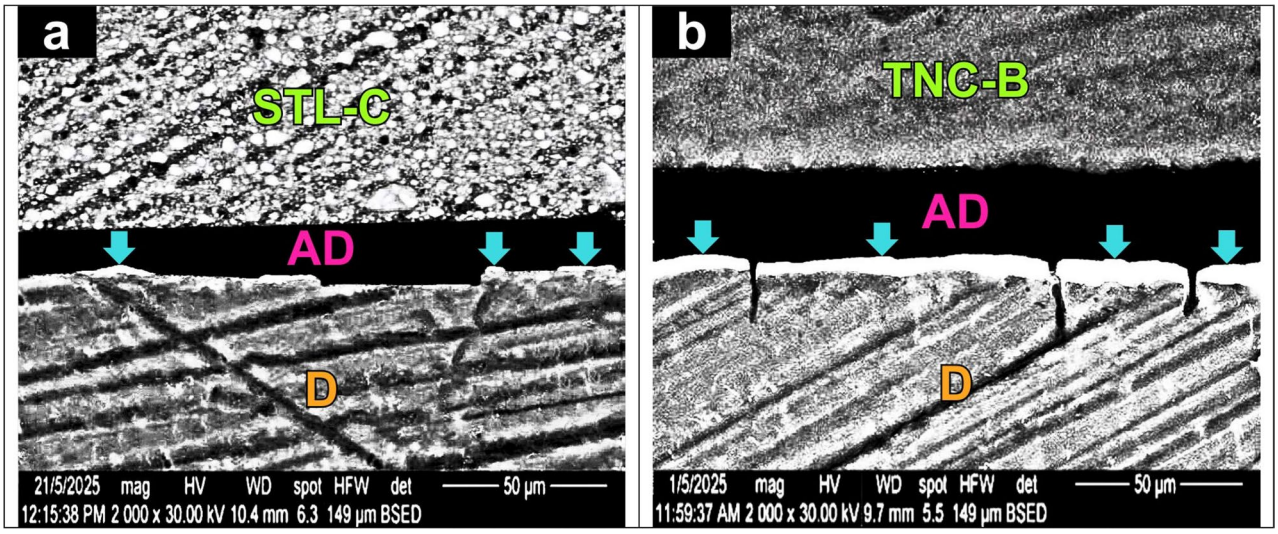

Fig. 3 Representative ESEM photomicrographs of silver nitrate penetration for the two bulk-fill composite groups after 24 h water storage and TCML (at the dentin-resin interface of the proximal margin, under 2000× magnification, in an area of 149 × 149 µm). **a** STL-C specimens showed less degradation at the dentin-resin interface with faint silver nitrate deposits characterized by minor porosities at the base of the hybrid layer. **b** TNC-B specimens showed greater degradation at the dentin–resin interface, with prominent tracer uptake characterized by isolated islands of heavy silver nitrate deposits at the base of the hybrid layer extending into the overlying adhesive. The symbols on the ESEM micrographs indicate the following: (D), dentin; (AD), adhesive layer; and arrows, silver granules

scenarios. This cavity design increases the volume of restorative material required and may intensify polymerization shrinkage stresses, thereby enhancing the likelihood of cusp displacement [36, 37].

A dental surveyor was employed to ensure consistent alignment of the preparation walls, following established methodologies [26, 38], thus minimizing variability among specimens. The preparation design and dimensions were standardized according to published protocols [26, 27] known to induce measurable cuspal displacement. The pulpal floor and gingival seats were prepared at the same level in both proximal boxes, further reducing preparation variability [36]. All operative procedures were performed by a single operator to limit technique-related inconsistencies [26].

A previous study [39] reported no significant differences in cuspal displacement before and after cavity preparation, supporting the use of post-preparation measurements as the baseline in the present study. The second measurement was performed 5 min post-restoration, as most polymerization shrinkage—and the associated cuspal displacement—occurs within this early period. A third measurement was obtained 24 h post-restoration to ensure completion of the polymerization process and stabilization of shrinkage stresses [37].

The ICD was recorded using a digital microscope, a non-invasive imaging method that offers precise and reproducible measurements without physically contacting the tooth surface. Compared with traditional tools such as calipers, the digital microscope allows accurate assessment of linear displacement while avoiding any restriction of cusp movement during measurement [17]. Regarding aging simulation, previous studies [28–30] indicated that approximately 1,250,000 mechanical cycles are needed to replicate five years of intraoral function. Therefore, in this study, the specimens were subjected to 250,000 cycles in a controlled chewing simulator to simulate one year of clinical service.

The STL-C group exhibited significantly lower mean cuspal displacement than the TNC-B group at both 5 min (4.96 µm vs. 29.4 µm) and 24 h (2.13 µm vs. 14.79 µm) post-restoration (Table 2). Cuspal displacement is generally influenced by several factors, such as the cavity size and design, the adhesive system used, and the physico-mechanical characteristics of the restorative material. Because both composite groups were subjected to the same experimental parameters, the differences observed between the two materials are most likely attributable to variations in their physico-mechanical properties. The mechanical behavior of resin composites is affected by several parameters such as polymerization mechanism and shrinkage, degree of conversion, elastic modulus, and chemical formulation [7, 12, 40].

The STL-C auto-cured composite exhibited a higher elastic modulus (12.07 GPa) than the light-cured TNC-B composite (8.04 GPa), which may limit cuspal deformation [12, 41]. According to Varghese et al. (2024) [12], STELA has a high stress intensity factor (1.41 $MPa.m^{0.5}$), microhardness (68.3 N/mm^2), compressive strength (4.1 GPa), and flexural strength (113.4 MPa). In contrast, previous studies [42, 43] reported lower microhardness

(11.15 N/mm^2) and flexural strength (93.3 MPa) for the TNC-B light-cured resin composite.

Although both tested composites contain UDMA—a high-molecular-weight, hydrophobic monomer known to reduce shrinkage stress—the STELA composite additionally incorporates GDMA. This monomer exhibits lower water sorption and solubility, a higher degree of conversion, and greater flexibility, which may enhance cross-linking between the resin matrix and filler particles [7, 12]. Conversely, the TNC-B composite contains Bis-GMA, a highly viscous monomer, which may reduce polymerization and conversion rates, resulting in increased water sorption and hydrolytic degradation [12].

In a recent study [13], two light-cured bulk-fill composites rapidly generated the highest polymerization shrinkage stress after light-curing, compared with their auto- and dual-cured counterparts. This rapid stress development limits the time available for monomer flow and stress relaxation. Even slight temperature increases in the light-cured composites can hasten polymerization and enhance monomer mobility before vitrification. Transient thermal expansion resulting from the exothermic reaction, along with the heat emitted by light-curing devices, can partially mask early polymerization shrinkage.

Following TCML, the STL-C group demonstrated significantly better marginal adaptation at the enamel–resin interface (scores 0 and 1) compared with the TNC-B group (score 1) (Table 3; Fig. 2). Additionally, the STL-C group demonstrated markedly reduced nanoleakage at the dentin–resin interface (0.99 wt%) compared with the TNC-B group (7.79 wt%) (Table 4; Fig. 3). These findings may be associated with differences in the stress levels of polymerization shrinkage between the two materials. For an adhesive interface to remain free of gaps, the shrinkage stress generated during polymerization must not exceed the bond strength between the composite and the tooth substrate [44]. Moreover, the greater gap formation observed with TNC-B may be attributed to the greater cuspal displacement induced by this material, resulting in disruption of the interfacial seal [3].

Auto-cured bulk-fill composites, such as STELA, exhibit lower polymerization stresses because their delayed gelation and prolonged viscous phase allow greater pre-gel flow, thereby reducing stress development. In contrast, light-cured bulk-fill composites generate higher shrinkage stress because of the rapid polymerization initiated in regions closest to the light source [9, 45]. Additionally, the STELA primer contains a catalyst that initiates polymerization at the tooth–primer–composite interface through synergistic chemical curing. This may enhance interfacial adaptation and reduce the risk of gap formation. Light-cured composites, however, rely predominantly on photoinitiation, which decreases in efficiency with increasing distance from the light source [7]. The STELA primer contains ingredients similar to those found in HEMA-free universal adhesives, including the functional monomer 10-MDP, and is free of both BPA and HEMA [46]. In contrast, Tetric N-Bond Universal, which was used with TNC-B, contains HEMA in its formulation. Although HEMA can enhance wetting and adhesion, its hydrophilic nature may promote hydrolysis and water sorption, which can increase the risk of interfacial gaps and reduce bond strength [31].

In a confocal microscopy study [5], visible dentin gaps were observed within the conventional composite (CERAM.X ONE, Dentsply Sirona), suggesting inadequate interfacial adaptation. In contrast, STELA automix exhibited improved interfacial adaptation, forming a compact hybrid layer with minimal nanoleakage. In another study [6], STELA automix also showed higher bond strength than the light-cured composite (Filtek One Bulk-Fill, 3 M Oral Care) after one day and one year of storage in artificial saliva. Although the filler contents of both bulk-fill materials examined in this study are comparable (76.8 wt% for STL-C and 75–77 wt% for TNC-B), their filler compositions differ chemically. TNC-B incorporates barium glass fillers, which are associated with increased water sorption and solubility [12, 47]. In contrast, the ionglass filler in STELA allows ion exchange at the restoration–tooth interface, promoting the release of calcium, strontium, and fluoride. This may enhance the interfacial seal through mineral deposition and biomimetic activity [5].

In a recent study [8], the STELA composite exhibited greatest calcium release under basic conditions (pH 8.8) when compared with different bioactive auto- and light-cured restorative materials. In another recent study [48] using Fourier-transform infrared spectroscopy (FTIR), the STL-C composite had a greater capacity to form carbonated hydroxyapatite after 24 h of immersion in PBS than the light-cured composite (SDR Flow+, York). One possible explanation for the early remineralization effect of STL-C is the synergistic action of its strontium- and fluoride-containing fillers, which enhances remineralization by increasing hydroxyapatite crystallization.

However, Tavangar et al. (2025) [31] reported contradictory results: the STELA composite with its primer exhibited a significantly lower mean microshear bond strength than the Luna light-cured composite with Clearfil SE Bond. Additionally, microgaps in the STELA composite with its primer were slightly larger than those in the Luna light-cured composite with Clearfil SE Bond. The differences in the results between our study and the Tavangar study may be attributed to variations in the types of teeth used, the STELA delivery methods, and the aging protocols. In the Tavangar study, bovine teeth were restored with STELA automix and then subjected

to thermocycling. However, in our study, human teeth were restored with STL-C and subsequently subjected to TCML.

Future research should address several points to enhance the understanding and clinical relevance of these findings: (1) Since this study lacked a control group, future studies should include a conventional resin composite as a control group to provide a more comprehensive comparison of the performance of the restorative materials. (2) As an in vitro investigation, the findings may not fully capture the dynamic biological conditions of the oral cavity, such as pH variations and salivary interactions that contribute to material degradation over time. (3) It is essential to investigate the behavior of the tested materials in different tooth types with varying anatomical characteristics and functional demands, as the present study was limited to maxillary premolars. (4) It is important to examine additional cavity preparation designs, since this study focused exclusively on MOD Class II preparations. (5) The restorative materials were applied using their respective adhesive systems in accordance with the manufacturers' instructions, reflecting current clinical practice. While this approach limits the direct isolation of individual bonding mechanisms, the results provide relevant information on the overall performance of the tested restorative systems under standardized conditions. (6) This study did not measure bond strength, volumetric shrinkage, modulus development, or post-polymerization behavior. Therefore, the results apply only to the test conditions used. (7) Studies evaluating the cost–benefit ratio and patient-centered outcomes of various restorative options are needed to further inform clinical decision-making. (8) Further insights could be achieved by incorporating advanced analytical techniques, such as confocal laser scanning microscopy, since this study utilized a digital microscope to measure cuspal displacement, SEM to assess marginal adaptation, and ESEM to evaluate nanoleakage. (9) Finally, clinical studies are necessary to validate these in vitro findings by including large patient populations and extending the observation period [4, 31, 46].

Conclusions

Within the limitations of this in vitro study—notably the use of different adhesive systems with each composite as recommended by the manufacturers—the tested restorative protocols (STELA composite with its dedicated primer vs. Tetric N-Ceram Bulk Fill with Tetric N-Bond) were associated with lower cuspal displacement, better marginal adaptation, and less nanoleakage for the STELA protocol in this model. This restorative protocol can serve as a viable clinical alternative to light-cured bulk-fill composites, particularly for restoring MOD Class II preparations in maxillary premolars. It offers several potential clinical benefits, including reduced cuspal displacement, improved marginal adaptation, and decreased nanoleakage due to its low polymerization shrinkage. However, additional researches are required to confirm its long-term efficacy.

Abbreviations

ICD	Intercuspal distance
BPA	Bisphenol A
SEM	Scanning electron microscopy
PBS	Phosphate-buffered saline
TCML	Thermocycling and mechanical loading
MOD	Mesio-occluso-distal
STL-C	STELA Capsule bulk-fill composite
TNC-B	Tetric N-Ceram Bulk Fill
UDMA	Urethane dimethacrylate
GDMA	Glycerol dimethacrylate
10-MDP	10-Methacryloyloxydecyl dihydrogen phosphate
DUDMA	Diurethane dimethacrylate
MEK	Methyl ethyl ketone
4-META	4-Methacryloxyethyl trimellitic anhydride
Bis-GMA	Bisphenol A glycidyl methacrylate
Bis-EMA	Bisphenol ethyl methacrylate
HEMA	2-Hydroxyethyl methacrylate
D3MA	Decandiol dimethacrylate
MCAP	Methacrylate carboxylic acid polymer
CQ	Camphorquinone
CEJ	Cementoenamel junction
LED	Light-emitting diode
SiC	Silicon carbide
PMMA	Polymethyl methacrylate
$AgNO_3$	Silver nitrate
ESEM	Environmental scanning electron microscopy
wt%	Weight percentage
EDAX	Energy-dispersive X-ray analysis
SD	Standard deviation
µm	Microns
FTIR	Fourier-transform infrared spectroscopy

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Authors' contributions

Conceptualization: KWA, MAB. Methodology: KWA, MAB. Data curation: KWA, AMNA, DYR, KB, DF. Investigation: KWA, MAB. Validation: KWA, MAB, SMN. Formal analysis: KWA, AMNA, DYR, KB, DF. Supervision: KWA, AMNA, DYR, KB, DF. Visualization: KWA, MAB, SMN. Resources: KWA, AMNA, DYR, KB, DF. Writing – original draft: KWA. Writing – review and editing: MAB, AMNA, DYR, SMN, KB, DF. All authors approved the final manuscript.

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Data availability

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

Declarations

Ethics approval and consent to participate

The Research Ethics Committee of the Faculty of Oral and Dental Medicine at Nahda University approved the study (protocol number: **001-7-25-1**). This in vitro study utilized extracted sound teeth collected from anonymous patients who provided informed consent for the use of their extracted teeth in research. All methods were carried out in in accordance with the Declaration of Helsinki.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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