

Effects of Preparation Height, Luting Cement Type, and Thermal Aging on the Retention Resistance of 3D-Printed Crowns in Primary Anterior Teeth: An In Vitro Study

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Research Article

Keywords: 3D printing, adhesive cements, anterior primary teeth, CAD-CAM, pediatric crowns, pediatric dentistry, retention, thermal aging

Posted Date: October 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11124443/v1>

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Additional Declarations: No competing interests reported.

Abstract

Background

Restoring severely damaged primary anterior teeth is challenging due to limited tooth structure. This study evaluated the effects of preparation height, luting cement, and thermal aging on the retention resistance of three-dimensional (3D)-printed crowns in primary anterior teeth.

Methods

A total of 180 caries-free maxillary primary central incisors were prepared to heights of 2, 3, or 4 mm. Crowns were fabricated from a permanent crown resin material (VarseoSmile TriniQ, BEGO) using a masked stereolithography printer (Form 4B, Formlabs). Crowns were cemented with resin-modified glass ionomer cement (RMGIC) or resin cement (RC). Each height/cement group was divided into control and thermal aging subgroups ($n = 15$). Aged specimens underwent 10,000 thermal cycles between 5°C and 55°C. Retention resistance was determined using a pull-out test, and failure modes were examined under a stereomicroscope. Data were analyzed using three-way factorial ANOVA and Bonferroni post-hoc tests ($\alpha = 0.05$).

Results

Preparation height had no significant main effect ($p = 0.320$), whereas cement type ($p < 0.001$) and thermal aging ($p = 0.024$) had significant effects on retention resistance. Height $\times$ cement type ($p = 0.009$) and cement type $\times$ thermal aging ($p = 0.047$) interactions were significant. In control groups, resin cement provided greater retention resistance than RMGIC (91.33 ± 29.69 N vs. 65.27 ± 20.41 N; $p < 0.001$). Thermal aging reduced retention resistance with resin cement (73.98 ± 35.36 N; $p = 0.003$), eliminating the difference between cements ($p = 0.088$). Debonding alone occurred in 10.6% of specimens; 89.4% showed debonding with crown and/or tooth fracture.

Conclusions

Preparation heights of 2,3, and 4 mm showed no significant overall effect on retention resistance, although their influence varied by cement type. Resin cement provided greater initial retention than RMGIC, but this advantage diminished after thermal aging. Clinical studies are needed to confirm the performance of custom 3D-printed crowns in primary anterior teeth.

Introduction

Early childhood caries (ECC) remains a prevalent global health issue, frequently leading to the rapid, rampant, and extensive destruction of primary maxillary anterior teeth in preschool children [1].

Premature loss or severe deterioration of primary anterior teeth may have functional, esthetic, and psychosocial consequences, including disturbances in speech and mastication, reduced self-esteem, and an increased risk of negative social experiences [2, 3]. Restoring extensively damaged primary anterior teeth is also clinically challenging because of their small dimensions, relatively large pulp chambers, thin enamel and dentin, and limited surface area available for bonding [4].

Several restorative approaches have been proposed for primary anterior teeth. Direct resin-composite restorations and resin-bonded composite strip crowns provide favorable esthetics and allow the natural tooth morphology to be reproduced. However, their clinical performance depends on the amount and quality of the remaining tooth structure, adequate moisture control, and the adhesive procedure. In particular, the number of carious surfaces has been identified as a factor associated with the clinical outcome of direct composite restorations in primary maxillary incisors [4, 5]. Consequently, the American Academy of Pediatric Dentistry (AAPD) recommends full coronal restorations for primary anterior teeth presenting with extensive multisurface carious lesions, incisal edge involvement, or a history of vital or non-vital pulp therapies [6]. Prefabricated pediatric zirconia crowns (PZCs) have become an alternative for the full coronal restoration of extensively damaged primary anterior teeth. Available evidence indicates that PZCs provide favorable esthetics, retention, and clinical durability [1, 7, 8]. A recent systematic review and meta-analysis reported lower rates of restoration failure and secondary caries with PZCs than with resin-bonded composite strip crowns. However, PZCs were associated with greater wear of the opposing dentition [1]. Nevertheless, zirconia crowns are rigid and cannot be crimped or contoured intraorally. Consequently, they require passive seating and comparatively extensive circumferential tooth reduction, which may increase the risk of pulpal exposure in small primary teeth. Their predetermined shapes and dimensions may also limit adaptation to individual anatomical variations [6, 7, 9]. Furthermore, PZCs fit passively and lack chemical bonding to tooth structure, making decementation their primary mode of clinical failure [10, 11]. Clinical decementation necessitates additional chairside visits, escalates treatment costs, and poses a critical risk of accidental crown swallowing or aspiration. The clinical longevity and retention of PZCs are therefore dependent on the properties of luting cement and preparation geometry [10, 11]. The luting cement may influence retention through its mechanical properties, chemical interactions with dental tissues, and resistance to degradation [12, 13]. Resin-modified glass ionomer cements (RMGIC) are commonly used in pediatric dentistry for their simplified application and relative moisture tolerance. In contrast, resin cements may provide stronger initial bond strength. The long-term behavior of these materials may be affected by thermal changes in the oral environment, which can be simulated in vitro through thermal aging [13, 14]. In addition to cement performance, preparation height may influence crown retention and resistance to dislodging forces by determining the available surface area and the geometric resistance to displacement [15–17]. A previous investigation of prefabricated zirconia crowns reported a marked increase in retention when the preparation height was increased from 1 to 2 mm, whereas further increases did not yield a significant improvement [17]. Nevertheless, these findings were obtained for prefabricated posterior zirconia crowns and may not be directly applicable to primary anterior teeth.

Three-dimensional (3D) printing, or additive manufacturing, enables the fabrication of restorations with patient-specific dimensions and morphology through a digital workflow [18–20]. Photopolymer resins intended for permanent restorations have expanded the potential applications of this technology in crown fabrication. Utilizing masked stereolithography (mSLA) or digital light processing (DLP) printers and advanced biocompatible permanent photopolymer resins, clinicians can fabricate patient-specific restorations that precisely match individual tooth anatomy [20–22]. Unlike prefabricated zirconia crowns, customized 3D-printed crowns can be designed according to the individual tooth anatomy and may provide improved marginal and internal adaptation. A recent in vitro study of primary molar crowns reported favorable marginal and internal adaptation for 3D-printed crowns compared with prefabricated zirconia crowns [23]. Resin-based 3D-printed crowns have demonstrated mechanical properties that support their potential use as full-coronal restorations in primary molar teeth [14, 18]. Recent evidence has expanded the application of 3D-printed resin crowns to primary incisors. An in vitro study evaluated their fracture resistance and color stability, while a recent case report described their clinical use within a digital workflow [24, 25]. Previous investigations have also shown that printing technology and luting cement can affect the mechanical behavior of permanent resin crowns fabricated for primary molars [14]. However, because additive manufacturing is a relatively novel modality in pediatric dentistry, studies evaluating 3D-printed crowns specifically in primary anterior teeth remain limited, and the factors affecting their retention have not yet been adequately investigated.

Therefore, the purpose of this in vitro study was to evaluate the retention resistance of 3D-printed anterior primary tooth crowns fabricated from a permanent crown resin using an mSLA 3D printer under different preparation heights (2 mm, 3 mm, and 4 mm), luting cement types (RMGIC versus RC), and thermal aging. The null hypothesis was that preparation height, luting cement type, thermal aging, and their interactions would have no significant effect on the retention resistance of the 3D-printed primary crowns.

Materials and Methods

Ethical Approval and Sample Size Calculation

Ethical approval for this study was obtained from the Clinical Research Ethics Committee of the Faculty of Dentistry, Gazi University (approval no. GÜDHKAEK.2023.24/3; December 14, 2023). The required sample size was determined based on a three-factor factorial analysis of variance (ANOVA) to evaluate the effects of luting cement type, preparation height, and thermal aging on the retention resistance of the crowns. The sample size calculation was performed using G*Power version 3.1.9.4. An effect size of 0.25 was calculated based on mean and standard deviation values reported in previous studies investigating retention-related outcomes [12, 15, 16, 17, 26, 27]. With an alpha level of 0.05 and a statistical power of 0.85, a minimum of 15 specimens per experimental group was required. Accordingly, a total of 180 primary maxillary central incisors were included in the study.

Tooth Selection and Group Randomization

A total of 180 caries-free primary maxillary central incisors with similar mesiodistal dimensions were selected. The mesiodistal and buccolingual dimensions of the teeth were measured using a digital caliper. Teeth deviating from the reported normal dimensions (6–7 mm mesiodistally and 4–5 mm buccolingually) were excluded [28]. The teeth were obtained from primary maxillary central incisors extracted at Gazi University Faculty of Dentistry, Department of Pediatric Dentistry, due to mobility, prolonged retention, or dental trauma. Following extraction, the teeth were stored in physiological saline solution until use. Before inclusion in the study, all specimens were examined under a light microscope, and only teeth with intact enamel and no visible cracks were selected. The teeth were vertically embedded in autopolymerizing acrylic resin up to 1 mm apical to the cemento-enamel junction.

The 180 teeth were randomly allocated to 12 experimental groups ($n = 15$ per group), including three preparation heights (2, 3, and 4 mm), two luting cement types (resin-modified glass ionomer cement [RMGIC] and resin cement [RC]), and two aging conditions (control and thermally aged). For randomization, the teeth were numbered from 1 to 180, and a computer-based randomization program (www.randomizer.org) was used to assign each specimen to an experimental group (Fig. 1).

Standardized Tooth Preparation

The teeth were prepared under water cooling using diamond burs while maintaining the anatomical contours of the primary incisors. A 1-mm-wide chamfer finish line was prepared, and approximately 1 mm of axial reduction was performed. Following axial reduction, the remaining clinical crown height was adjusted to 2, 3, or 4 mm according to the assigned experimental group. The remaining crown height was measured using a digital caliper to ensure the desired preparation height. All preparation surfaces were inspected, and sharp edges and line angles were rounded. All tooth preparations were performed by a single investigator (M.B.G.).

CAD Design and 3D Printing of Crowns

The prepared teeth were scanned using an intraoral scanner (Ovo, 3DISC, VA, USA), and the digital data were imported into dental design software (DentalCAD®, exocad). The preparation margins were determined on the digital models, and an individual crown was designed for each prepared tooth according to its anatomy. During the design stage, a standardized horizontal opening was incorporated into the incisal portion of each crown for subsequent tensile loading. The incisal portion was extended so that the opening was positioned outside the cemented crown-tooth interface and did not reduce the intended cementation area. The opening was incorporated into the original CAD design and was therefore fabricated together with the crown during 3D printing, without any post-printing drilling. The finalized crown designs were exported in the Standard Tessellation Language (STL) format and imported into PreForm software (Formlabs Inc., MA, USA) to prepare the printing files. The required material and printing parameters were specified in the software, and the files were converted to the proprietary “.form” format for fabrication. The crowns were fabricated using a permanent crown resin (VarseoSmile TriniQ;

BEGO GmbH & Co. KG) with a Formlabs 4B printer (Formlabs Inc., Somerville, MA, USA). Following printing, all crowns were washed in a Form Wash & Cure unit (Formlabs Inc., Somerville, MA, USA) using 95% isopropyl alcohol for 3 minutes to remove residual uncured monomer. The crowns were subsequently dried with compressed air. To ensure dimensional stability, post-curing was performed for 2 × 20 minutes in the Form Cure unit (Formlabs Inc., Somerville, MA, USA). The precise fit of all printed crowns on their corresponding prepared teeth was clinically verified before cementation.

Surface Conditioning and Cementation Protocols

Before cementation, the fabricated crowns were dried with compressed air. The intaglio surfaces of the 3D-printed permanent resin crowns were airborne-particle abraded with 53-µm aluminum oxide particles (Al_2O_3 ; AquaCare, Velopex, London, UK). The crowns were then ultrasonically cleaned in ethanol, rinsed, and air-dried. A universal bonding agent (3M Scotchbond Universal Plus) was then applied according to the manufacturer's instructions and air-dried. Before cementation, the prepared tooth surfaces were etched with 35% phosphoric acid (Scotchbond Etchant, 3M ESPE, St. Paul, MN, USA) and treated with a universal adhesive (Single Bond Universal, 3M ESPE, St. Paul, MN, USA). Within each preparation-height group, the specimens were randomly divided into two luting cement types. All cementation procedures were performed according to the respective manufacturer's instructions:

RMGIC Group (GC FujiCEM Evolve, GC, Tokyo, Japan): Equal pastes of the cement were mixed on a pad for 10 seconds. The crown intaglio was loaded with cement, the crown was seated immediately, and moderate finger pressure was applied. Excess cement was removed with a hand explorer during its rubbery phase, and each surface was light-cured for 3 seconds.

Resin Cement Group (G-CEM ONE, GC, Tokyo, Japan): G-Multi Primer (GC Corp.) was applied to the bonding surfaces and air-dried. The auto-mixed cement was directly injected into the crown using a GC Automix Tip. The crown was immediately seated, and finger pressure was applied. Excess cement was tack-cured for 1 second per surface until it reached a rubbery consistency, and then cleared with an explorer.

Following final cementation, G-Multi Primer was applied to all outer crown surfaces and air-dried. A thin, uniform layer of transparent glazing agent (Optiglaze, GC Corporation, Tokyo, Japan) was applied with a fine brush and light-polymerized for 40 seconds per surface using a curing unit (Valo, Ultradent, UT, USA).

Thermal Aging

Specimens assigned to the aging groups underwent artificial aging using a thermocycling device (MOD Dental, Ankara, Türkiye). The protocol consisted of 10,000 thermal cycles between 5°C and 55°C, with a 30-second dwell time in each water bath, simulating approximately 1 year of thermal aging [29]. Control groups received no aging treatments.

Retention Resistance Testing (Pull-Out Test) and Failure Mode Analysis

Retention resistance was evaluated using a universal testing machine (Lloyd Instruments Ltd., UK). Specimen blocks were secured to the machine's lower holding jig. For tensile loading, a 12-cm segment of 1-mm-diameter orthodontic wire was cut, and one end was bent into a U-shaped, approximately 5–6 mm in length. The wire was passed through the pre-designed horizontal opening in the incisal portion of the 3D-printed crown and secured to the upper load jig. A uniaxial tensile pull-out force was applied along the long axis of the tooth at a crosshead speed of 0.5 mm/min until failure occurred. The maximum force at failure was recorded in Newtons (N) (Fig. 1).

Following the retention test, all specimens were examined under a stereomicroscope. Failure modes involving the crown, luting cement, and tooth substrate were classified into four categories:

Group 1: Debonding only: separation of the crown without fracture of the crown or tooth.

Group 2: Debonding with tooth fracture: debonding accompanied by fracture of the tooth substrate.

Group 3: Debonding with crown and tooth fracture: debonding accompanied by fractures of both the crown and tooth.

Group 4: Debonding with crown fracture: debonding accompanied by fracture of the crown.

Specimens exhibiting debonding without crown or tooth fracture were further classified according to the distribution of cement remnants on the tooth and restoration surfaces, following the classification described by Sellers et al. [30]:

- Adhesive failure: the cement was predominantly present on either the tooth surface or the internal surface of the restoration.
- Cohesive failure: cement remnants were present on both the tooth and restoration surfaces.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics version 23.0 (IBM Corp., Armonk, NY, USA) and RStudio: Integrated Development Environment for R (version 2025.05.0 + 496). Descriptive statistics were reported as mean $\pm$ standard deviation, median, first and third quartiles (Q1 and Q3), and minimum and maximum values. The effects of preparation height, luting cement type, and thermal aging on the retention resistance of the crowns were evaluated using a three-way factorial analysis of variance (ANOVA). Before the analysis, multivariate normality was assessed using the Henze–Zirkler multivariate normality test implemented in the mvn package in RStudio. Homogeneity of variances was assessed using the Levene test. For statistically significant main effects and two-way interactions identified by the

three-way factorial ANOVA, Bonferroni-adjusted multiple comparisons were performed to determine the source of the differences between groups. The level of statistical significance was set at $p < 0.05$.

Results

Descriptive Statistics of Retention Resistance

Descriptive statistics for the retention resistances of the 3D-printed permanent resin crowns according to preparation height, luting cement type, and thermal aging are presented in Table 1. The overall mean retention resistance values for the 2-, 3-, and 4-mm preparation height groups were 70.85 ± 25.67 N, 77.95 ± 27.91 N, and 72.23 ± 34.88 N, respectively. The mean retention resistance was higher for the resin cement (82.66 ± 33.61 N) than for RMGIC (64.70 ± 22.05 N). Across aging conditions, the mean retention resistance decreased from 78.30 ± 28.52 N in the unaged groups to 69.06 ± 30.37 N after thermal aging. Among the 12 experimental groups, the highest mean retention resistance was observed in the control group with a 4-mm preparation height and resin cement (103.33 ± 32.05 N). In contrast, the lowest value was observed in the control group with a 4-mm preparation height and RMGIC (48.00 ± 10.11 N) (Table 1).

Table 1
Descriptive statistics of retention resistance (N) according to preparation height, luting cement type, and thermal aging.

Preparation height	Aging	Luting cement	Mean $\pm$ SD	Median (Q1–Q3)	Minimum–Maximum
2 mm	Control	RMGIC	73.93 ± 21.99	74 (64–84)	20–112
		RC	80.73 ± 25.01	81 (57–99)	45–138
	Aged	RMGIC	61.60 ± 20.21	62 (53–80)	24–91
		RC	67.13 ± 32.24	56 (43–95)	24–146
3 mm	Control	RMGIC	73.87 ± 15.63	74 (68–79)	36–106
		RC	89.93 ± 28.98	90 (64–101)	45–157
	Aged	RMGIC	69.87 ± 26.61	66 (60–79)	28–131
		RC	78.13 ± 35.34	78 (53–103)	31–154
4 mm	Control	RMGIC	48.00 ± 10.11	46 (42–56)	35–73
		RC	103.33 ± 32.05	102 (82–127)	53–164
	Aged	RMGIC	60.93 ± 24.71	61 (35–82)	23–103
		RC	76.67 ± 39.55	77 (49–88)	21–172

Values are presented as mean ± standard deviation, median (Q1–Q3), and minimum–maximum. RMGIC, resin-modified glass ionomer cement.

Descriptive Statistics Three-Way Factorial ANOVA Results

The main effect of preparation height on retention resistance was not statistically significant ($F(2,168) = 1.146, p = 0.320$). In contrast, luting cement type ($F(1,168) = 19.558, p < 0.001$) and thermal aging ($F(1,168) = 5.184, p = 0.024$) had statistically significant main effects. Significant interactions were observed for preparation height × luting cement type ($F(2,168) = 4.868, p = 0.009$) and luting cement type × thermal aging ($F(1,168) = 3.991, p = 0.047$). The preparation height × thermal aging interaction ($F(2,168) = 0.216, p = 0.806$) and the three-way interaction ($F(2,168) = 2.126, p = 0.123$) were not statistically significant (Table 2).

Table 2

Three-way ANOVA for the effects of preparation height, luting cement type, and thermal aging on retention resistance.

Source	Sum of squares	df	Mean square	F	p
Preparation height	1700.078	2	850.039	1.146	0.320
Luting cement type	14508.089	1	14508.089	19.558	< 0.001
Thermal aging	3845.689	1	3845.689	5.184	0.024
Preparation height × luting cement type	7222.011	2	3611.006	4.868	0.009
Preparation height × thermal aging	319.744	2	159.872	0.216	0.806
Luting cement type × thermal aging	2960.556	1	2960.556	3.991	0.047
Preparation height × luting cement type × thermal aging	3154.211	2	1577.106	2.126	0.123
Error	124620.933	168	741.791		
Total	158331.311	179			

Post-Hoc Pairwise Comparisons

1.Preparation Height × Luting Cement Type

Bonferroni-adjusted pairwise comparisons were performed to further explore the significant interaction between preparation height and luting cement type (Table 3). At 2-mm and 3-mm preparation heights, no statistically significant differences in retention resistance were observed between RMGIC and resin cement ($p = 0.382$ and $p = 0.085$, respectively). At 4 mm, however, resin cement resulted in significantly higher retention resistance than RMGIC (90.00 ± 37.88 N vs 54.47 ± 19.68 N, $p < 0.001$).

Among crowns cemented with RMGIC, retention resistance differed significantly between the 3-mm and 4-mm preparation heights ($p = 0.043$). In contrast, no significant differences were observed between 2 mm and 3 mm ($p = 1.000$) or between 2 mm and 4 mm ($p = 0.181$). For resin cement, no significant differences were observed among the preparation heights (all $p > 0.05$).

Table 3
Bonferroni-adjusted pairwise comparisons of retention resistance (N)
according to preparation height and luting cement type.

Preparation height	RMGIC (n = 30)	RC (n = 30)	p-value†
2 mm	67.77 ± 21.68 ^{ab}	73.93 ± 29.18 ^{ab}	0.382
3 mm	71.87 ± 21.54 ^{ab}	84.03 ± 32.32 ^{ab}	0.085
4 mm	54.47 ± 19.68 ^{ab}	90.00 ± 37.88 ^{ab}	< 0.001

Values are presented as mean ± standard deviation. Different lowercase superscript letters indicate statistically significant differences between luting cement types within the same preparation height. In contrast, different uppercase superscript letters indicate statistically significant differences between preparation heights within the same luting cement type (Bonferroni-adjusted $p < 0.05$). RMGIC: resin-modified glass ionomer cement, RC: resin cement.

2. Luting Cement Type × Thermal Aging

Bonferroni-adjusted pairwise comparisons further examined the significant interaction between luting cement type and thermal aging (Table 4). Thermal aging did not significantly affect retention resistance in the RMGIC groups (65.27 ± 20.41 N vs 64.13 ± 23.80 N, $p = 0.844$). In contrast, thermal aging significantly reduced the retention resistance of crowns cemented with resin cement, from 91.33 ± 29.69 N to 73.98 ± 35.36 N ($p = 0.003$).

For the control groups, resin cement provided significantly greater retention resistance than RMGIC ($p < 0.001$). After thermal aging, however, the difference was no longer statistically significant (73.98 ± 35.36 N vs 64.13 ± 23.80 N, $p = 0.088$).

Table 4
Bonferroni-adjusted pairwise comparisons of retention resistance
(N) according to luting cement type and thermal aging.

Thermal aging	RMGIC (n = 45)	RC (n = 45)	p-value†
Control	65.27 ± 20.41 ^a	91.33 ± 29.69 ^a	< 0.001
Aged	64.13 ± 23.80 ^a	73.98 ± 35.36 ^a	0.088

Values are presented as mean ± standard deviation. Different lowercase superscript letters indicate statistically significant differences between luting cement types within the same aging condition. In contrast, different uppercase superscript letters indicate statistically significant differences between

aging conditions within the same luting cement type (Bonferroni-adjusted $p < 0.05$). RMGIC: resin-modified glass ionomer cement, RC: resin cement.

Failure Mode Analysis

Failure mode distributions observed following the retention resistance test are presented in Table 5. Debonding without crown or tooth fracture was observed in 19 specimens (10.6%). Among these, adhesive failure was observed in 12 specimens (63.2%), and cohesive failure was observed in 7 (36.8%).

The remaining 161 specimens (89.4%) exhibited debonding accompanied by crown and/or tooth fracture. Crown fracture with debonding was the most frequent failure mode (96 specimens, 53.3%), followed by tooth fracture with debonding (52 specimens, 28.9%) and simultaneous crown and tooth fracture with debonding (13 specimens, 7.2%).

Table 5
Distribution of failure modes following the retention resistance test.

Failure category	Failure mode	n	%
Group 1: Debonding alone	Type 1:Adhesive failure	12	6.7
Group 1: Debonding alone	Type 2: Cohesive failure	7	3.9
Group 2: Debonding accompanied by abutment tooth fracture	—	52	28.9
Group 3: Debonding accompanied by both crown and abutment tooth fracture	—	13	7.2
Group 4: Debonding accompanied by crown fracture	—	96	53.3
Total	—	180	100.0

Values are presented as n (%). For specimens showing debonding without crown or tooth fracture, adhesive and cohesive failures were classified by the predominant failure location. Percentages for adhesive and cohesive failures are calculated within the debonding-only category, whereas all other percentages are calculated based on the total specimens (n = 180).

Discussion

The effect of restoration type on the marginal and internal gap and absolute marginal discrepancy values of the 3D printed, milled, and prefabricated crowns for the primary teeth was investigated in the present study. The results showed that the restoration type was effective on the tested parameters. Thus, the null hypothesis was rejected.

In this in vitro study, the effects of three clinical parameters-preparation height, luting cement type, and thermal aging-on the retention resistance of 3D-printed permanent resin crowns for maxillary primary

incisors were evaluated. Based on the statistical findings, no statistically significant difference in mean retention resistance was observed among the 2-, 3-, and 4-mm preparation height groups ($p = 0.320$). In contrast, luting cement type and thermal aging demonstrated statistically significant main effects on the retention resistance of the 3D-printed crowns ($p < 0.001$ and $p = 0.024$, respectively). Furthermore, significant two-way interactions were observed between preparation height and luting cement type ($p = 0.009$) and between luting cement type and thermal aging ($p = 0.047$). Thus, the null hypothesis was partially rejected.

Preparation height is an important geometric factor that may influence the retention of full-coverage restorations [17, 27, 31]. In primary anterior teeth, however, the available coronal height is often limited, making the relationship between preparation height and retention of the restoration particularly relevant when a conservative approach is intended [2, 6, 17]. To the best of our knowledge, the present study may be the first in the literature to evaluate the retentive influence of remaining preparation height specifically on primary anterior teeth. In pediatric dentistry, prior investigations into the biomechanical threshold of preparation height have been limited to the posterior primary molars [17]. In the study conducted by Jing et al. [17], the influence of occluso-cervical preparation heights (1, 2, 3, and 4 mm) in primary molar teeth on the retentive force of prefabricated posterior zirconia crowns was evaluated. In the evaluation of specimens luted with a conventional glass ionomer cement and subjected to thermal aging, the 1-mm-high group exhibited a significantly lower mean retentive strength of 1.7 ± 1.0 MPa (116.0 N) compared with all other cohorts. Conversely, no significant differences in retentive force were observed among the 2-mm (2.9 ± 1.4 MPa / 251.4 N), 3-mm (3.1 ± 0.7 MPa), and 4-mm (3.3 ± 0.6 MPa) height groups. The authors reported that a remaining preparation height of 2 mm represents a critical mechanical threshold required to secure clinical and mechanical retention for prefabricated primary posterior zirconia crowns, above which further height extension does not yield proportional retentive benefits [17]. Based on these findings, preparation heights of 2, 3, and 4 mm were selected for evaluation in the present study to investigate whether the effect of preparation height on retention observed in primary posterior teeth would also be applicable to anterior primary teeth. By excluding the 1-mm preparation height, which has previously been reported to provide insufficient mechanical retention, the present study aimed to assess the retention of customized crowns at clinically relevant preparation heights in anterior primary teeth. Wilson et al. [9] quantified the volume of tooth structure removed during crown preparations on primary molar typodont teeth across three prefabricated zirconia crown systems (NuSmile, EZCrowns, and Kinder Krowns) and a preformed stainless steel crown. They were found that prefabricated zirconia crowns required significantly more aggressive occlusal and circumferential tooth reduction than preformed stainless steel crowns to achieve a passive fit. The study observed that zirconia preparation depths in primary first molars approached the pulpal horns very closely, concluding that pediatric dentists must adhere to conservative preparation boundaries and maintain a remaining axial wall height of at least 2 mm to avoid iatrogenic pulpal exposure while securing sufficient crown retention [9]. Considering the limitations of the extensive tooth reduction required for prefabricated zirconia crowns, customized 3D-printed crowns were used in the present study. Potential advantages of 3D-printed crowns for primary teeth include patient-specific design, digitally controlled restoration dimensions and

cement space, favorable marginal and internal adaptation, and mechanical properties that support their use as full-coronal restorations. Because these restorations are individually designed rather than selected from predetermined crown forms, the digital workflow may also provide greater flexibility in adapting crown geometry to the remaining tooth structure [14, 18–20, 23].

In the present study, the overall mean retention resistance values for the 2-, 3-, and 4-mm preparation height groups were 70.85 ± 25.67 N, 77.95 ± 27.91 N, and 72.23 ± 34.88 N, respectively. Although the 3-mm group showed the highest retention resistance value, the differences among the three preparation heights were not statistically significant ($p = 0.320$). These findings suggest that, within the range of preparation heights evaluated in the present study, increasing the remaining preparation height from 2 mm to 3 or 4 mm did not significantly increase retention resistance. Although preparation height alone did not have a significant effect, its effect became significant when considering cement type, as indicated by a significant interaction between preparation height and cement type ($p = 0.09$). The resin cement demonstrated higher retention values across all preparation heights compared with the other cement groups. This difference reached statistical significance only in the 4-mm preparation height group, in which the resin cement exhibited the highest retention resistance value (90.00 ± 37.88 N). Previous investigations to evaluate the effect of preparation height were conducted on the permanent dentition [15, 16, 27, 31]. These studies generally suggest a threshold pattern rather than a simple linear relationship. Gillette et al. [15] found that adhesively luted lithium-disilicate crowns with a 0-mm axial wall height (i.e., a preparation without occlusocervical axial walls) demonstrated significantly lower failure stress than crowns with 1-, 2-, or 3-mm axial wall heights, whereas no significant differences in failure stress were observed among the 1-, 2-, and 3-mm groups. Similarly, Hoopes et al. [16] reported comparable failure loads for 2-, 3-, and 4-mm axial wall heights, whereas preparations with no axial wall height (0-mm flat preparations) and those with a 1-mm axial wall height demonstrated significantly lower failure loads. Goodacre et al. [31] similarly proposed a minimum occlusocervical dimension of 3 mm for premolars and anterior teeth prepared within a recommended total occlusal convergence range of 10° – 20° to provide adequate resistance form. Taken together with the findings of Jing et al. [17] in primary posterior zirconia crowns, this literature suggests that retention loss related to preparation height becomes clinically relevant mainly below a critical minimum height, above which further increases in height do not proportionally improve retention. The absence of a significant overall effect of preparation height in the present study may therefore be consistent with a retention plateau within the range of preparation heights evaluated. Alahmari et al. [27], evaluating lithium-disilicate crowns bonded with resin cements at 2-, 3-, and 4-mm occlusocervical heights, reported a trend toward increased tensile bond strength with increasing height, although this did not reach statistical significance (2.72 ± 0.687 , 3.06 ± 0.817 , and 3.25 ± 0.784 MPa, respectively; $p = 0.054$), together with a highly significant effect of cement type. This finding is broadly consistent with the height-dependent, cement-specific pattern observed in the present study, in which preparation height did not exert a significant independent main effect but interacted significantly with cement type. This finding suggests that the contribution of cement type to retention may become more apparent at greater remaining preparation heights in primary incisors. The small dimensions and reduced surface area of primary anterior teeth limit the available bonding area,

which may reduce the extent to which differences in cement performance are expressed at shorter preparation heights [7, 28, 32]. It is thought that the superior bonding potential of resin cement may become measurable when the preparation height, and consequently the bonding area, increases to 4 mm. Specimen-to-specimen anatomical variability and remaining dentin thickness after preparation among extracted primary incisors may have contributed to the variability in retention values despite standardization of tooth dimensions and preparation height. The present interaction also differs from findings reported for permanent teeth. Alahmari et al. [27] evaluated lithium-disilicate crowns with 2-, 3-, and 4-mm occlusocervical preparation heights and found a significant effect of cement type, but no significant preparation height $\times$ cement type interaction ($p = 0.63$). Differences between the findings may be related to the distinct experimental conditions, including tooth type, crown material, preparation geometry, and luting materials. In addition, it was shown that cement viscosity and adaptation can influence retention, with high-viscosity luting materials potentially exhibiting less complete adaptation and greater void formation under some experimental conditions [33]. However, cement thickness or void formation was not evaluated in the present study; therefore, their contribution cannot be determined.

Previous studies have tested various cement types across different restorative systems, but have not identified a superior cement for all systems. Rosato et al. [12] compared five luting cements for prefabricated primary molar zirconia crowns after 5,000 thermal cycles. Conventional glass ionomer cement (Ketac Cem) showed the highest mean retention force with (482.4 ± 87.3 N), followed by a bioactive resin-modified glass ionomer cement (BioCem), a resin cement (RelyX Unicem 2), and two conventional RMGICs (FujiCEM 2; RelyX Luting Plus Automix) [12]. In contrast, Walia et al. [11] evaluated the retentive force of prefabricated posterior primary zirconia crowns luted with three glass ionomer-based materials (BioCem [bioactive RMGIC], FujiCEM 2 [RMGIC], and Ketac Cem [conventional GIC]) following 5,000 thermal cycles and one week of artificial saliva immersion. They found significantly greater retention with resin-modified glass ionomer cements, including BioCem (117 ± 9 N) and FujiCEM 2 (115 ± 10 N), than with conventional glass ionomer cement (Ketac Cem; 31 ± 10 N) for prefabricated zirconia crowns [11]. Pengpue et al. [13] investigated the tensile bond strength of prefabricated maxillary incisor zirconia crowns luted with bioactive cement (NuSmile BioCem), resin cement (RelyX U200), and RMGIC (RelyX Luting 2). They reported significantly greater tensile bond strength with bioactive cement (1.43 ± 0.85 MPa) than with RMGIC (0.56 ± 0.39 MPa), whereas resin cement (0.91 ± 0.63 MPa) did not differ significantly from either material [13]. More recently, Morsy et al. [34] evaluated the retentive performance and failure modes of three prefabricated pediatric crowns-Bioflx, NuSmile, and SSCs. They found significantly greater retention with RMGIC than with conventional GIC for both Bioflx and zirconia crowns after 2,000 thermocycles. In contrast, no significant difference was detected between the two cements for stainless steel crowns ($p = 0.513$). The study also demonstrated significant crown-material-cement interactions, indicating that the effect of cement type varied among restorative materials. The authors reported that retentive performance cannot be attributed to cement type alone, but should be interpreted in relation to the particular crown material, substrate, and cementation protocol [34]. Other studies highlight the importance of crown-cement compatibility. Aktaş and Bankoğlu Güngör [14] demonstrated that luting cement selection influenced the fracture resistance of 3D-printed permanent

resin crowns for primary teeth, with the effect also varying according to thermal aging and printing method. Although fracture resistance and retention represent different mechanical outcomes, these findings indicate that luting material selection can affect the mechanical behavior of 3D-printed resin crowns. Iampinitkul et al. [35] likewise demonstrated significant differences in microleakage among resin cement, RMGIC, and bioactive cement in both custom-made and prefabricated zirconia crowns for primary maxillary incisors. RMGIC showed significantly greater microleakage than bioactive cement in custom-made zirconia crowns, whereas in prefabricated crowns, both RMGIC and resin cement exhibited greater microleakage than bioactive cement. Microleakage associated with RMGIC occurred at both the cement–tooth and cement–crown interfaces, whereas leakage with resin and bioactive cements was observed at the cement–tooth interface. While microleakage cannot be directly equated with retentive strength, these results demonstrated that cement performance interacts with the crown type [35]. The significant main effect of luting cement type observed in the present study: resin cement yielded higher retention resistance than RMGIC under unaged (control) baseline conditions (91.33 ± 29.69 N vs. 65.27 ± 20.41 N; $p < 0.001$). This situation highlights the importance of cement selection in the retention of pediatric crown restorations. Thermal aging significantly reduced overall retention resistance in the present study ($p = 0.024$). Retention of crowns luted with resin cement decreased significantly after thermal aging, from 91.33 ± 29.69 N to 73.98 ± 35.36 N ($p = 0.003$), whereas no significant change was observed with RMGIC (65.27 ± 20.41 N vs. 64.13 ± 23.80 N; $p = 0.844$). Consequently, the significant difference between resin cement and RMGIC observed under unaged conditions ($p < 0.001$) was no longer statistically significant after aging ($p = 0.088$). The relative stability observed with RMGIC after thermal aging may be related to the cement's material characteristics. RMGICs combine the conventional acid–base reaction of glass-ionomer cements with an additional resin-polymerization reaction [6]. The formulation of the use of RMGIC in this study specifically contains HEMA, dimethacrylate, and UDMA in Paste A, together with polyacrylic and polybasic carboxylic acids in Paste B [14]. Compared with conventional GICs, RMGICs have been reported to exhibit lower solubility, reduced susceptibility to early erosion during setting, and higher compressive and tensile bond strengths [13]. In addition, glass-ionomer-based materials are generally less sensitive to moisture than resin-based materials [6]. These material characteristics may have contributed to the relatively stable retention observed with RMGIC after thermal cycling.

The retention difference between the two cement groups after thermal aging should also be interpreted with caution in clinical practice. In a split-mouth randomized controlled trial, Bani-Hani et al. [36] compared resin cement (Breeze) with conventional glass ionomer cement (Fuji IX) for prefabricated zirconia crowns in primary maxillary anterior teeth. One crown cemented with GIC debonded at the 1-week follow-up (2.4%). Among the crowns remaining under follow-up, both groups showed 100% retention at 12 months, with no statistically significant difference between the cement groups ($p = 1.000$) [36]. Bani-Hani et al. [37], a 36-month prospective split-mouth randomized trial, reported no debonding in the resin cement group. In contrast, three crowns cemented with conventional GIC debonded, resulting in cumulative retention rates of 96.9%, 95.3%, and 95.3% at 12, 24, and 36 months, respectively. However, the results did not show a statistically significant difference in 36-month retention ($p = 0.250$) [37]. In

contrast, Alrashdi and Alhunti [38], in a retrospective cohort study of prefabricated zirconia crowns placed on primary maxillary anterior teeth, compared resin cement (RelyX Unicem) with conventional GIC. Retention with resin cement remained 95.1% at both 12 and 24 months. In contrast, retention with GIC decreased from 91.4% at 12 months to 84.0% at 24 months, with a significant difference favoring resin cement ($p = 0.019$) [38]. Taken together, these clinical findings suggest that the effect of luting cement on the retention of pediatric zirconia crowns remains variable across studies. However, these studies evaluated prefabricated zirconia crowns rather than 3D-printed resin crowns, limiting direct comparison with the present findings.

Stereomicroscopic evaluation indicated that failure during the retention test was predominantly fracture-associated rather than limited to simple debonding. Only 10.6% of specimens exhibited isolated debonding, whereas most failures involved fracture of the crown, the tooth, or both, with crown fracture representing the most frequent pattern. This distribution suggests that, under the present testing conditions, failure was often not confined to the luting interface. Accordingly, the pull-out force should be interpreted as reflecting the mechanical response of the crown–cement–tooth complex rather than the bonding resistance of a single interface. Although airborne-particle abrasion and adhesive surface conditioning may have contributed to crown retention, the present failure-mode analysis does not permit the relative contributions of the cement–tooth and cement–crown interfaces to be distinguished. This failure pattern differs from that commonly reported for prefabricated pediatric zirconia crowns, in which dislodgement is predominantly associated with interfacial adhesive failure rather than structural fracture. Morsy et al. [34] observed adhesive failure in all zirconia crowns cemented with either conventional GIC or RMGIC, with the luting cement remaining predominantly attached to the tooth surface. Similar interfacial failure patterns have been reported in retention studies of prefabricated zirconia crowns [11, 13]. However, differences between these findings and those of the present study should be interpreted in the context of variations in restorative materials, surface procedures, luting protocols, and testing methodologies. The high frequency of crown fracture observed in the present study may also warrant consideration of the experimental design. Tensile force was applied through a steel wire passing through an opening incorporated into the crown design during the CAD stage and fabricated as part of the crown during 3D printing. Thus, unlike experimental approaches in which an opening is created in a polymerized restorative material using a bur, the opening in the present study was not produced by post-fabrication drilling. Memarpour et al. [33] noted that drilling a hole in polymerized composite may introduce a source of stress within the material. This issue was avoided by incorporating the opening into the original crown design in the present study. Nevertheless, the presence of the opening and the application of tensile force through a steel wire may still have altered the stress distribution within the crown during loading. Clinical studies are required to determine whether the failure patterns observed under the present in vitro conditions are reproduced under functional intraoral conditions.

The use of extracted human primary incisors, individually designed 3D-printed crowns, standardized preparation procedures, and a factorial design evaluating preparation height, luting cement type, and thermal aging are strengths of the present study. Nevertheless, several limitations should be considered.

The uniaxial pull-out test does not reproduce the multidirectional and repetitive forces present intraorally, and it does not simulate mechanical fatigue, pH changes, salivary enzymes, or biofilm-related effects. In addition, tensile force was transmitted through an orthodontic wire passing through a CAD-designed incisal opening. However, the opening was incorporated into the original crown design and positioned outside the cemented region; this loading configuration may have influenced stress distribution within the crown. Additionally, anatomical variability among extracted primary teeth could not be eliminated. Only one 3D-printed crown resin and two luting cements were evaluated, which may limit the generalizability of the findings to other material combinations. Furthermore, because preparation heights below 2 mm were not investigated, the present findings should not be interpreted as establishing 2 mm as a minimum clinically acceptable preparation height.

Conclusions

Within the limitations of this in vitro study, preparation heights of 2–4 mm did not significantly affect the overall retention resistance of custom 3D-printed permanent resin crowns for primary anterior teeth. However, the effect of preparation height varied according to the luting cement used. Resin cement provided greater retention than RMGIC under unaged conditions; however, this difference was no longer statistically significant after thermal aging. Thermal aging significantly reduced retention with resin cement, whereas no significant change was observed with RMGIC. Failure was predominantly fracture-associated rather than limited to simple debonding, indicating that the measured pull-out response involved the crown–cement–tooth complex rather than the luting interface alone. These findings support the potential of custom 3D-printed resin crowns as a conservative restorative option for primary anterior teeth; however, clinical studies are required to confirm their long-term retention and failure behavior under functional conditions.

Abbreviations

ECC

Early childhood caries

AAPD

American Academy of Pediatric Dentistry

PZCs

Prefabricated pediatric zirconia crowns

RMGIC

Resin-modified glass ionomer cements

3D

Three-dimensional

mSLA

Masked stereolithography

DLP

Digital light processing

STL
standard tessellation language

Declarations

Ethics approval and consent to participate:

Ethical approval for this study was obtained from the Clinical Research Ethics Committee of the Faculty of Dentistry, Gazi University (approval no. GÜDHKA EK.2023.24/3; December 14, 2023). Written informed consent for the use of the extracted teeth for research purposes was obtained from the parents or legal guardians of all participants prior to inclusion in the study.

Consent for publication:

Not applicable.

Competing interests:

The authors declare no conflict of interest.

Funding:

This research was funded by the Scientific and Technological Research Council of Türkiye (TÜBİTAK), grant number 224S776.

Author Contribution

N.A. and M.B.G. designed the research study. N.A., E.K.Ö., M.B., and M.B.G. performed the research. M.B.G. analyzed the data. N.A. wrote the manuscript. M.B.G. reviewed and edited the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

Acknowledgement

The authors gratefully acknowledge the Scientific and Technological Research Council of Türkiye (TÜBİTAK) for supporting this study (Project No. 224S776).

Availability of data and materials:

The datasets generated and/or analyzed during the current study are available from the corresponding author upon request.

Clinical Trial Number

Not applicable.

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Figures

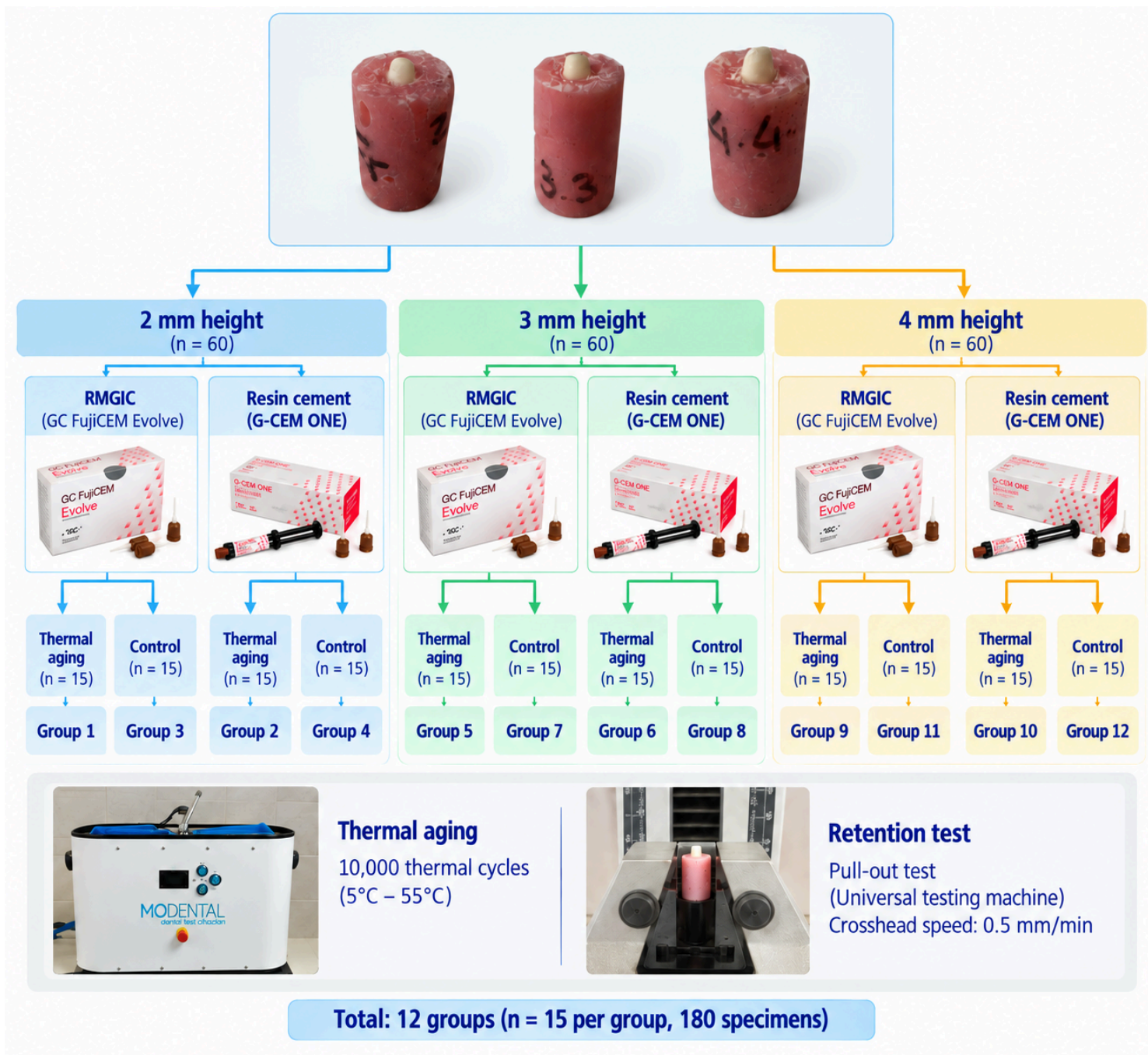


Figure 1

Experimental design and allocation of specimens according to preparation height, luting cement type, and thermal aging condition.

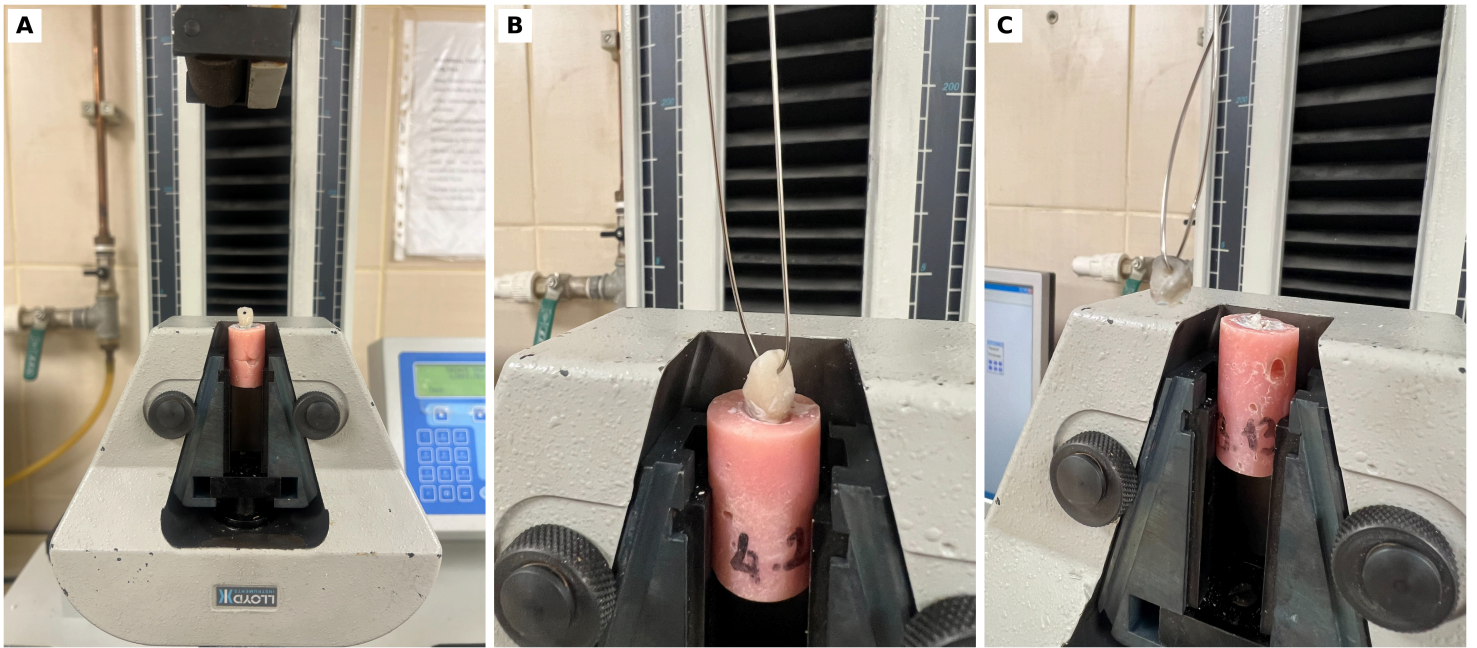


Figure 2

Experimental configuration for the pull-out retention test. (A) Specimen secured in the lower holding jig of the universal testing machine. (B) Close-up view of the crown and tensile-loading assembly. (C) Representative specimen after completion of the pull-out test.