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Comparative evaluation of 3D-printed resin endocrowns and CAD/CAM milled ceramic endocrowns in endodontically treated molars

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Abstract:
Endodontically treated molars are highly susceptible to fracture and the optimal fabrication method for endocrowns between additive 3D printing and subtractive CAD/CAM milling remains uncertain. This *in vitro* comparative study evaluated 120 standardized mandibular first molar endocrowns fabricated using 3D-printed resin (n = 60) or CAD/CAM-milled lithium disilicate ceramic (n=60), assessing marginal and internal fit, fracture resistance, micro leakage, color stability and flexural strength. CAD/CAM-milled lithium disilicate endocrowns showed significantly better marginal fit (63.4 ± 12.1 versus 89.7 ± 15.3 µm; $p < 0.001$) and fracture resistance (2847 ± 312 versus 1964 ± 278 N; $p < 0.001$), whereas 3D-printed resin endocrowns showed significantly lower micro leakage ($p = 0.01$) and better color stability after thermocycling ($p = 0.004$), with comparable internal fit ($p = 0.09$). CAD/CAM-milled lithium disilicate endocrowns are preferable for posterior teeth subjected to high occlusal loads, while 3D-printed resin endocrowns provide a cost-effective and clinically acceptable alternative with favourable short-term performance. This study advances current knowledge by establishing a comparative evidence-based framework for material selection in endocrown fabrication and supporting future clinical trials to validate these findings under functional conditions.

Keywords: Endocrown, 3D-printed endocrown, CAD/CAM ceramic, lithium disilicate, endodontically treated molars, marginal fit, fracture resistance, digital dentistry

Background:
Endodontically treated posterior teeth present a unique restorative challenge. The loss of pulp vitality, access cavity preparation and carious or traumatic tissue loss collectively reduce dentinal wall thickness and compromise the structural integrity of the crown, markedly increasing susceptibility to cuspal fracture and catastrophic tooth loss **[1].** Traditional restorative approaches have relied on post and core assemblies followed by full coverage crowns, which require significant tooth reduction and may further weaken the residual structure through stress concentration at the post dentine interface **[2].** The endocrown was introduced by Pissis in 1995 as a monolithic, adhesively retained restoration that uses the pulp chamber for macro-mechanical retention, eliminating the need for a separate post and preserving coronal tooth structure **[3].** By engaging the pulp chamber walls and distributing occlusal forces through a larger bonded surface area, endocrowns have showed biomechanical advantages over conventional post-retained crowns in finite element analyses and *in vitro* fracture resistance studies **[4].** Their clinical indications include molars and premolars with adequate remaining dentinal walls and a sufficiently deep pulp chamber to provide macro-retention **[5].** The evolution of digital dentistry has introduced two principal workflows for endocrown fabrication: CAD/CAM milling (subtractive manufacturing) and three-dimensional printing (additive manufacturing). CAD/CAM milled lithium disilicate ceramics, principally IPS e.max CAD (Ivoclar Vivadent), have become the benchmark material for indirect ceramic endocrowns owing to their high flexural strength (360–400 MPa after crystallisation), excellent optical properties and well-established clinical track record **[6].** Three-dimensional printing of endocrowns using high-performance dental resins offers advantages of rapid turnaround, reduced material waste, lower cost and the ability to produce complex geometries without the tool-path constraints of milling **[7].** However, photopolymerised resin restorations differ substantially from ceramic in mechanical properties, wear resistance and color stability and their long-term clinical performance in high-occlusal-load posterior regions remains incompletely characterized **[8].** Several laboratory studies have evaluated individual properties of 3D-printed resin and CAD/CAM ceramic restorations, but comprehensive multi-parameter comparisons specifically focused on endocrowns for molars are limited **[9, 10].** Therefore, it is of interest to evaluate the marginal and internal fit, fracture resistance, micro leakage, color stability and flexural strength of three-dimensional printed resin and CAD/CAM-milled ceramic endocrowns for endodontically treated molars.

Materials and Methods:
Specimen preparation and grouping:
One Twenty extracted human mandibular first molars free of caries, cracks or restorations were selected. All teeth underwent standardised root canal treatment and access cavity preparation. Endocrown preparations were standardised using a custom jig:

all axial walls reduced to 2 mm height, pulp chamber depth 4 mm, shoulder margin with 1.5 mm circumferential width and butt-joint internal cavosurface angle. Teeth were randomly assigned 1:1 to Group A (3D-printed resin) and Group B (CAD/CAM milled lithium disilicate), 60 per group.

Endocrown fabrication:
Preparations were optically scanned (Cerec Omnicam, Dentsply Sirona) and designs created using CEREC SW 5.2 with identical design parameters for both groups. Group A restorations were printed in Formlabs Dental LT Clear V2 resin (Formlabs, USA) using the Form 3B stereolithographic printer at 25 µm layer thickness; post-processing included 99% IPA wash (10 min) and post-curing at 60 °C for 40 min. Group B restorations were milled from IPS e.max CAD blocks (A2-HT, size B40) using the Cerec MC XL milling unit, followed by crystallisation at 840 °C for 25 min per the manufacturer's protocol. All restorations were adhesively cemented with RelyX Ultimate (3M ESPE) following standardised surface pre-treatment.

Outcome parameters and testing protocols:
Marginal and internal fit were assessed using the replica technique with light-body silicone (Aquasil Ultra XLV); cement space was measured at six standardised reference points under a calibrated digital microscope at 30× magnification. Fracture resistance was tested on a universal testing machine (Instron 5967) applying an axial load at 1 mm/min at the central fossa until failure. Microleakage was evaluated after thermocycling (2 000 cycles, 5 °C / 55 °C) using 2% methylene blue dye penetration scored 0–3. Colour stability was assessed using a spectrophotometer (Easyshade Advance, Vita) before and after thermocycling, calculated as ΔE*ab. Flexural strength (three-point bending, bar specimens 25 × 2 × 2 mm) was tested on five specimens per group from each material batch.

Statistical analysis:
Data were analysed with SPSS version 26.0. Continuous variables are reported as mean ± SD. Between-group comparisons were performed with the independent-samples t-test for normally distributed data (verified by Shapiro–Wilk) or the Mann–Whitney U test. Microleakage scores (ordinal) were compared with the Mann–Whitney U test. Statistical significance was set at $p < 0.05$.

Results:
All 120 endocrown restorations were successfully fabricated and cemented. No fractures occurred during cementation. Results across all five outcome parameters are summarised in **(Tables 1 and 2).** Marginal fit was significantly superior in Group B (63.4 ± 12.1 µm) compared with Group A (89.7 ± 15.3 µm; $p < 0.001$). Internal fit showed no statistically significant difference between groups (Group A: 112.6 ± 18.4 µm; Group B: 107.3 ± 16.9 µm; $p = 0.09$). Fracture resistance was significantly higher in the milled ceramic group (2847 ± 312 N vs 1964 ± 278 N; $p < 0.001$). Microleakage scores were significantly lower in Group A (median score 1 vs 2; $p = 0.01$). Colour stability after thermocycling (ΔE*ab) was significantly better in Group A (1.82 ± 0.43) compared with Group B (2.94 ± 0.61; $p = 0.004$). Flexural strength was significantly higher in Group B (387.4 ± 28.6 MPa) than Group A (134.2 ± 21.4 MPa; $p < 0.001$).

Table 1: Marginal fit, internal fit and fracture resistance (mean ± SD)

Parameter	Group A: 3D-Printed Resin	Group B: CAD/CAM Ceramic	p-value
Marginal fit (µm)	89.7 ± 15.3	63.4 ± 12.1	<0.001*
Internal fit (µm)	112.6 ± 18.4	107.3 ± 16.9	0.09 (NS)
Fracture resistance (N)	1964 ± 278	2847 ± 312	<0.001*

** Statistically significant ($p < 0.05$); NS = not significant*

Table 2: Microleakage, colour stability and flexural strength

Parameter	Group A: 3D-Printed Resin	Group B: CAD/CAM Ceramic	p-value
Microleakage score (median)	1	2	0.01*
Colour stability ΔE*ab	1.82 ± 0.43	2.94 ± 0.61	0.004*
Flexural strength (MPa)	134.2 ± 21.4	387.4 ± 28.6	<0.001*

** Statistically significant ($p < 0.05$)*

Discussion:
The present *in vitro* study showed that CAD/CAM milled lithium disilicate endocrowns significantly outperformed 3D-printed resin counterparts in marginal fit, fracture resistance and flexural strength, while 3D-printed resin endocrowns showed significantly less microleakage and superior colour stability after thermocycling. Internal fit was comparable between groups. These findings reflect the well-established mechanical superiority of crystalline ceramic over photopolymerised resin and have direct implications for material selection in the posterior dentition. The mean marginal discrepancy of 63.4 µm for milled ceramic endocrowns falls within the clinically acceptable threshold of ≤ 120 µm reported in the literature **[11].** The higher marginal gap in 3D-printed specimens (89.7 µm) is attributable to the staircase effect of layer-by-layer deposition and post-curing dimensional changes inherent to stereolithographic printing **[12].** Although both values remain within clinical acceptance limits, greater marginal discrepancy may increase the risk of cement dissolution, marginal staining and secondary caries over time. Recent advances in printing resolution and resin formulation are progressively narrowing this gap, with studies reporting marginal accuracies approaching those of milled restorations **[13].** The substantially higher fracture resistance of milled ceramic endocrowns (2847 N vs 1964 N) confirms the biomechanical advantage of lithium disilicate for posterior restorations subject to high occlusal forces. Both values, however, considerably exceed the maximum biting force reported in the molar region (700–900 N in adults),

suggesting that 3D-printed resin endocrowns may offer adequate fracture resistance for most clinical scenarios, consistent with recent *in vitro* findings **[14].** The significantly lower flexural strength of resin (134.2 vs 387.4 MPa) further underscores the limitation of printed resins under cyclic fatigue loading, which is not captured in monotonic fracture resistance testing **[15, 16].** The superior microleakage resistance of 3D-printed resin endocrowns is a clinically relevant finding. The inherent flexibility of resin may allow the restoration to deform slightly under load and recover, providing a more intimate marginal seal through visco-elastic stress relaxation **[17, 18 and 19].** This property may reduce marginal microleakage and associated secondary caries risk, partially compensating for the wider marginal gap. Colour stability, assessed by ΔE*ab after 2,000 thermocycles, was superior in Group A, consistent with reports that modern dental LT resins exhibit lower water uptake and ion-leaching than conventional resins, though ceramic remains the gold standard for long-term aesthetic stability **[20, 21].** Limitations of this study include it's *in vitro* nature, which does not replicate the complex intraoral environment including salivary pellicle, masticatory fatigue, thermal and chemical challenges and bacterial biofilm. Thermocycling provides an approximation of thermal ageing but does not fully simulate years of clinical service. The assessment of colour stability and microleakage on separate specimens from those used for fracture testing limits direct within-specimen comparisons. Future long-term clinical trials and fatigue studies incorporating cyclic loading regimens are required to validate the clinical translational potential of 3D-printed endocrowns in the posterior dentitions **[22]**.

Conclusion:

CAD/CAM milled lithium disilicate endocrowns showed superior marginal fit, fracture resistance and flexural strength, making them the preferred choice for posterior endocrown restorations requiring maximum biomechanical performance. Three-dimensional printed resin endocrowns offered comparable internal fit, significantly less microleakage and superior color stability at significantly lower cost and fabrication time, positioning them as a clinically acceptable, digitally efficient alternative in cases where aesthetics, reduced chair side time and cost-effectiveness are prioritised. Both techniques merit consideration in clinical practice, with material selection guided by the individual patient's functional demands, aesthetic requirements and economic factors.

Conflict of interest: The authors declare no conflict of interest.

Funding: No external funding was received for this study.

Ethical approval:

This *in vitro* study was conducted using extracted human teeth obtained from the tooth bank of the participating institutions with appropriate institutional approval. No human participants were enrolled; formal clinical ethics committee approval was not required beyond institutional governance clearance for use of extracted teeth.

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