prosthesis

MDPI

Article

Accuracy and Fit of Ceramic Filled 3D-Printed Resin for Permanent Crown Fabrication: An In Vitro Comparative Study

Anwar Al-Ramadan [1], Reem Abualsaud [2], Yousif A. Al-Dulaijan [2], Ahmad M. Al-Thobity [2] and Haidar Alalawi [2,*]

[1] Fellowship in Prosthodontics Program, College of Dentistry, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Saudi Arabia; 2210600055@iau.edu.sa
[2] Department of Substitutive Dental Sciences, College of Dentistry, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Saudi Arabia; rabualsaud@iau.edu.sa (R.A.); yaaldulaijan@iau.edu.sa (Y.A.A.-D.); aalthobity@iau.edu.sa (A.M.A.-T.)
* Correspondence: haalalawi@iau.edu.sa

Abstract: This in vitro investigation aimed to compare the trueness, precision, internal fit, and marginal adaptation of Varseo Smile Crown Plus (VSCP), CROWNTEC (C), and milled Enamic crowns (E) using a 5-axis dental milling machine (prograMill PM7). 39 crowns (VSCP, E, C; n = 13) were designed and fabricated. Internal/marginal adaptation, precision, and trueness were assessed via die scans with/without a fit checker. Dimensional discrepancies were determined by superimposing the scans. One-way ANOVA ($\alpha = 0.05$) analyzed the results. No significant differences were found in internal fit or marginal adaptation between groups. However, group E exhibited the best fit (axial: 82.9 µm). Trueness differed significantly ($p < 0.05$) across all groups and areas. Group E had the highest trueness (intaglio: 25.8 µm), while VSCP had the lowest (marginal: 31.9 µm). Precision varied significantly within the occlusal area of printed groups (highest for C: 17.8 µm) and the marginal area between printed/milled (VSCP vs. E) and C vs. E (lowest for E: 20.5 µm, highest for VSCP: 27.9 µm). In conclusion, both milled and 3D-printed crowns achieved comparable internal fit and marginal adaptation. However, group E displayed superior fit and trueness. While C exhibited higher occlusal precision, E had higher marginal precision. These findings suggest the potential for 3D-printed hybrid polymer crowns, warranting further investigation.

Keywords: additive manufacturing; CAD-CAM; definitive crown; milled restoration; precision; trueness

check for updates

Citation: Al-Ramadan, A.; Abualsaud, R.; Al-Dulaijan, Y.A.; Al-Thobity, A.M.; Alalawi, H. Accuracy and Fit of Ceramic Filled 3D-Printed Resin for Permanent Crown Fabrication: An In Vitro Comparative Study. *Prosthesis* **2024**, *6*, 1029–1041. https://doi.org/10.3390/prosthesis6050075

Academic Editors: Roberto Sorrentino, Fernando Zarone and Gennaro Ruggiero

Received: 3 June 2024
Revised: 25 August 2024
Accepted: 26 August 2024
Published: 2 September 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The emergence of industrial three-dimensional (3D) printing in the early 1980s, with the first patent in 1986 [1], revolutionized rapid prototyping. This technology significantly impacted restorative dentistry, particularly with the development of 3D-printed dental materials and restorations [2]. The subsequent integration of computer-aided design/computer-aided manufacturing (CAD/CAM) had a transformative impact on clinical dentistry and further reshaped the dental practice by introducing a new era of precision and efficiency [3]. This technological progress, coupled with enhanced availability for both manufacturers and users, spurred a swift expansion of 3D printing applications in dentistry. This growth is supported by the proliferation of novel procedures and commercially accessible products documented in clinical and scientific literature [4,5].

Within the domain of 3D printing technologies employed in dentistry, digital light processing (DLP) stands out as a prominent contender, demonstrably achieving superior dimensional accuracy and resolution compared to alternative fabrication techniques [6]. It also provides superior detail through the building of depositing successive layers of photosensitive material and polymerization [7]. Unlike alternative 3D printing techniques, DLP uses a digital projector to facilitate the simultaneous photopolymerization of entire

resin layers. This streamlined approach engenders superior dimensional accuracy and expedited fabrication times [8].

While dentistry is widely acknowledged as a field that can greatly benefit from 3D printing technologies, the literature addresses issues concerning the parameters that govern the features and qualities of 3D-printed restorative dental materials [9,10]. In the dental laboratory, digital techniques enhance accuracy and repeatability (precision) while improving material characteristics and user comfort [11]. During the 3D construction process, both the mechanical and aesthetic features of the object to be printed can still be altered. This customizable capability has made additive manufacturing a cornerstone of digital dentistry [12].

The achievement of optimal marginal and internal adaptation for restorations generated by 3D printing and milling processes, analogous to those fabricated using conventional techniques, remains a paramount factor influencing the prognosis of the definitive restorative intervention [13]. A primary objective in restorative fabrication and cementation procedures is minimizing the marginal discrepancy between the restoration and the prepared tooth structure. This optimization strategy aims to promote favorable periodontal and pulpal responses while fostering optimal performance characteristics of the luting cement [14,15]. The marginal discrepancy at the contact point between the restoration and the tooth can compromise the integrity of the cement [14,15], leading to potential issues such as microleakage and posing a risk to pulpal health [16], triggering secondary caries [14,17], and increasing periodontal inflammation [17]. A critical appraisal of the extant dental literature unveils a continuum of clinically acceptable marginal gap thresholds. This observed variability can be attributed to the specific luting agent selection, the intrinsic material properties of the restoration, and the employed methodology for quantifying the marginal interface discrepancy [17,18]. Despite ongoing investigations, a universally standardized threshold for clinically acceptable marginal gap dimensions remains elusive within the dental community. The current consensus suggests a range of 50–120 µm for indirectly fabricated restorations, while ideally, marginal discrepancies should be minimized to less than 25 µm [17,18].

Trueness, a concept distinct from precision, characterizes the systematic error associated with a measurement. It quantifies the deviation or disparity between the measured and actual or intended values. Conversely, precision reflects the level of agreement or reproducibility among replicated measurements [16]. A preponderance of contemporary dental research endeavors to illuminate the dimensional accuracy of restorations fabricated via milling techniques compared to alternative restorative modalities, as characterized by both trueness and accuracy [16]. Conversely, a lack of investigations exists regarding the dimensional fidelity of restorations fabricated through additive manufacturing processes [15,19].

The expanding integration of polymer-based computer-aided design/computer-aided manufacturing (CAD/CAM) systems in restorative dentistry necessitates a meticulous assessment of the material properties governing the performance of permanent crown resins. Commercially available materials designed for composite restorations typically consist of a resin-matrix reinforced with dispersed ceramic filler particles. The precise composition and weight ratio of these components exhibit variation across distinct CAD/CAM materials and are believed to be a primary determinant of their resultant material properties [20–22]. The lack of knowledge concerning their long-term clinical behavior underscores the critical need for a comprehensive evaluation to elucidate their inherent advantages and potential limitations that may influence their efficacy in vivo.

A critical appraisal of the existing literature reveals that some investigations evaluated the marginal adaptation and dimensional accuracy (encompassing both trueness and precision) of full-contour, additively manufactured, ceramic-filled resin-polymer crowns. This knowledge necessitates further rigorous research to ascertain whether these 3D-printed restorations can achieve a level of precision and accuracy comparable with their milled counterparts [9,10,23–26]. Therefore, the present investigation was designed to assess the

trueness, precision, and marginal adaptation of 3D-printed crowns fabricated from two distinct ceramic-filled hybrid permanent crown resin materials in direct comparison to milled ceramic-filled material. The null hypothesis states that there would be no statistically significant discrepancies in trueness, precision, and fit between the evaluated 3D-printed and milled crowns.

2. Materials and Methods

This in vitro study evaluated the accuracy (trueness and precision), internal fit, and marginal adaptation of 3D-printed ceramic-filled hybrid crown specimens. Specimens were fabricated following ISO 10477:2020 standards (Dentistry—Polymer-based crown and veneering materials) and manufacturer recommendations [1]. The sample size for each group was determined to be 13 specimens (n = 13) using a power analysis website (www.Clincalc.com, accessed on 17 September 2023). The averages and standard deviations were obtained from a related article that had previously been published [26]. The power was set at 85%, the significance level at 0.05, and the enrollment ratio at 1. Two experimental groups were formed, comprising permanent crown resins produced using additive manufacturing: Varseo Smile Crown Plus (VSCP) by BEGO (Bremen, Germany) and CROWNTEC (C) by Saremco Print Dental AG (Rebstein, Switzerland). The control group consisted of milled crowns made from VITA ENAMIC CAD/CAM material (E) manufactured by Vita (Bad Säckingen, Germany), characterized by a hybrid ceramic structure incorporating a dual ceramic-polymer network. Details of the materials are provided in Table 1.

Table 1. Materials used and manufacturing process.

Material	Manufacturer	Description and Composition	Production Parameters	Post-Production Processing
VarseoSmile Crown Plus (VSCP)	Bego Bremen, Germany	Resin matrix ceramic (RMC) [27] is a ceramic-infiltrated hybrid composite methacrylic ester matrix with ceramic fillers. Photopolymer: 4.4′-isopropylidiphenol, ethoxylated, and 2-methylprop-2enoic acid.	NextDent 5100 printing orientation: 45° Layer thickness: 50 µ	Cleaning in 96% ethanol NextDent light curing unit for 10 min
CROWNTEC (C)	Saremco, Dental AG, Rebstein, Switzerland	Esterification products of 4,4′-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid,	NextDent 5100 printing orientation: 45° Layer thickness: 50 µ	Cleaning in 96% ethanol NextDent light curing unit for 5 min
Enamic (E)	(Vita Zhanfabric, Bad Säckingen, Germany)	Hybrid ceramic with a dual interpenetrating network structure Ceramic network (~86% by weight) Acrylate polymer network (~14% by weight)	Wet milled using prograMill PM7 5-axis dental milling machine (Ivoclar Vivadent AG, Schaan, Liechtenstein)	Pre-polymerized No post-processing was needed

2.1. Die Preparation

A 3D-printed metal alloy die replicating a prepared mandibular left first molar stump served as the master die. The die design incorporated a 1.5 mm reduction in both occlusal and axial dimensions, a chamfer margin, and a 10-degree total occlusal convergence for optimal crown fit. Additionally, four 2 mm diameter reference buttons were positioned at 90-degree intervals around the die within a 2 mm perimeter to facilitate precise measurement during crown fabrication. The crown settings were adjusted to achieve a 40 µm gap for cement, a 0.10 mm extension offset, and an angle of 55 degrees.

Following preparation, the master die was digitized as a "reference scan" using a desktop scanner (3Shape E3 Dental Lab scanner, 3Shape, Copenhagen, Denmark). The resulting digital model was then imported into CAD software version 2.23.1.0 (3Shape Dental system, Copenhagen, Denmark) for crown design. Subsequently, Standard Tessellation Language (STL) files were generated and used to fabricate the ceramic-filled hybrid permanent crown specimens (ISO 10477:2020).

2.2. Sample Nesting and Printing

Printing of (VSCP) and (C) was carried out according to manufacturer instructions using the NextDent 5100 3D system printer at an ambient temperature ranging between 18–28 °C. In preparation for printing, the resin underwent a homogenization process via agitation within a designated resin agitator (NextDent 5100 LC-3D Mixer) for a duration of five minutes, according to manufacturer instructions. Upon completion of the printing process and subsequent detachment of the fabricated objects from the build platform, a particular cleaning protocol was implemented. This protocol entailed a sequential cleansing with 96% ethanol, followed by submersion in a sonication bath containing fresh 96% ethanol for 3 min. Afterward, specimens were washed in another 96% ethanol ultrasonic bath for 2 min. The printed items were then thoroughly rinsed with additional ethanol (96%) to remove any residual resin. Finally, the specimens were dried using compressed air to ensure consistent results.

After printing, the (VSCP) and (C) specimens were subjected to light curing in the NextDent curing unit. The (VSCP) were cured for 10 min, while the (C) specimens were cured for 5 min according to the manufacturer's recommendation. Subsequently, they were allowed to cool for 3–5 min before further handling [9].

2.3. Fit Assessment

The evaluation process commenced with utilizing the reference scan of the master die as a reference for comparison. Subsequently, a minimal amount of polyvinyl siloxane (PVS) impression adhesive was applied to the occlusal surface of the die. To ensure smooth insertion and minimize resistance during the fit assessment, the internal aspect of the crown received a superficial layer of lubricant, followed by partial filling (approximately 50%) with a validated fit assessment material (Fit Checker™ Advanced Blue; GC America Inc., Alsip, IL, USA).

Following this, a compressive load of 5 kg was steadily applied to the crowns until the fit assessment material achieved a fully cured state. Then, any residual fit checker material was eliminated using a new sterile #15 Bard-Parker blade. Finally, the crown was cautiously detached from the master die, ensuring the complete retention of the fit checker material on the die surface.

Following crown removal, a subsequent digitalization process, designated as the "fit scan", was captured by scanning the master die with the adhered fit checker material. The resulting STL files for both the "fit scan" and the previously acquired "reference scan" were then imported into a dedicated 3D morphometric analysis software (Geomagic Control X v2018; 3D Systems Inc., Rock Hill, SC, USA) for comprehensive 3D superimposition evaluation. Afterward, these digital representations were superimposed to facilitate a detailed visual comparison of their surface geometries. To further enhance the analysis, the "reference scan" was strategically segmented into four distinct anatomical ROI for targeted evaluation: occlusal, axial, marginal, and overall (Figure 1).

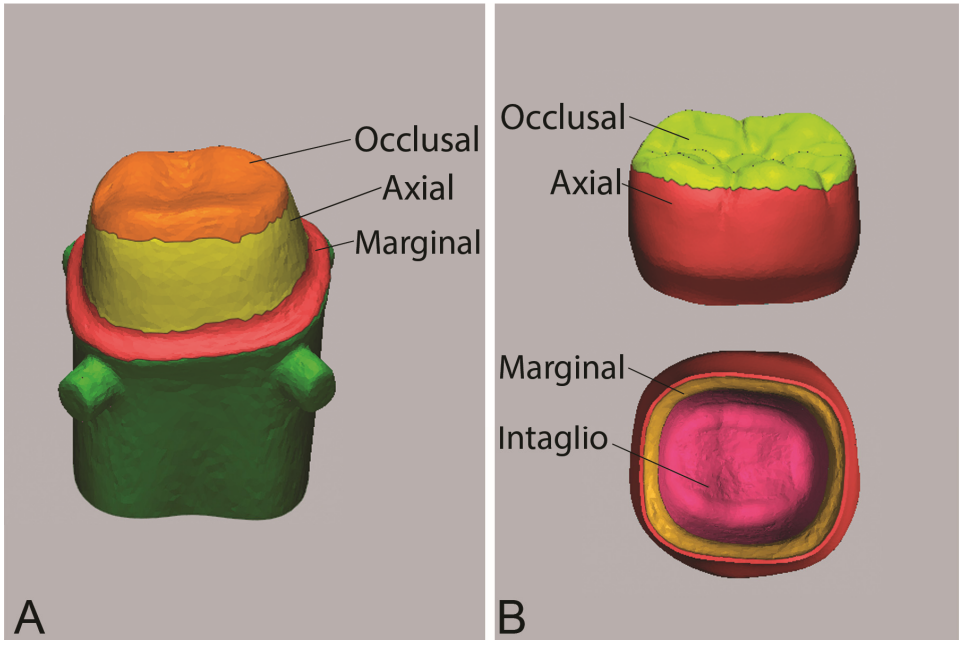


Figure 1. (**A**) Internal fit comparison areas. (**B**) Trueness and precision comparison areas.

The analysis process entailed the implementation of two distinct alignment strategies: a "transform alignment" and a "best-fit alignment." These alignments facilitated the precise co-registration of the "measured data scan" and the "reference scan" to comprehensively compare their surface geometries. Subsequently, evaluation of the four predefined anatomical ROI—occlusal, axial (between occluso-axial line angles and medial borders of marginal area), marginal (extending 1.0 mm medially from the finish line), and overall—was conducted using a dedicated "3D compare" function within the software. This function employed a color map ranging from positive 0.12 to negative 0.12 mm to represent minute dimensional discrepancies between the two scans visually. Finally, an automated report was generated, quantifying the cement gap as the positive average value, which served as the crown's overall fit value.

2.4. Trueness Assessment

ISO (12836:2015) was followed to assess accuracy (trueness and precision), in which each crown underwent scanning in the following sequence. First, a putty was applied to the occlusal surface of the crown to provide stability, and then the crown's intaglio (inner) surface was scanned. Then, the putty was inverted into the intaglio surface to support the crown as the outer surface was scanned. The resulting 3D crown scans represent the "measured data". For trueness evaluation, each scanned crown was initially aligned and subsequently best aligned with its CAD design. After, 3D morphometric analysis was conducted using Geomagic Control to comprehensively assess ROI, including occlusal, axial, marginal, and intaglio surfaces. Overall values were computed after that. Root Mean Square (RMS) values were utilized to quantify the deviation between measured data and the original crown design, with higher RMS values indicating lower trueness.

2.5. Precision Assessment

The "measured data" obtained from each individual crown within a group underwent a superimposition process to enable visual comparison of their surface geometries. This comparison aimed to detect potential differences in dimensional accuracy among the crowns. Each crown scan underwent an "initial alignment" and then "best-fit alignment" with the first crown. Discrepancies in ROI, such as occlusal, axial, marginal, and intaglio surfaces, were quantified to assess inter-specimen variability. Subsequently, overall values were computed. Then, the RMS value was generated. A higher RMS value indicates greater

dimensional deviations between the compared "measured data" scans, suggesting lower overall precision across the crown specimens within the group.

2.6. Statistical Analysis

The statistical analysis was performed using SPSS software version 23 (IBM Corp., New York, NY, USA) to assess mean differences between test groups for trueness, precision, internal fit, and marginal adaptation. The data are normally distributed. One-way analysis of variance (ANOVA) was conducted to identify statistically significant differences ($p \leq 0.05$) in these parameters between groups. After that, post hoc Tukey's multiple comparison test analysis using appropriate correction methods would be employed if the significance of the mean difference between the groups was detected.

3. Results

The data was tabulated, and the means ± standard deviation (SD) were calculated per tested property. Overall, (E) demonstrated the lowest measurements, while (C) exhibited the highest internal fit and marginal adaptation values across all assessed regions. Analysis of variance (ANOVA) results revealed no statistically significant difference in internal fit and marginal adaptation across the occlusal (p = 0.220), axial (p = 0.339), marginal (p = 0.250), and overall (p = 0.236) evaluations. The most significant measurements were observed in the occlusal region. (E) exhibited superior fit compared to the experimental groups, followed by (VSCP), and finally, (C) (Table 2 and Figure 2).

Table 2. Internal fit and marginal gap mean ± standard deviation (SD) at the measurement of the different areas (µm).

Area Measured	Varseo Smile Crown Plus Printed Mean ± SD	CROWNTEC Printed Mean ± SD	Enamic Milled Mean ± SD	*p*-Value
Occlusal	183.100 ± 35.8462	186.308 ± 66.8505	156.938 ± 25.6208	0.220
Axial	86.285 ± 17.3755	111.123 ± 88.6660	82.915 ± 11.2574	0.339
Marginal	125.046 ± 32.1901	138.677 ± 58.0090	112.585 ±14.5458	0.250
Overall	131.869 ± 21.2528	147.677 ± 69.8194	118.531 ± 13.9868	0.236

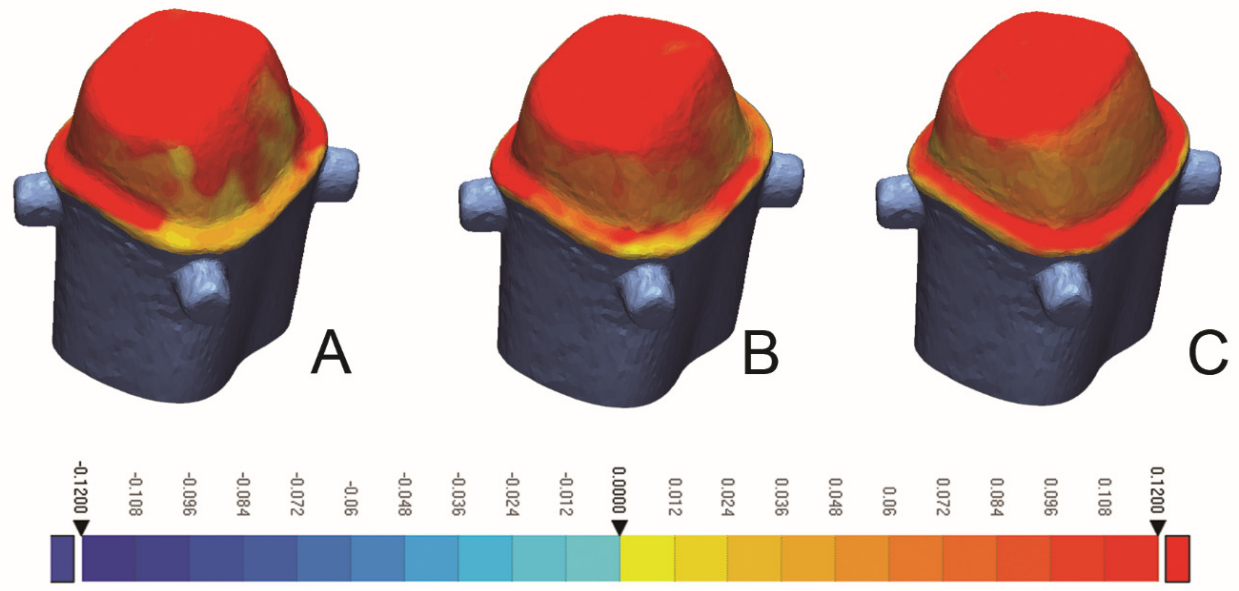


Figure 2. Internal fit and marginal gap comparison areas: (**A**) Varseo smile crown plus. (**B**) CROWNTEC. (**C**) Enamic.

In the trueness assessments (Table 3), a significant statistical contrast was noted between all specimens, whether printed and milled or printed and printed, across the occlusal, axial, marginal, and overall dimensions, at a significance level of ($p \leq 0.00$) (refer to Figure 3). Generally, (E) displayed the smallest measurements. At the same time, Varseo exhibited the highest values for occlusal, axial, and overall dimensions, with (C) leading to the marginal dimension. (E) demonstrated the highest trueness, while (VSCP) displayed the lowest trueness.

Table 3. Trueness means (RMS) root mean square and ±(SD) standard deviation in (μm).

Area Measured	Varseo Smile Crown Plus Printed Mean ± SD	CROWNTEC Printed Mean ± SD	Enamic Milled Mean ± SD	*p*-Value
Occlusal	44.6 ± 6.45 a	38.2 ± 3.25 a	28.6 ± 6.58 a	$p \leq 0.05$ *
Axial	98.4 ± 16.83 a	65.5 ± 23.86 a	45.7 ± 6.00 a	$p \leq 0.05$ *
Marginal	54.9 ± 11.38 a	36.7 ± 16.17 a	29.0 ± 8.27 a	$p \leq 0.05$ *
Intaglio	31.9 ± 13.19 a	43.8 ± 6.70 a	25.8 ± 4.56 a	$p \leq 0.05$ *
Overall	57.5 ± 9.17 a	46.1 ± 6.48 a	32.3 ± 12.38 a	$p \leq 0.05$ *

* Indicates significant differences between groups. a post hoc analysis of Tukey HSD indicates significance between the groups.

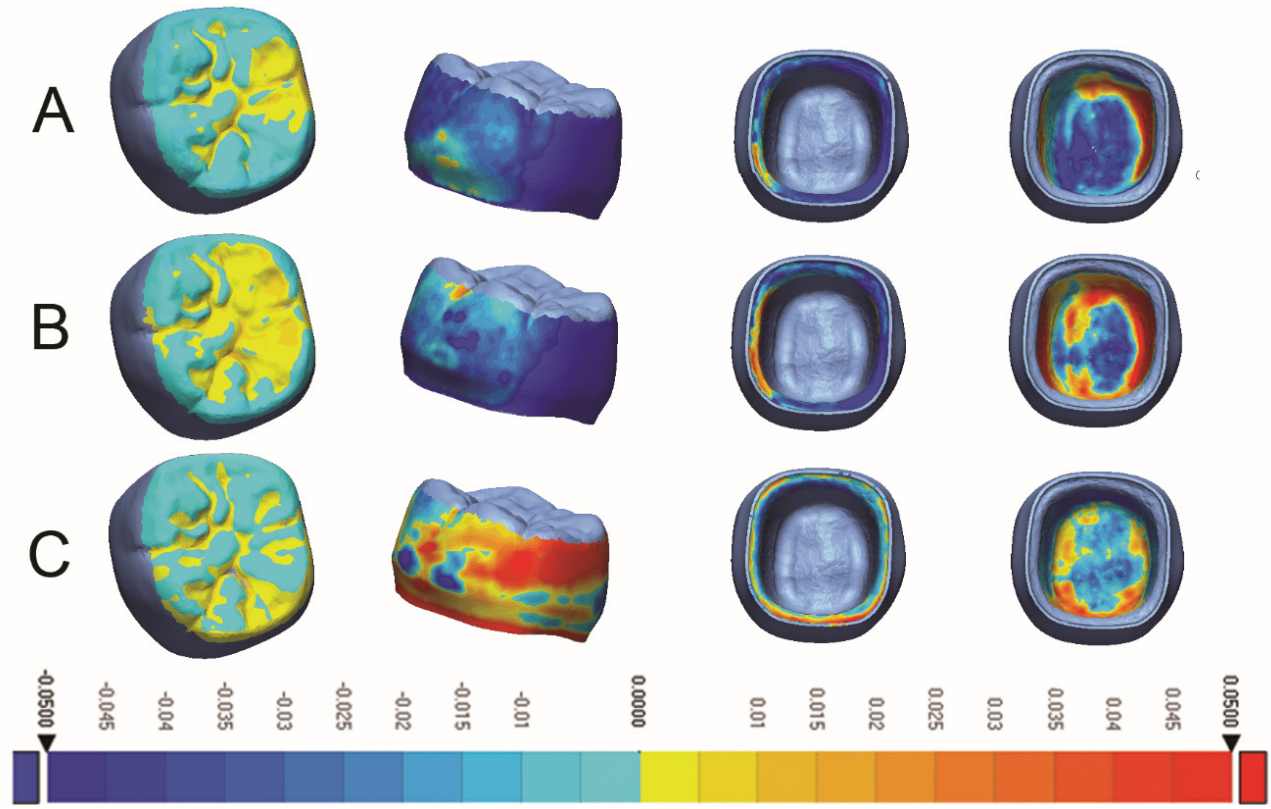


Figure 3. Trueness comparison areas (occlusal, axial, intaglio, marginal), respectively. (**A**) Varseo smile crown plus. (**B**) CROWNTEC. (**C**) Enamic.

Table 4 presents the descriptive statistics for precision evaluation. Statistically significant differences were observed in the occlusal region among printed specimens (VSCP) and (C) ($p \leq 0.009$). Notably, (C) displayed the lowest value, while (VSCP) exhibited the highest. In the marginal area, significant differences emerged between printed and milled specimens (VSCP) and (E) ($p \leq 0.020$), as well as between (C) and (E) ($p \leq 0.001$). In this regard, (E) recorded the lowest value at 20.5, contrasting with (VSCP), which had the

highest at 27.9. Conversely, no statistically significant differences were detected in the axial and intaglio regions (Figure 4).

Table 4. Precision root mean square (RMS) values and standard deviation ±(SD) in (μm).

Area Measured	Varseo Smile Crown Plus Printed Mean ± SD	CROWNTEC Printed Mean ± SD	Enamic Milled Mean ± SD	*p*-Value
Occlusal	26.4 ± 9.14 a	17.8 ± 2.45 a	22.5 ± 7.45	0.013 *
Axial	37.1 ± 19.02	32.1 ± 3.76	35.9 ± 2.88	0.611
Marginal	27.9 ± 7.22 a	31.0 ± 7.20	20.5 ± 5.33 a	0.001 *
Intaglio	22.3 ± 10.52	20.9 ± 4.54	19.7 ± 6.85	0.695
Overall	28.4 ± 9.58	25.5 ± 3.19	24.7 ± 7.09	0.377

* Indicates significant differences between groups. a post hoc analysis of Tukey HSD indicates significance between the groups.

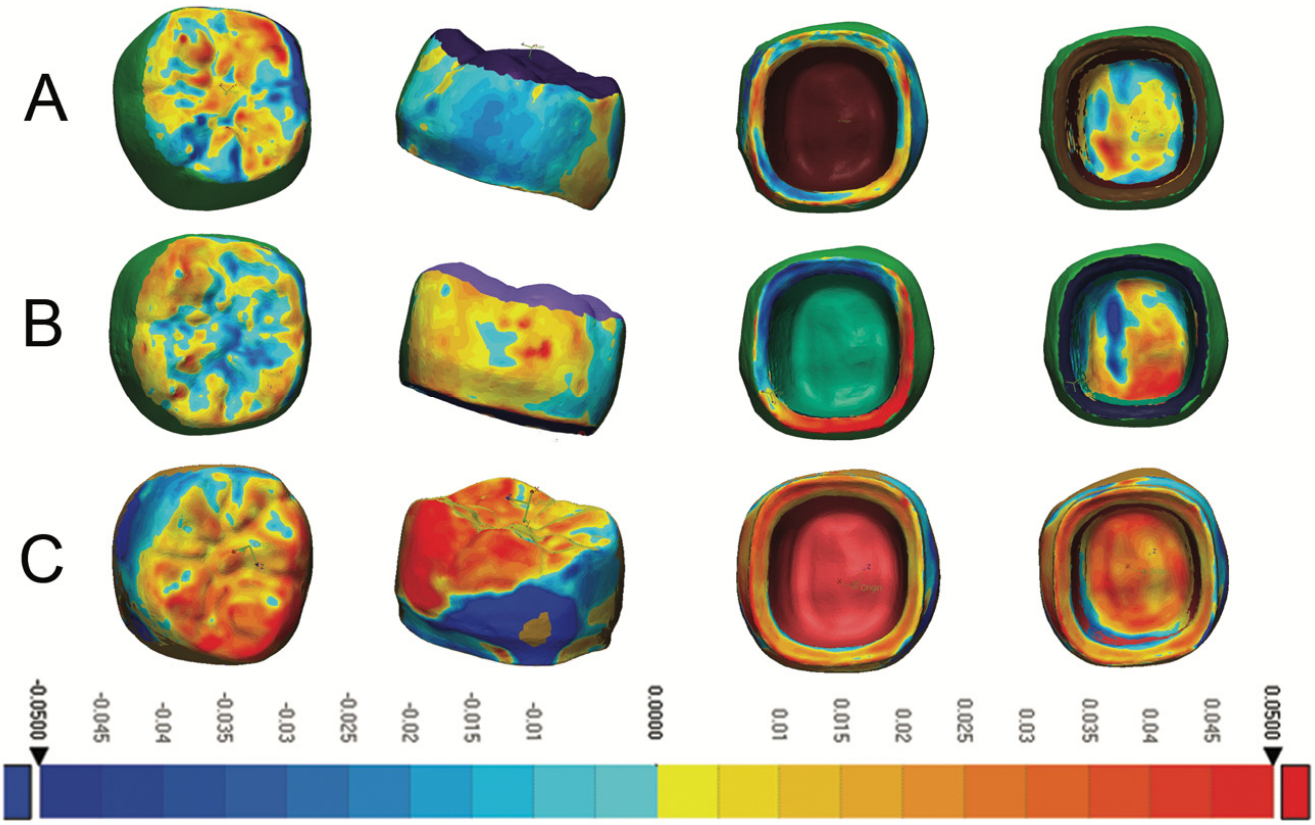


Figure 4. Precision comparison areas (occlusal, axial, intaglio, marginal), respectively. (**A**) Varseo smile crown plus. (**B**) CROWNTEC. (**C**) Enamic.

4. Discussion

This study investigated the marginal adaptation and internal fit of hybrid crowns manufactured through milling and 3D printing processes in three dimensions. Additionally, it evaluated the precision and trueness of these crowns compared to the original design and each other. The findings indicate that the null hypothesis concerning internal fit and marginal adaptation was accepted, suggesting no significant differences. However, the null hypothesis was rejected for trueness and partially rejected for precision.

In this research, specimens were fabricated using both additive and subtractive manufacturing methods, utilizing identical STL files to standardize and maintain uniformity across the produced crowns. Additive manufacturing was selected due to its numerous advantages for the manufacturing industry. These include achieving mass production,

minimizing material waste, fabricating complex shapes, reducing residual stresses, and eliminating the need for tool maintenance [28,29].

The marginal fit plays a crucial role in the longevity and overall success of prosthetic restorations, especially in the case of prostheses supported by natural teeth [13,14,17,30]. The formation of a marginal gap between the dental structure and the restoration resulting from inadequate marginal adaptation can lead to clinical complications such as the dissolution of the dental cement [17,30], microleakage, and the risk of pulp inflammation [13]. Additionally, it can lead to the formation of secondary caries and inflammation of the periodontal tissues [17].

Our investigation found no statistically significant differences in the internal fit and marginal adaptation of 3D-printed crowns created using (VSCP) compared to those made with (C). Similarly, no significant differences were observed when comparing printed crowns (VSCP, C) to milled crowns manufactured from (E), noting that the 3D-superimposition digital method was employed.

It is important to highlight that the results from both milling and 3D-printed techniques yield similar outcomes, falling within the clinically acceptable marginal gap of up to 120 µm, as supported by several studies [8,31]. Several studies have proposed a maximum permissible misfit of 200 µm, which has been deemed clinically acceptable [7,30,32]. The marginal differences noted in specific research on 3D-printed provisional crowns are similar to those found in crowns made through CAD/CAM milling, which is consistent with the results of our investigation [33–36]. Some reported minimal internal discrepancies for CAD/CAM-milled restorations [37–40].

The rationale behind this could be attributed to the method of milling the restoration from a dense, pre-polymerized block using an automated machine, which eliminates polymerization shrinkage [41,42]. Furthermore, the choice of assessment method significantly influences the outcomes of studies. Researchers have employed various techniques to evaluate the fit of restorations, including silicone replica methods, micro-CT scanning, and cross-sectional analysis [7,8,30–33]. The cross-sectional method introduces measurement errors because of potential deformation that occurs during the cross-sectioning process [43]. Alternatively, measurement errors may arise from operator dependency, leading to inconsistent sectioning in terms of the plane [44]. However, in our study, the 3D-superimposition digital method utilized for assessing adaptation and fit offers extensive visualization of the intaglio surface, aligning scan data and allowing the measurement of numerous points across the entire surface area, in contrast to restricted point measurements. Furthermore, it eliminates the necessity for silicone material sectioning [31].

Overall, fit measurements obtained for the axial and marginal regions across all samples were generally lower than those for the occlusal region. Previous research has consistently indicated that the mean occlusal discrepancy surpasses that of the marginal and axial areas [7,8,30,31]. This phenomenon could be attributed to the influence of the milling bur size and its cutting range on the manufacturing process [8,31–33].

An investigation was conducted to evaluate the marginal adaptation of 3D-printed provisional crowns comprehensively and fixed dental prosthesis (FDP) resins compared to those fabricated using CAD/CAM milling and conventional techniques. The analysis of multiple studies revealed that 3D-printed provisional restorations exhibited statistically significant reductions in marginal discrepancies. This advantageous outcome is attributed to the inherent nature of 3D printing, specifically the incremental layer-by-layer addition process that effectively mitigates polymerization shrinkage [7,8,30–34,45,46].

High trueness and precision in the final crown are critical for optimal clinical outcomes. Precise crowns minimize chairside adjustments and ensure proper fit on the prepared tooth [26]. Trueness refers to the dimensional accuracy of the final crown compared to the intended design. In simpler terms, it reflects how closely the final product resembles the digital blueprint.

The trueness values from this study reveal that milled (E) exhibited the highest level of trueness and closest representation of the original crown with the highest level of trueness in

the intaglio surface, while the printed (VSCP) displayed the lowest trueness. The rationale for this phenomenon may stem from the milling process's methodology, which entails shaping using milling equipment and burs [31]. The diameter of the burr constrains the extent of reproducibility [31]. Notably, employing a smaller bur diameter can prolong manufacturing time due to increased tool path but might yield superior trueness outcomes, as it creates a broader spectrum of burr movement [30]. Consequently, opting for a smaller bur diameter enables more precise milling of the angle region on the intaglio surface, acknowledged as the most challenging area to mill and prone to machining errors [7]. Hence, errors in the angle region between the axial and occlusal regions in crowns must be factored in during milling [32].

Additionally, the number of burs utilized could closely correlate with accuracy, with studies indicating enhanced trueness when employing multiple burs [7,34,45]. Like previous studies, the number of axes on a milling machine can affect how well it replicates the designed crown (trueness). Notably, five-axis machines consistently produce more accurate crowns [34,45,46].

The trueness values documented in our study fall within the range deemed clinically acceptable (<100 μm). However, our findings diverge from certain prior studies assessing the trueness of dental crown intaglio surfaces, which asserted that the 3D printing group exhibited superior trueness compared to milling technology [30,31]. Nonetheless, our results are consistent with other research that indicated improved intaglio surface trueness for milled specimens [7].

Achieving high dimensional precision in dental restorations is paramount to ensure optimal marginal adaptation and minimize potential adverse biological responses. The fidelity of a 3D-printed object is demonstrably influenced by a multitude of variables, including the chosen additive manufacturing technique, the strategic implementation and configuration of support structures, and the selection of the digitization method or scanner employed for the initial model acquisition [26]. This study aimed to assess the precision of crowns manufactured using different production methods. To achieve this goal, the measured data from one crown were compared to those of the other crowns within each manufacturing technique.

In this study's precision evaluation, significant differences were noted between printed samples of (VSCP) and (C) in the occlusal area, with (C) having the highest precision. However, differences between milled and printed specimens were observed in the marginal area. It was noted between (VSCP) and (E) and between (C) and (E). Here, the highest precision was for (E) and the lowest for (C).

Our findings regarding dimensional precision are further corroborated by the established understanding that a group of variables demonstrably influences the accuracy of additively manufactured (3D-printed) dental restorations. These factors encompass the specific type of 3D printer employed, the chosen layer thickness and total number of layers utilized, the energy delivered per layer (UV intensity), the printer's operating wavelength, the overall restoration thickness and die-spacer thickness, the spatial arrangement of the crowns within the printing bed, the post-processing methodologies implemented, and the design and placement optimization of support structures [7,8,10,30–34]. Furthermore, achieving high precision in photopolymerizable 3D printing is inherently limited by the maximum projection size, restricting the fabrication of large objects and model geometry. Additionally, volume shrinkage during the curing process technique and shrinkage over time remains a well-documented drawback associated with this 3D-printed resin [23].

Among the limitations of this study is that it uses only one method to assess the fit and tests the samples in static conditions for fit without subjecting them to cyclic loading or thermal conditions. There are no potential biases in this research. Recommendations for future studies include changing the printing orientation and the post-processing curing time, testing the samples under cyclic loading or thermos cycling, and comparing the results.

5. Conclusions

Considering the limitations of this study, both the additive and subtractive specimens demonstrated sufficiently comparable internal fit and marginal adaptation within the clinically acceptable limits. Notably, milled specimens exhibited superior trueness. CROWNTEC has high occlusal precision, and Enamic has the highest marginal precision. However, printed crowns are still within clinically acceptable values.

Author Contributions: Conceptualization, H.A. and R.A.; methodology, A.A.-R.; software, A.A.-R.; validation, Y.A.A.-D. and A.M.A.-T.; formal analysis, H.A.; investigation, A.A.-R.; resources, R.A.; writing—original draft preparation, A.A.-R.; writing—review and editing, Y.A.A.-D., R.A., A.M.A.-T. and H.A.; supervision, H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The author would like to thank Ashwin Shetty Yermal for his help and technical support.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Hull, C.W. Apparatus for Production of Three-Dimensional Objects by Stereolithography. U.S. Patent 638905, 8 August 1984.
2. Abduo, J.; Lyons, K.; Bennamoun, M. Trends in computer-aided manufacturing in prosthodontics: A review of the available streams. *Int. J. Dent.* **2014**, *2014*, 783948. [CrossRef] [PubMed]
3. Mainjot, A.K.; Dupont, N.M.; Oudkerk, J.C.; Dewael, T.Y.; Sadoun, M.J. From Artisanal to CAD-CAM Blocks: State of the Art of Indirect Composites. *J. Dent. Res.* **2016**, *95*, 487–495. [CrossRef] [PubMed]
4. Dawood, A.; Marti Marti, B.; Sauret-Jackson, V.; Darwood, A. 3D printing in dentistry. *Br. Dent. J.* **2015**, *219*, 521–529. [CrossRef] [PubMed]
5. Stansbury, J.W.; Idacavage, M.J. 3D printing with polymers: Challenges among expanding options and opportunities. *Dent. Mater.* **2016**, *32*, 54–64. [CrossRef] [PubMed]
6. Tsolakis, I.A.; Papaioannou, W.; Papadopoulou, E.; Dalampira, M.; Tsolakis, A.I. Comparison in Terms of Accuracy between DLP and LCD Printing Technology for Dental Model Printing. *Dent. J.* **2022**, *10*, 181. [CrossRef]
7. Quan, H.; Zhang, T.; Xu, H.; Luo, S.; Nie, J.; Zhu, X. Photo-curing 3D printing technique and its challenges. *Bioact. Mater.* **2020**, *5*, 110–115. [CrossRef]
8. Wu, L.; Zhao, L.; Jian, M.; Mao, Y.; Yu, M.; Guo, X. EHMP-DLP: Multi-projector DLP with energy homogenization for large-size 3D printing. *Rapid Prototyp. J.* **2018**, *24*, 1500–1510. [CrossRef]
9. Alharbi, N.; Osman, R.B.; Wismeijer, D. Factors Influencing the Dimensional Accuracy of 3D-Printed Full-Coverage Dental Restorations Using Stereolithography Technology. *Int. J. Prosthodont.* **2016**, *29*, 503–510. [CrossRef]
10. Alharbi, N.; Osman, R.; Wismeijer, D. Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations. *J. Prosthet. Dent.* **2016**, *115*, 760–767. [CrossRef]
11. Schweiger, J.; Edelhoff, D.; Guth, J.F. 3D Printing in Digital Prosthetic Dentistry: An Overview of Recent Developments in Additive Manufacturing. *J. Clin. Med.* **2021**, *10*, 2010. [CrossRef]
12. van Noort, R. The future of dental devices is digital. *Dent. Mater.* **2012**, *28*, 3–12. [CrossRef] [PubMed]
13. Larson, T.D. The clinical significance of marginal fit. *Northwest Dent.* **2012**, *91*, 22–29.
14. Holmes, J.R.; Bayne, S.C.; Holland, G.A.; Sulik, W.D. Considerations in measurement of marginal fit. *J. Prosthet. Dent.* **1989**, *62*, 405–408. [CrossRef] [PubMed]
15. Laumbacher, H.; Strasser, T.; Knüttel, H.; Rosentritt, M. Long-term clinical performance and complications of zirconia-based tooth- and implant-supported fixed prosthodontic restorations: A summary of systematic reviews. *J. Dent.* **2021**, *111*, 103723. [CrossRef] [PubMed]
16. Al Hamad, K.Q.; Al-Rashdan, R.B.; Al-Rashdan, B.A.; Baba, N.Z. Effect of Milling Protocols on Trueness and Precision of Ceramic Crowns. *J. Prosthodont.* **2021**, *30*, 171–176. [CrossRef]
17. Hasanzade, M.; Aminikhah, M.; Afrashtehfar, K.I.; Alikhasi, M. Marginal and internal adaptation of single crowns and fixed dental prostheses by using digital and conventional workflows: A systematic review and meta-analysis. *J. Prosthet. Dent.* **2021**, *126*, 360–368. [CrossRef]
18. Revilla-León, M.; Methani, M.M.; Morton, D.; Zandinejad, A. Internal and marginal discrepancies associated with stereolithography (SLA) additively manufactured zirconia crowns. *J. Prosthet. Dent.* **2020**, *124*, 730–737. [CrossRef]

19. Lerner, H.; Nagy, K.; Pranno, N.; Zarone, F.; Admakin, O.; Mangano, F. Trueness and precision of 3D-printed versus milled monolithic zirconia crowns: An in vitro study. *J. Dent.* **2021**, *113*, 103792. [CrossRef]
20. Ruse, N.D.; Sadoun, M.J. Resin-composite Blocks for Dental CAD/CAM Applications. *J. Dent. Res.* **2014**, *93*, 1232–1234. [CrossRef]
21. Zimmermann, M.; Mehl, A.; Reich, S. New CAD/CAM materials and blocks for chairside procedures. *Int. J. Comput. Dent.* **2013**, *16*, 173–181.
22. Goujat, A.; Abouelleil, H.; Colon, P.; Jeannin, C.; Pradelle, N.; Seux, D.; Grosgogeat, B. Mechanical properties and internal fit of 4 CAD-CAM block materials. *J. Prosthet. Dent.* **2018**, *119*, 384–389. [CrossRef] [PubMed]
23. Lee, B.-I.; You, S.-G.; You, S.-M.; Kim, D.-Y.; Kim, J.-H. Evaluating the accuracy (trueness and precision) of interim crowns manufactured using digital light processing according to post-curing time: An in vitro study. *J. Adv. Prosthodont.* **2021**, *13*, 89. [CrossRef]
24. Osman, R.B.; Alharbi, N.; Wismeijer, D. Build Angle: Does It Influence the Accuracy of 3D-Printed Dental Restorations Using Digital Light-Processing Technology? *Int. J. Prosthodont.* **2017**, *30*, 182–188. [CrossRef] [PubMed]
25. Tahayeri, A.; Morgan, M.; Fugolin, A.P.; Bompolaki, D.; Athirasala, A.; Pfeifer, C.S.; Ferracane, J.L.; Bertassoni, L.E. 3D printed versus conventionally cured provisional crown and bridge dental materials. *Dent. Mater.* **2018**, *34*, 192–200. [CrossRef]
26. Sidhom, M.; Zaghloul, H.; Mosleh, I.E.-S.; Eldwakhly, E. Effect of Different CAD/CAM Milling and 3D Printing Digital Fabrication Techniques on the Accuracy of PMMA Working Models and Vertical Marginal Fit of PMMA Provisional Dental Prosthesis: An In Vitro Study. *Polymers* **2022**, *14*, 1285. [CrossRef] [PubMed]
27. Spitznagel, F.A.; Boldt, J.; Gierthmuehlen, P.C. CAD/CAM Ceramic Restorative Materials for Natural Teeth. *J. Dent. Res.* **2018**, *97*, 1082–1091. [CrossRef]
28. Osman, R.B.; van der Veen, A.J.; Huiberts, D.; Wismeijer, D.; Alharbi, N. 3D-printing zirconia implants; a dream or a reality? An in-vitro study evaluating the dimensional accuracy, surface topography and mechanical properties of printed zirconia implant and discs. *J. Mech. Behav. Biomed. Mater.* **2017**, *75*, 521–528. [CrossRef]
29. Methani, M.M.; Revilla-León, M.; Zandinejad, A. The potential of additive manufacturing technologies and their processing parameters for the fabrication of all-ceramic crowns: A review. *J. Esthet. Restor. Dent.* **2020**, *32*, 182–192. [CrossRef]
30. Jacobs, M.S.; Windeler, A.S. An investigation of dental luting cement solubility as a function of the marginal gap. *J. Prosthet. Dent.* **1991**, *65*, 436–442. [CrossRef]
31. Abualsaud, R.; Alalawi, H. Fit, Precision, and Trueness of 3D-Printed Zirconia Crowns Compared to Milled Counterparts. *Dent. J.* **2022**, *10*, 215. [CrossRef]
32. Park, J.-Y.; Jeong, i.-D.; Lee, J.-J.; Bae, S.-Y.; Kim, J.-H.; Kim, W.-C. In vitro assessment of the marginal and internal fits of interim implant restorations fabricated with different methods. *J. Prosthet. Dent.* **2016**, *116*, 536–542. [CrossRef] [PubMed]
33. Lee, W.-S.; Lee, D.-H.; Lee, K.-B. Evaluation of internal fit of interim crown fabricated with CAD/CAM milling and 3D printing system. *J. Adv. Prosthodont.* **2017**, *9*, 265–270. [CrossRef] [PubMed]
34. Kim, C.M.; Kim, S.R.; Kim, J.H.; Kim, H.Y.; Kim, W.C. Trueness of milled prostheses according to number of ball-end mill burs. *J. Prosthet. Dent.* **2016**, *115*, 624–629. [CrossRef] [PubMed]
35. Igreţ, A.; Rotar, R.N.; Ille, C.; Topală, F.; Jivănescu, A. Marginal fit of milled versus different 3D-printed materials for provisional fixed dental prostheses: An in vitro comparative study. *Med. Pharm. Rep.* **2023**, *96*, 298–304. [CrossRef]
36. Jivanescu, A.; Birkenheier, N.; Rotar, R.N.; Topala, F.; Goguta, L. Marginal fit of ceramic crowns fabricated with CAD-CAM technology using a direct and indirect digital workflow. *J. Clin. Med. Res.* **2019**, *3*, 1–6.
37. Peng, C.C.; Chung, K.H.; Ramos, V., Jr. Assessment of the Adaptation of Interim Crowns using Different Measurement Techniques. *J. Prosthodont.* **2020**, *29*, 87–93. [CrossRef]
38. Deeb, L.A.; Ahdal, K.A.; Alotaibi, G.N.; Alshehri, A.; Alotaibi, B.M.; Alabdulwahab, F.; Deeb, M.A.; AlFawaz, Y.F.; Vohra, F.; Abduljabbar, T. Marginal Integrity, Internal Adaptation and Compressive Strength of 3D Printed, Computer Aided Design and Computer Aided Manufacture and Conventional Interim Fixed Partial Dentures. *J. Biomater. Tissue Eng.* **2019**, *9*, 1745–1750. [CrossRef]
39. Sampaio, C.S.; Niemann, K.D.; Schweitzer, D.D.; Hirata, R.; Atria, P.J. Microcomputed tomography evaluation of cement film thickness of veneers and crowns made with conventional and 3D printed provisional materials. *J. Esthet. Restor. Dent.* **2021**, *33*, 487–495. [CrossRef]
40. Earar, K.; Iliescu, A.A.; Popa, G.; Iliescu, A.; Rudnic, I.; Feier, R.; Voinea-Georgescu, R.N. Additive vs. subtractive CAD/CAM procedures in manufacturing of the PMMA interim dental crowns. A Comparative in vitro Study of Internal Fit. *Rev. Chim.* **2020**, *71*, 405–410. [CrossRef]
41. Al-Aali, K.A.; Alhamdan, R.S.; Maawadh, A.M.; Vohra, F.; Abduljabbar, T. Influence of contemporary CAD-CAM milling systems on the fit and adaptation of partially stabilized Zirconia fixed partial dentures. *Pak. J. Med. Sci.* **2021**, *37*, 45. [CrossRef]
42. Karaokutan, I.; Sayin, G.; Kara, O. In vitro study of fracture strength of provisional crown materials. *J. Adv. Prosthodont.* **2015**, *7*, 27–31. [CrossRef]
43. Molin, M.; Karlsson, S. The fit of gold inlays and three ceramic inlay systems: A clinical and in vitro study. *Acta Odontol. Scand.* **1993**, *51*, 201–206. [CrossRef] [PubMed]
44. Nawafleh, N.A.; Mack, F.; Evans, J.; Mackay, J.; Hatamleh, M.M. Accuracy and reliability of methods to measure marginal adaptation of crowns and FDPs: A literature review. *J. Prosthodont.* **2013**, *22*, 419–428. [CrossRef] [PubMed]

45. Lee, D.H. Digital approach to assessing the 3-dimensional misfit of fixed dental prostheses. *J. Prosthet. Dent.* **2016**, *116*, 836–839. [CrossRef] [PubMed]
46. Bosch, G.; Ender, A.; Mehl, A. A 3-dimensional accuracy analysis of chairside CAD/CAM milling processes. *J. Prosthet. Dent.* **2014**, *112*, 1425–1431. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.