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Marginal and internal adaptation and absolute marginal discrepancy of 3D-printed, milled, and prefabricated crowns for primary molar teeth: an in vitro comparative study

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Abstract

Background The quality of marginal and internal adaptation plays a crucial role in the clinical longevity of pediatric crowns. This study aimed to evaluate the effect of restoration type (3D-printed, milled, and prefabricated) on the marginal and internal adaptation and absolute marginal discrepancy (AMD) values of crowns for primary molar teeth.

Methods Three restoration groups were created: 3D-printed resin, milled resin-matrix ceramic, and prefabricated zirconia crowns ($n = 10$ per group). A typodont tooth was prepared according to the guidelines for prefabricated zirconia crowns and scanned to design restorations. 3D-printed and milled crowns were fabricated from the same design. All crowns were cemented on standardized 3D-printed resin dies with self-adhesive resin cement. Marginal and internal adaptation and AMD values were evaluated using micro-computed tomography (micro-CT) at multiple measurement points. Data were analyzed using one-way analysis of variance (ANOVA) and Tukey HSD tests, with statistical significance set at $P < 0.05$.

Results The restoration type significantly influenced the marginal and internal gap and AMD values ($P < 0.05$). The prefabricated crown group exhibited the highest marginal gap (233.5 ± 33.4 µm) and internal gap (538.6 ± 47.4 µm). The 3D-printed group showed the highest AMD value (299.5 ± 70.2 µm). The milled group demonstrated the lowest gap values, which remained within clinically acceptable limits.

Conclusions Prefabricated zirconia crowns displayed the highest marginal and internal gaps, whereas milled crowns exhibited the most favorable adaptation values within clinically acceptable limits. Given their superior adaptation, CAD-CAM-produced restorations may be a recommendable alternative for pediatric patients.

Keywords Marginal adaptation, Internal adaptation, Absolute marginal discrepancy, 3D-printed crowns, Prefabricated zirconia crowns, Pediatric dentistry, Micro-CT analysis, CAD-CAM restorations, Primary teeth

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Introduction

Stainless steel crowns (SSCs) have been the restoration choice for most pediatric dentists to restore severely decayed and damaged teeth, developmental defects, and primary teeth treated with pulpotomy or pulpectomy. These crowns are easy to place, cost-effective, and have a high success rate. Nevertheless, their notable disadvantage is non-esthetic appearance, which has become a primary concern among parents and patients in pediatric dentistry [1, 2]. Several alternatives to SSCs have been developed, including open-faced and pre-veneered crowns for an esthetic restorative option in children; however, these restorations have been associated with poor gingival health and exposure to restorative margins [3, 4].

Prefabricated pediatric zirconia crowns (PZCs) offer superior mechanical strength, biocompatibility, and esthetics, making them a reliable option for primary tooth restoration [1, 4, 5]. Made from yttria-stabilized tetragonal zirconia polycrystals, they provide excellent fracture toughness, wear resistance, and durability. Their monolithic design prevents chipping, while the smooth surface minimizes plaque accumulation, promoting better oral health [1, 6]. Clinical studies have reported good gingival health, plaque accumulation performance, and high parental satisfaction in restoring primary teeth [6–10]. Additionally, their tooth-like translucency enhances esthetics compared to SSCs. However, their rigidity necessitates precise tooth preparation for optimal fit and retention [1]. Although long-term clinical research on PZCs is limited, studies have demonstrated that the retention rates of prefabricated metal crowns are comparatively better than those of PZCs [7, 9, 11]. It has been observed that prefabricated zirconia crowns induce more wear on the antagonistic tooth structure [9]. PZCs lack the capacity for flexing, crimping, or contouring. Therefore, manufacturers advise a strategy for passive seating for their placement. Additionally, the inherent thickness of PZCs necessitates a more extensive tooth reduction, elevating the risk of pulp exposure within the primary dentition [1]. The American Academy of Pediatric Dentistry (AAPD) stated in its guideline, which aims to help practitioners make decisions regarding restorative dentistry in children and adolescents, that the evidence on the use of prefabricated zirconia crowns as esthetic crowns on primary posterior teeth is limited [2].

Rapid developments in digital technologies have completely changed pediatric dentistry [12]. The advancement in computer-aided design and computer-aided manufacturing (CAD-CAM) technologies has facilitated the creation of both esthetic and functionally practical restorations for primary dentition. Starting from intraoral scanning to milling (subtractive manufacturing) or three-dimensional (3D) printing (additive manufacturing) processes, utilizing these advanced technologies, customized crowns can be fabricated within a completely digital workflow. Digital processes provide greater accuracy more quickly at a lower cost [13–16]. Resin matrix ceramics are preferred for primary tooth restorations because their elastic modulus is close to dentin. These ceramics are hybrid materials that integrate a polymer-infiltrated ceramic network or nanoceramic-filled resin, offering a balance of strength, flexibility, and esthetics for primary tooth restorations. They provide high fracture resistance, superior marginal adaptation, and reduced brittleness compared to traditional ceramics. Their machinability allows for precise CAD-CAM milling, ensuring an accurate fit with minimal adjustments. Additionally, their enamel-like translucency enhances esthetics, while their ability to absorb occlusal forces helps protect primary teeth, making them a durable and practical choice for pediatric dentistry [17–20].

3D printing is a manufacturing technique that builds an object layer by layer using raw material guided by its digital model. This digital model is derived from a 3D file in standard tessellation language (STL) format, which is then virtually sliced into multiple layers for precise fabrication [21, 22]. 3D-printed crowns for primary teeth represent a new strategy, with limited research available on the efficacy and outcomes of this restorative approach [16, 23–28]. Photopolymer resins are light-activated materials used in 3D printing and indirect restorations for primary teeth. Composed of a polymer matrix with reinforcing fillers, they offer improved strength and wear resistance. Their digital design and layer-by-layer fabrication ensure precise fitting, while rapid light-curing enables efficient production. With good translucency and color-matching properties, photopolymer resins provide durability and esthetic appeal for pediatric restorations [16, 21–24, 29].

Considering the lifespan of materials used for primary teeth, the cost of restorations applied to these teeth is an essential concern for parents [30–32]. Abukabbos reported that the cost of ceramic preformed crowns ranges from 20 to 35 USD, while metal preformed crowns are priced at less than 10 USD [31]. In line with this, the cost of prefabricated zirconia crowns (NuSmile) for primary teeth is approximately 30 USD [32]. However, Huang et al. reported that the production cost of 3D-printed resin crowns was approximately 3 USD [33]. Daher et al. examined the marginal adhesive integrity and efficiency of restorations made from 3D-printed composite resin, milled composite resin, milled polymethyl methacrylate (PMMA), and milled lithium disilicate. They assessed the percentage of continuous margin before and after thermal and mechanical fatigue, production time, and costs. Before fatigue, the marginal adaptation of the 3D-printed composite resin was comparable to CAM-milled composite resins and lithium disilicate. Its cost advantage stemmed from lower material expenses and the additional cost of replacing rotary instruments in subtractive methods. The 3D-printed resin was 1.6 times more affordable than PMMA, 2.75 times less expensive than composite resin blocks, and 3.3 times cheaper than lithium disilicate. It remained more economical than milled PMMA as a long-term interim material. While milling was faster for low production quantities, 3D printing became more time-efficient when producing at least eight restorations. With slower milling machines, this threshold might decrease to six restorations if milling took 15 min per unit instead of the 10 min recorded in the study [34].

The biofunctionality of a restoration relates to its performance in a biological environment. The longevity of fixed restorations is influenced by the periodontal health of the supporting teeth, as the surrounding mucosa undergoes constant mechanical stress and exposure to bacteria [35]. In this regard, precise marginal and internal adaptations play a crucial role in the long-term success of dental restorations [36]. Marginal discrepancies in restorations lead to a thicker cement layer, which is more susceptible to degradation in the oral environment. Over time, this can result in cement dissolution, increased biofilm accumulation, microleakage, and marginal discoloration. Additionally, it may contribute to elevated gingival crevicular fluid flow, recurrent caries, and potential pulp infections. If not managed properly, these complications can advance to periodontal damage and bone resorption, ultimately jeopardizing the effectiveness of the treatment [35]. Bacterial biofilm structures have been found on dentinal axial walls when the marginal gap exceeds 10 µm. Larger gaps are thought to provide sufficient space and nutrient access for microbial colonization. Additionally, Maske et al. reported that a marginal gap of 30 µm may contribute to secondary caries formation [37–40]. Besides, internal misfits are implicated in deteriorated mechanical retention and reduced fracture resistance. The adaptation of the restoration is essential for both pediatric and adult fixed prostheses, as a poor fit can affect not only the restoration's lifespan but also overall oral health. Furthermore, the adaptation is subject to variation based on the type of restorative material or the fabrication technique of the restoration [14, 28, 41].

Micro-computed tomography (micro-CT) has been used in a wide variety of applications in dentistry. It has the advantages of being nondestructive and enabling high-resolution three-dimensional analysis [7]. Aktaş et al. [25] evaluated the marginal and internal adaptation of milled and 3D-printed crowns for primary molar teeth using micro-CT. These crowns were designed utilizing various software programs, including CAD and artificial intelligence, with micro-CT employed for evaluation. The outcomes of the study demonstrated that all examined groups displayed marginal and internal gaps within clinically acceptable limits. The literature review revealed an absence of studies comparing the marginal and internal adaptation of these crowns with prefabricated zirconia crowns utilized as esthetic restorations.

The effect of restoration type (3D-printed, milled, and prefabricated) on the marginal and internal gap and absolute marginal discrepancy values of the crowns for primary molar teeth were investigated in the present study. The null hypothesis of this study is that the type of restoration does not significantly affect these adaptation parameters.

Materials and methods

The mandibular second primary molar in the pediatric dental model (AK-6/2 M, Frasaco GmbH, Tettnang, Germany) was prepared according to the suggested preparation design for prefabricated zirconia crowns [42]. The preparation geometry was in accordance with the anatomical form of the tooth and had 1.5 mm occlusal reduction and 1 mm axial, a chamfer margin with a width of 1 mm, and rounded internal angles. All margins were adjusted to allow passive seating of the prefabricated zirconia crowns.

In the study, it was planned to use resin dies produced from similar forms and materials to eliminate the bias resulting from individual tooth preparation and to ensure standardization. For this purpose, the prepared typodont tooth was scanned using an intraoral dental scanner (CEREC Omnicam; Sirona Dental Systems, Bensheim, Germany), and virtual models were generated through the software (Cerec SW 4.4.4; Dentsply Sirona). Thirty standard 3D-printed resin dies ($n = 10$ for each group) were produced using a 3D printer (Formlabs Inc., Somerville, MA, USA) and model resin.

In the prefabricated zirconia crown group (NuSmile, Houston, TX, USA), the appropriate crown size (E1R) was selected on the prepared typodont tooth. In the milled and 3D printing crown groups, the images of the virtual models were converted to STL file format. Then, these files were transferred to the CAD software program (Exocad DentalCAD®, Darmstadt, Germany). The restoration design for the mandibular primary second molar was done in this software by setting the cement thickness to 50 µm. The restoration design was exported in.STL file format for the manufacturing process. In the milled crown group, the nanoceramic blocks (GC Cerasmart, GC Corporation, Tokyo, Japan) were milled in the milling unit (Redon, Hybrid Dental CNC, Redon Technology). In the 3D-printed crown group, the STL file was transferred to PreForm (Formlabs Inc., MA, USA) software, where the support structures required for printing were added, and material parameters were determined. 3D-printed crowns were produced on a 3D printer (Formlabs Form 3, Formlabs, MA, USA) using permanent crown resin (Photopolymer Permanent Resin, Formlabs). After manufacturing, the 3D-printed crowns were washed with 95% isopropyl alcohol for 3 min in the Form Wash unit (Formlabs Inc.) to remove any residual uncured resin. Then, the specimens were placed in a FormCure unit (Formlabs Inc.) to undergo a curing process. After the curing process, the supports were detached, and the 3D-printed crowns were exposed to an additional post-curing phase for 20 min at 60 °C to ensure dimensional stability.

Before cementation, the resin dies were airborne-particle abraded using 50 µm aluminum oxide particles to enhance the surface for optimal adhesion and then cleaned in an ultrasonic cleaner. A bonding agent (Scotchbond Universal Plus; 3 M ESPE, Neuss, Germany) was applied to the resin dies for 20 s and air dried. Additional procedures were performed on the intaglio surfaces of the restorations in line with the manufacturers' recommendations. The materials used in the study and the procedures applied before the cementation of the materials are presented in Table 1.

Self-adhesive resin cement (RelyX Universal Resin Cement, 3 M ESPE) was used to cement all crown groups. The restorations were cemented on the 3D-printed resin dies. The crowns were placed on 3D-printed resin dies and polymerized for 2–3 s by applying finger pressure. After removing excess cement, polymerization was continued from the buccal, lingual, and occlusal surfaces for 10 s, and five minutes waited for cementation to be completed.

Micro-CT analysis

The marginal and internal adaptation and marginal discrepancy of the crowns were evaluated by using a micro-CT device (Skyscan 1275; Bruker Corp., Kontich, Belgium). The imaging protocol involved using a 1-mm aluminum filter, with a rotation step tuned to 0.2 degrees, under scanning parameters set at 80 mA, 125 kVp, and 10 µm. To reconstruct the acquired data and to avoid potential artifacts, software (NRecon version 1.6.4.8; Bruker Corp) was used, and two-dimensional (2D) cross-sectional images of each specimen were obtained. After scanning, the images were uploaded to a software program for further analysis (CTan version 1.14.4.1; Bruker Corp). Nine measurement points (2 marginal, 4 axial, and 3 occlusal) were determined for marginal and internal adaptation, and the 2D linear measurements were made in both coronal and sagittal sectional images (Figs. 1 and 2).

The marginal gap value, defined as the vertical distance from the intaglio surface of the restoration to the preparation margin, was obtained by calculating the mean value of 4 measurement points from the marginal edge of the coronal and sagittal images. The internal gap value, defined as the vertical distance from the intaglio surface of the restoration to the axial wall of the preparation, was obtained by calculating the mean value of 14 measurement points (8 from the axial area and 6 from the occlusal area). The absolute marginal discrepancy (AMD) value is an angular measurement encompassing both the marginal gap and the extension of the restoration margin. AMD was measured from the mesial and distal aspects of the crowns across both coronal and sagittal sections, utilizing a total of 4 measurement points per specimen. A total of 660 two-dimensional linear measurements were conducted across three crown types for the marginal and internal gap and AMD values.

Statistical analyses

All statistical analyses were performed using a statistical software program (IBM SPSS Statistics for Windows, v20.0; IBM Corp). The effect of the restoration type on the marginal and internal gap and absolute marginal discrepancy values were investigated with a one-way Analysis of Variance (ANOVA). The assumptions of the one-way ANOVA were checked with Shapiro-Wilk and

Table 1 The restorative materials used in the study and the procedures applied before the cementation of the materials

Restoration type	Product	Composition	Manufacturer	Cementation/ Application
3D-printed	Permanent crown resin (Photopolymer Permanent Resin)	Organic Matrix: 50-<75% wt. Bis-EMA Esterification products of 4.4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid. Silanized dental glass, methyl benzoylformate, diphenyl [2,4,6-trimethylbenzoyl] phosphine oxide. Inorganic Filler: Silanized dental glass (particle size 0.7 µm) (30–50% wt.)	Formlabs, MA, USA	- Sandblasting with Al_2O_3 particles - Ultrasonic bath with ethanol - Bonding agent (3 M Scotchbond Universal Plus)
Milled	Nanoceramic block (GC Cerasmart)	Composite resin material 71% silica and barium glass nanoparticles by weight	GC Corporation, Tokyo, Japan	- Application of 5% Hydrofluoric acid (IPS Ceramic Etching Gel; Ivoclar Vivadent) - Bonding agent (3 M Scotchbond Universal Plus)
Prefabricated	Prefabricated zirconia crown (NuSmile)	ZrO_2 88–96%, Y_2O_3 4–6%, HfO_2 5%, an organic binder, pigment	Houston, TX, USA	No procedure required

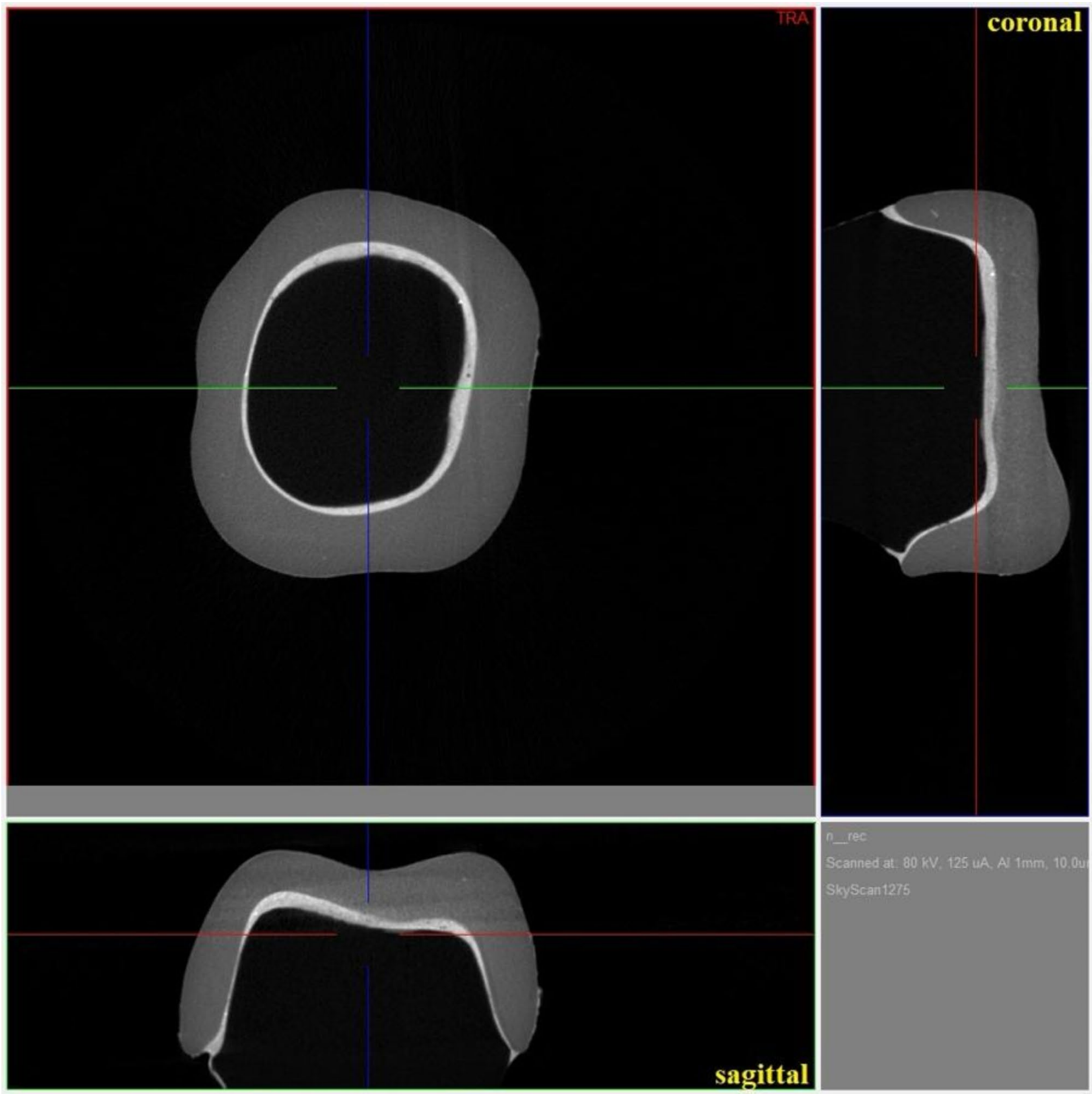

Fig. 1 Sagittal and coronal sections of the Micro-CT images

Levene tests. The data were normally distributed, and the variances were homogeneous. The comparisons among the restoration types were performed by using the Tukey HSD test. The results were considered as significant for $P < 0.05$.

Results

The one-way ANOVA results showed that the restoration type was effective on the marginal gap values ($P < 0.001$). The descriptive and comparative analyses of the marginal gap values are shown in Table 2. The prefabricated crown group showed the significantly highest marginal gap value (233.5 ± 33.4 μm) among the experimental groups. In contrast, the marginal gap values of the 3D-printed and milled crown groups were not significantly different ($P = 0.244$).

The same upper-case letters indicate that the marginal gap values of the restoration type groups were not significantly different ($P > 0.05$).

The one-way ANOVA results showed that the restoration type was effective on the internal gap values ($P < 0.001$). The descriptive and comparative analyses of

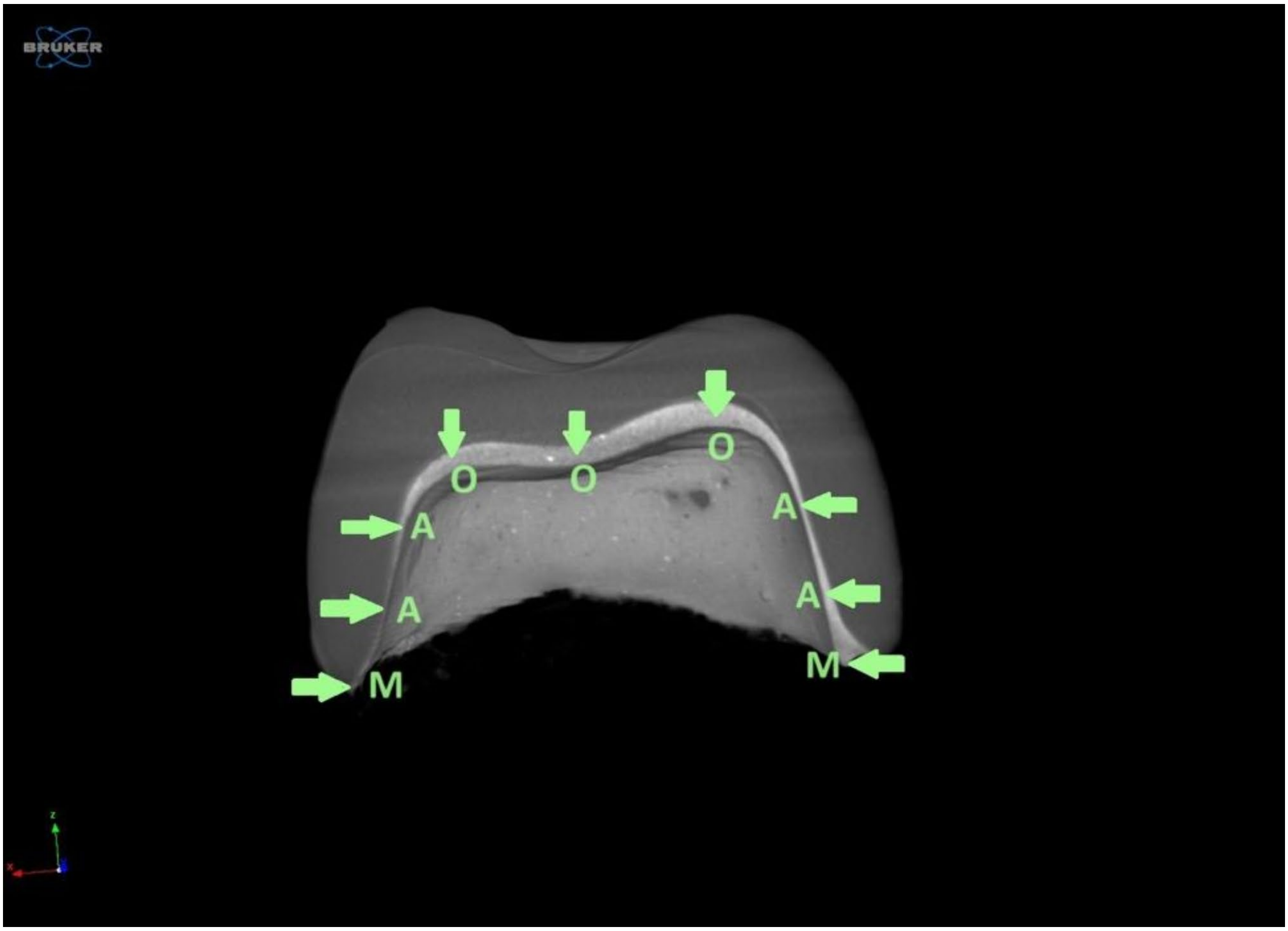

Fig. 2 View of the gaps on the Micro-CT image (Arrows are showing the measurement points; M: marginal, A: axial, and O: occlusal)

Table 2 The descriptive and comparative statics of the marginal gap values (μm) of the restoration types

Restoration type $n=10$	Mean (±SD)	95% Confidence Interval for Mean		Minimum value	Maximum value
		Lower Bound	Upper Bound		
3D-printed	167.5 ± 31.7 [B]	144.81	190.22	125.01	215.02
Milled	138.2 ± 51.2 [B]	101.62	174.86	65.01	222.27
Prefabricated	233.5 ± 33.4 [A]	209.61	257.43	195.02	285.02

SD: Standard deviation

Table 3 The descriptive and comparative statics of the internal gap values (μm) of the restoration types

Restoration type $n=10$	Mean (±SD)	95% Confidence Interval for Mean		Minimum value	Maximum value
		Lower Bound	Upper Bound		
3D-printed	171.3 ± 28.7 [B]	150.76	191.85	125.73	212.87
Milled	167.1 ± 47.5 [B]	133.17	201.07	108.58	279.67
Prefabricated	538.6 ± 47.4 [A]	504.7	572.53	450.04	617.19

SD: Standard deviation

the internal gap values are shown in Table 3. The prefabricated crown group showed the significantly highest internal gap value (538.6 ± 47.4 μm) among the experimental groups; in contrast, the internal gap values of the 3D-printed and milled crown groups were not significantly different ($P=0.973$).

The same upper-case letters indicate that the internal gap values of the restoration type groups were not significantly different ($P>0.05$).

The one-way ANOVA results showed that the restoration type was effective on the absolute marginal discrepancy (AMD) values ($P=0.010$; $P<0.05$). The descriptive and comparative analyses of the absolute marginal

Table 4 The descriptive and comparative statics of the AMD values (μm) of the restoration types

Restoration type *n* = 10	Mean (± SD)	95% Confidence Interval for Mean		Minimum value	Maximum value
		Lower Bound	Upper Bound		
3D-printed	299.5 ± 70.2 ^{A}	249.29	349.76	185.02	405.03
Milled	235.8 ± 53.8 ^{B}	197.28	274.26	145.01	310.03
Prefabricated	227 ± 26.4 ^{B}	208.15	245.89	200.02	275.02

SD: Standard deviation

discrepancy values are shown in Table 4. The 3D printed resin group showed the significantly highest AMD value (299.5 ± 70.2 μm) among the experimental groups, while AMD values of the milled and prefabricated crown groups were not significantly different ($P = 0.929$).

The same upper-case letters indicate that the AMD values of the restoration type groups were not significantly different ($P > 0.05$).

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.

An ideal pediatric crown should be biocompatible, withstand occlusal forces, maintain oral hygiene, have a bonding mechanism to the primary tooth structure, and do not cause wear on the antagonist teeth [6]. Because of the appropriate clinical properties of the prefabricated SSCs, they have been the gold standard for the treatment of primary teeth with extensive loss of tooth structure [11]. However, SSCs have some limitations, such as improper adaptation of the tooth margins and poor retention in severely damaged teeth. Also, the grayish color of these crowns can be unacceptable to the parents and children [24]. The increasing demands for more esthetic restorations have led clinicians to look for esthetic full coverage restorative alternatives. The most commonly preferred restorations instead of SSCs are prefabricated zirconia crowns. The prefabricated zirconia crowns have high mechanical strength, and the white color of these restorations meets the patients' esthetic expectations. However, prefabricated zirconia crowns have some drawbacks despite their favorable properties. The rigidity of these crowns disables the adaptation of them to teeth; thus, preparation becomes necessary for the adaptation [1]. On the other hand, the size of the prefabricated zirconia crown must be carefully selected to provide an appropriate fit and to avoid preparing too much tooth structure [13, 42]. Applying these crowns requires the pediatric patient's cooperation. Another disadvantage of the prefabricated zirconia crowns was that they caused wear on the opposite tooth. Agrawal et al. [11] reported that prefabricated zirconia crowns resulted in an 80% wear rate on the opposing teeth after a three-month follow-up period. Taran et al. reported that prefabricated monolithic zirconia crowns induced significantly more enamel wear than stainless steel or composite resins using micro-CT analysis and highlighted the material's abrasive potential [43]. However, different studies have reported varying results. Choi et al. evaluated the effects of full-coverage crowns made of stainless steel, leucite glass-ceramic, lithium disilicate glass-ceramic, and zirconia on antagonistic primary tooth wear. The results showed that leucite glass ceramic caused the greatest tooth wear, followed by lithium disilicate, zirconia, and stainless steel. Leucite and lithium disilicate caused significantly more wear than stainless steel, while no significant difference was found between zirconia and stainless steel [44]. In a recent study by Aktaş and Bankoğlu Güngör, although the type of esthetic crown restoration did not significantly affect primary tooth wear, 3D-printed and composite-based crowns demonstrated comparable or higher surface wear compared to other groups, particularly in two-dimensional measurements [19]. These studies emphasize the importance of considering the wear behavior of crown materials on antagonist enamel -especially given that restorations in primary dentition are temporary and should ideally preserve the opposing dentition until exfoliation. In recent years, digital technologies such as 3D printing and milling have been rapidly increased in pediatric dentistry, and these systems have enabled the use of various biocompatible and esthetic materials. Customized restorations (milled or 3D-printed) could be alternatively used instead of prefabricated zirconia crowns. Hayek et al. [45] investigated the fracture strength of prefabricated and milled zirconia crowns for restoring primary molars. It was stated that milled zirconia crowns had significantly higher fracture strength (2888.6 ± 1060 N) than prefabricated zirconia crowns (646.5 ± 224 N). Elkhodary et al. investigated the vertical marginal gap distance and fracture resistance of esthetic restorative materials used for primary molars after cyclic loading. Four groups were tested, such as stainless steel veneered crowns with tooth-colored material, prefabricated monolithic zirconia crowns, yttria-partially stabilized zirconia CAD-CAM crowns, and hybrid ceramic CAD-CAM crowns. It was found that CAD-CAM crowns had significantly better marginal adaptation than prefabricated crowns. Among the CAD-CAM options, Enamic crowns showed superior marginal accuracy compared to zirconia crowns, while NuSmile Zirconia crowns demonstrated promising results for pediatric dentistry. All crowns tested had fracture resistance higher than indicated bite forces in children and adolescents [46]. Al-Halabi et al. [23] evaluated the clinical performance of the 3D-printed and milled primary crowns. They reported that these crowns were esthetic alternatives for restoring pulp-treated primary molars, demonstrating good marginal adaptation and retention. Also, it was noted that 3D-printed resin crowns exhibited lower rates of cementation failure and a more favorable gingival response than PMMA crowns. These restorations also present better marginal and internal adaptation to prepared teeth. Besides, adjustments can be easily made to the restoration design [45]. Composite resin materials are primarily used for 3D-printed provisional crowns, which serve as short-term restorations. However, recent studies have shown promising outcomes for newly developed 3D-printed permanent materials, suggesting their potential for use in definitive crown restorations [34, 47, 48]. Suksuphan et al. investigated the marginal adaptation and fracture resistance of milled and 3D-printed crowns made with occlusal thicknesses of 0.8, 1, and 1.5 mm. The study concluded that the type of the crown material significantly influenced marginal adaptation and fracture resistance. It was found that 3D-printed materials provided superior marginal adaptation to milling techniques. Additionally, all tested crowns demonstrated favorable marginal adaptation and fracture resistance, even with a reduced occlusal thickness of 0.8 mm [49]. In another study, Kim et al. investigated the bonding ability of resin cements to 3D-printed resin and compared it with other indirect resin materials used for pediatric crown fabrication. It was stated that there was no significant difference in the mean shear bond strength values among the 3D-printed resin groups and the nano-hybrid ceramic group, except for the PMMA group, which exhibited the lowest value. Despite the relatively low shear bond value of the PMMA group, all materials tested in the study had shear bond values above the clinically acceptable thresholds. Therefore, it could be concluded that 3D-printed resin demonstrated adequate adhesion with resin cement, meeting the essential bonding requirements for clinical use [16]. Based on the results of these studies, considering the crown height and retention period of the primary teeth, 3D-printed resins are believed to offer a cost-effective solution for producing well-fitting and mechanically durable restorations.

The marginal and internal adaptation of crown restorations is essential for their long-term service in the oral cavity. Because inadequate adaptation of the crown margins is associated with dementation, plaque accumulation, microleakage, secondary caries, pulpal, and periodontal diseases [20]. The internal adaptation of the crown restorations is reported to be effective in their mechanical performance [50]. Many factors may influence the marginal and internal adaptation of the restorations. Restoration type in terms of restorative material and its production technique significantly affect the adaptation values [14, 41]. Several studies have emphasized the adaptation of the restorations in different restorative materials and techniques. In a systematic review by Mathar, it was stated that CAD-CAM-fabricated crowns demonstrated smaller marginal discrepancies and improved internal adaptation and could enhance the fit of ceramic crowns and fixed dental prostheses. However, variations in study findings highlight the influence of factors such as material selection and fabrication techniques [51]. Paul et al. also found that CAD-CAM crowns exhibited superior fit and highlighted the advantages of digital design and automated milling, which help minimize human error and improve reproducibility [52]. In the present study, the marginal and internal adaptation and absolute marginal discrepancies of the 3D-printed and milled crowns for primary teeth were investigated using the micro-CT technique, and the results were compared with pediatric prefabricated zirconia crowns. Several methods were used to examine the adaptation of the restorations [14, 49]. The micro-CT technique was selected for its nondestructive nature, permitting extensive measurements from a single dataset while facilitating the assessment of both marginal and internal adaptation of the restoration without inflicting any damage [49, 53].

Clinically acceptable values for marginal and internal gaps in cemented restorations have been reported to range between 100 and 150 μm for marginal gaps and 200 to 300 μm for internal gaps [54–57]. Elkhodary et al. reported that the CAD-CAM anatomical crowns had significantly smaller median marginal gap distances on all surfaces than prefabricated crowns. Stainless steel crowns showed the significant largest total median vertical marginal gap distance, followed by prefabricated zirconia crowns, CAD-CAM-produced zirconia crowns, and CAD-CAM-produced hybrid ceramic crowns with distances of 418.3 μm, 341.7 μm, and 86.7 μm, respectively. The improved fit can be attributed to customizing CAD-CAM crowns for primary teeth. Using prefabricated blocks and standardized scanning and milling procedures in CAD-CAM systems reduced the impact of manual labor by laboratory technicians, leading to better margin quality in the restorations [46]. In the present study, the highest marginal (233.5 ± 33.4 μm) and internal (538.6 ± 47.4 μm) gap values were observed in the prefabricated zirconia crown group ($P < 0.05$). The lowest marginal (138.2 ± 51.2 μm) and internal (167.1 ± 47.5 μm) adaptation values were in the milled group. The gap values in the milled group were in the clinically acceptable limits for the marginal (between 100 and 150 µm) and internal (between 200 and 300 µm) adaptation. Manufacturers of the CAD-CAM resin ceramic blocks reported that the improved machinability of these ceramics provided smoother and better-adapted margins after milling [14]. Although the internal gap value (171.3 ± 28.7 µm) of the 3D-printed group was within the clinically acceptable limit, the marginal gap value (167.5 ± 31.7 µm) was slightly higher than the acceptable limit in the present study. The 3D-printed groups showed higher marginal and internal gap values than the milled groups; however, the differences between these groups were not significant. The different values of the milled and 3D-printed groups may be observed due to using prefabricated homogenous resin matrix ceramic CAD-CAM blocks for the milling technique and the post-curing process of the 3D printing technique. It is important to note that very few studies assess the marginal gap of 3D-printed permanent hybrid ceramics. However, numerous studies have compared the fit of interim crowns produced by additive and subtractive manufacturing, with findings indicating a better fit for 3D-printed crowns [58–60]. In a recent study, Aktaş et al. [25] evaluated the marginal and internal adaptation of resin-based milled and 3D-printed crowns for primary teeth designed with different software programs (CAD and artificial intelligence) using micro-CT. It was reported that all of the tested groups showed clinically acceptable marginal and internal gap values. The marginal gap values of CAD-designed groups were 54 ± 43 µm and 103 ± 30 µm for the milled and 3D-printed primary crowns, respectively. The different results between the two studies may arise from two factors. One is measuring the adaptation values of the crowns after cementing them to the resin dies. The other is the adaptation values of the milled and 3D printed crowns were measured on the prepared typodont tooth by Aktaş et al. [25]. However, the adaptation values of milled and 3D-printed crowns were measured by cementing them to the 3D-printed resin dies in the present study. This material was selected based on a previous study demonstrating its dimensional accuracy and suitability for evaluating crown adaptation [61]. Acrylic, composite, and metallic dies have limitations. Acrylic dies are prone to wear and dimensional instability. In contrast, though more durable, composite dies may deform under pressure, struggle to replicate natural tooth texture, and are susceptible to shrinkage during curing [62]. Metallic dies are rigid and durable but lack the flexibility of natural teeth, can cause wear on milling tools, casting defects may be seen, and may not bond effectively with some restorative materials [63, 64]. In the present study, 3D-printed resin dies were used to achieve consistency and reproducibility when assessing the marginal fit of restorations for primary teeth. Unlike extracted teeth, which can vary in shape, size, and surface properties, 3D-printed dies offer uniformity, helping to minimize potential variables that could affect the results [65]. Al-Haj Ali [56] reported that prefabricated zirconia crowns cemented with resin cement demonstrated lower marginal and internal gap values than those cemented with glass and resin-modified glass ionomer cements. In the present study, all crown restorations were cemented with resin cement. However, the 3D manufacturing process of the resin dies may affect their accuracy, and even small dimensions of the resin die could cause differences in adaptation values.

The absolute marginal discrepancy is a combination of the marginal gap and the extension error (negative or positive marginal discrepancy) [25, 53]. The negative marginal discrepancy represents the underextension of the crown margin, and the positive discrepancy represents the overextension of the crown margin [20]. An increased AMD indicates that the restoration margin is positioned too far from the tooth preparation, creating a gap that could facilitate plaque accumulation. This can ultimately contribute to the development of periodontal disease. As a result, assessing the effectiveness and suitability of such fixed restorations is crucial to ensure they do not pose risks to oral health [41]. Suksuphan et al. evaluated the AMD values of milled hybrid nanoceramic (Cerasmart, CE), polymer-infiltrated ceramic network (Vita Enamic, VE), and 3D-printed (Varseosmile, VS) crowns. They stated that the VS crowns showed the smallest AMD values, which were significantly lower than those of the other two milling groups ($P < 0.05$) across all the tested occlusal thicknesses (0.8, 1, and 1.5 mm) [49]. Daghrery et al. compared the AMD values between the cavity walls and the 3D-printed inlays made from two types of hybrid resin composite materials with differing compositions compared to milled inlays. Optical impressions were taken for three groups to fabricate CAD-CAM inlays: Group PVC, 3D-printed VarseoSmile Crownplus; Group PVT, 3D-printed VarseoSmile TriniQ; and Group MVE, milled using Vita Enamic. For Group CGP (control), inlays were conventionally fabricated using Gradia Plus. The AMD of MVE was the highest (0.48 ± 0.06), while the AMD of CGP was the lowest (0.25 ± 0.13). The AMD values of the two 3D-printed groups showed significant differences; the PVT demonstrated better dimensional accuracy and fit than the PVC. The results indicated that the composition of the 3D-printed resin may be effective in determining the adaptation values [66]. There are limited studies that evaluated the AMD values of the crowns for primary teeth [20, 25]. Oğuz et al. [20] investigated the marginal adaptation of three different CAD-CAM-produced resin ceramics by superimposing the STL images of the master die and crowns, and it was reported that the negative and positive marginal discrepancy values of the tested resin ceramics were similar. In another study, Aktaş et al. [25] reported that CAD designed and milled group showed higher absolute marginal discrepancy than CAD designed and 3D-printed crown group, and marginal adjustments were recommended for the resin-based milled or 3D-printed crowns with positive marginal discrepancy. In the present study, the 3D-printed crowns had the highest AMD values; however, the results were not significantly different for the milled and prefabricated crowns. The lower AMD values for the prefabricated zirconia crowns may arise from the thin marginal edges of these crowns.

The limitations of the present study must be considered while evaluating the results. In the present study, a single intra-oral scanner was used, and the scanning accuracy of the device may be affected by many factors in the mouth. Only three types of restorations were tested in the present study; however, several restorative materials can be used, particularly for the milled restorations. Further clinical studies are needed to comprehensively evaluate the marginal and internal adaptation of prosthetic options for primary teeth.

Conclusions

Within the limitations of the study, the following conclusions were drawn:

The highest marginal and internal gap values were observed in the prefabricated zirconia crown groups. The lowest marginal and internal gap values were observed in the milled resin matrix ceramic groups. The marginal and internal gap values for the milled groups were within the clinically acceptable limits and can be recommendable for pediatric patients. CAD-CAM-produced restorations offer a well-adapted and customizable option for pediatric patients.

The highest absolute discrepancy value was found for the 3D printed group, and the values were similar for the milled and prefabricated crown groups.

Abbreviations

AMD	Absolute Marginal Discrepancy
CAD	CAM–Computer–Aided Design and Computer–Aided Manufacturing
3D	Three–Dimensional
PMMA	Polymethyl Methacrylate
Micro-CT	Micro–Computed Tomography
PZC	Prefabricated Zirconia Crown
ANOVA	Analysis of Variance
SSCs	Stainless Steel Crowns
STL	Standard Tessellation Language

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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Author contributions

N. A. conceived the study idea, collected the data, and contributed to manuscript writing.Y. A. and D. (A) collected the data.M. O. performed the Micro-CT evaluations.M. (B) G. analyzed the data and contributed to manuscript writing.All authors reviewed and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

It is not necessary.

Competing interests

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