Evaluation of marginal and internal adaptation of fixed dental restorations on alveolar casts printed with different 3D printers.

A Thesis

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Abstract

Background:

Achieving precision in dental restoration fit is crucial for preventing adverse outcomes such as plaque accumulation, marginal discoloration, and periodontal disease, which are often exacerbated by marginal discrepancies. Recent advancements in digital dental technologies, particularly 3D printing, have shown potential to enhance the accuracy of such restorations.

Aim and Hypothesis:

This in-vitro study tested the null hypothesis that there are no differences in the accuracy of marginal and internal adaptations among restorations fabricated using three different 3D printing technologies: Carbon Digital Light Synthesis™ (Carbon DLS™), Straumann P30, and Formlabs Form 3B+. Each system represents a unique approach to 3D printing, employing different mechanisms that could influence the fit and overall success of the final dental restorations.

Material and Methods:

This study employed a meticulously designed reference cast (K-2 crowns and bridge model, Kilgore) featuring preparations for a veneer, two single crowns, and a three-unit tooth-supported fixed dental prosthesis (FDP). The cast was digitized using a Trios4 intra-oral scanner (3Shape, Copenhagen, Denmark) and modeled in Exocad software (Version 3.1, Rijeka) to create printable STL files for the alveolar casts. These files were printed using three advanced 3D printers: Carbon Digital Light Synthesis™ (Carbon DLS™), Straumann P30, and Formlabs Form 3B+. Adaptations were measured using a light microscope at 5X magnification to determine the precision of each 3D printer in producing dental restorations.

Results:

Significant differences in adaptation were observed among the printers, particularly in the incisal buccal regions where Carbon DLS™ demonstrated consistently superior performance with the smallest mean marginal gap compared to Straumann P30 and Formlabs. In the middle and cervical regions, non-significant differences were frequently observed among the printers.

Conclusion:

The study highlights the importance of selecting appropriate 3D printing technology for dental restorations based on specific clinical requirements. Carbon DLS™ proved to be particularly effective in achieving the highest precision in critical aesthetic zones, suggesting its suitability for complex dental restorations that demand high accuracy.

Keywords:

Dental Restoration, 3D Printing in Dentistry, Marginal Adaptation, Internal Adaptation, Digital Dentistry, Dental Prosthetics, CAD/CAM Technology, Digital Impression Systems, Dental Materials, Prosthodontics

Dedication

I dedicate this research to my beloved parents, whose endless sacrifices and boundless love have guided me through every step of this remarkable journey, I owe my deepest gratitude. Your unwavering belief in me has been my source of strength and inspiration.

To my cherished husband, whose unwavering support and encouragement have been the cornerstone of my success, I am profoundly grateful. Your belief in my dreams and unwavering support have fueled my determination to achieve my aspirations. And to my precious son, whose innocent words of pride have been my constant motivation, I dedicate this work to you. Your love and unwavering faith in me remind me every day of the importance of perseverance and dedication.

To my dear siblings, whose encouragement and support have been a source of comfort and strength throughout this journey, I extend my heartfelt appreciation. Your belief in me has been a guiding light, propelling me forward in pursuit of my dreams.

To the Kingdom of Saudi Arabia for their unwavering support and generosity in granting me a full scholarship to pursue my education. Their investment in my future has empowered me to embark on this academic journey and strive for excellence. This research stands as a testament to the support, love, and encouragement of my family and the Kingdom of Saudi Arabia. Without their unwavering support, this journey would not have been possible.

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I would also like to express my appreciation to our esteemed Co-Investigators, whose contributions have been instrumental in the realization of this study:

Dr. Aikaterini Papathanasiou: Your expertise and collaborative spirit have been invaluable assets, contributing significantly to the depth and breadth of our study.

Dr. Matthew Finkelman: Your rigorous methodology and analytical prowess have been essential in ensuring the scientific rigor and integrity of the research findings.

Mr. Yukio Kudara: Your practical expertise and technical insights have provided invaluable perspectives, enhancing the applicability and relevance of the research outcomes.

Together, your collective efforts have propelled this research forward, advancing our understanding and contributing to the body of knowledge in our field. I am deeply grateful for your collaboration, mentorship, and unwavering support throughout this journey.

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I. Introduction:

A successful dental restoration should have four main characteristics: marginal adaptability, biocompatibility, esthetics, and mechanical strength. Marginal discrepancy promotes plaque buildup, alters the distribution of microflora, and increases the likelihood of caries in abutment teeth.[1]

Restorations that do not fit properly can cause a range of issues that can affect the health of the teeth and surrounding tissues. Plaque buildup can occur when there are gaps between the restoration and the tooth, leading to a higher risk of tooth decay and gum disease. Cement microleakage can also occur when there are gaps, which can lead to sensitivity and the need for additional dental work. [2]

Another potential issue caused by poor fit is marginal discoloration. If a dental restoration does not fit properly, it can cause marginal discoloration. This occurs when there are gaps between the restoration and the tooth, allowing staining materials to cause discoloration around the restoration's edges. As a result, the appearance of the tooth may be compromised, which may lead to lower patient satisfaction with the restoration..[3]

Another problem resulting from poor fit is tooth sensitivity. A gap between the restoration and the tooth exposes the delicate dentin layer, causing discomfort and sensitivity to hot, cold, or sweet foods and beverages.

If there is a gap between the restoration and the tooth, it can cause tooth decay and periodontal disease. Bacteria can build up in the crevices and damage the tooth structure and surrounding tissue, causing these conditions. Proper fit of the restoration is therefore critical to ensure the mechanical stability and durability of the restoration as well as the health of the surrounding tissue.[4]

Accuracy and fit are crucial to the long-term success of the restoration. Terms such as Margin Gap (MG), Absolute Marginal Distance (AMD), and vertical Marginal Distance (VMD) are important in this realm. The margin Gap is a measurement in microns that determines the distance between the restoration margin and the margin-prepared tooth structure. A smaller margin gap generally indicates a better fit for the restoration.

Horizontal MD is a term that refers to the distance between the deepest point of the restoration margin and the prepared tooth structure at the margin. This measurement is usually taken in micrometers (μm) and plays a vital role in ensuring the stability and retention of the restoration. The various terms that are related to the marginal accuracy of fixed dental restorations are critical for evaluating the quality and efficacy of dental treatments.

Absolute MD, on the other hand, represents the difference between the actual restorative margin and the margin-prepared tooth structure, regardless of whether it is positive or negative. This measurement is critical because it can help determine the accuracy of the restoration and whether adjustments need to be made.

The vertical MD is the distance in microns from the highest point of the restoration margin to the tooth structure prepared at the margin. This measurement is important because it can affect the stability and longevity of the restoration. Overall, these terms are essential for dental professionals to understand and consider when creating fixed dental restoration. By paying close attention to these measurements, they can ensure that the restorations are accurate and long-lasting, providing patients with the best possible outcome. [5]

A generally accepted approach for determining the optimal value of the margin gap is not yet recommended. Some researchers have stated that a value of 120 µm is optimal, while others have recommended 100 µm. Furthermore, it is still believed by some that an acceptable value should be between 20 and 75 µm.[6]

When fabricating dental restorations using traditional methods, the complexity of the process involving multiple steps, materials, and procedures can result in imperfections in the margins. Fortunately, the use of CAD/CAM technology and new materials allows for more precise fabrication methods, fewer steps, and higher-quality restorations. Despite these advances, some minor defects can still occur, requiring dentists to carefully investigate and correct problems with dental restoration fit and margins to ensure long-term effectiveness and functionality.

One of the primary focuses of research for dental applications was the development of a 3D intraoral scanning device that takes a digital image of the teeth rather than a conventional impression. Since the introduction of digital impressions in the late 1980s, there have been several commercial attempts to employ an intraoral scanning device to record digital impressions of the teeth. Yet, there are still technical challenges with the digital impressions' quality and the scanning system's speed. [7]

In the mid-1980s, 3D digital dental impression scanning systems were introduced. Since the development of the first digital scanner for making dental impressions, several companies' research and development sectors have advanced their technologies and created faster and more user-friendly system components. These technologies are capable of recording and reproducing three-dimensional (3D) virtual casts of tooth preparation, from which dental prostheses can be manufactured using Standard Tessellation Language (STL). The term STL refers to the process of dividing the geometry of a surface into a series of small triangles or polygons (tessellation). [9]

Additive manufacturing or 3D printing is a process of producing a three-dimensional object layer by layer, utilizing a design created by computer software. To create a 3D-printed object, the process usually involves three stages. The first stage is designing the 3D models using computer modeling software. The second stage involves cutting the 3D model into slices. The final stage is printing the model layer by layer.[10]

While digital workflows have become increasingly popular for the fabrication of indirect restorations, there are still challenges in achieving accurate definitive casts. Factors that can impact the accuracy of the cast include the materials used, the milling and scanning systems, the design of the preparation, the method of measurement, the amount of spacer, and whether the restoration is cemented or non-cemented.

Research has shown that different impression and production procedures can result in significant variations in the marginal fit of indirect restorations. A study published in the Journal of Prosthodontics in 2018 compared the marginal fit of restorations fabricated using conventional impressions and CAD/CAM systems. The study found that the CAD/CAM restorations had significantly better marginal fit than those fabricated using conventional impressions. [12]

To improve the accuracy of definitive casts, dental professionals can take steps to optimize their digital workflows and ensure that all factors are taken into account. This may involve using high-quality materials and scanning and milling systems, designing preparations with optimal parameters for digital fabrication, and carefully measuring and evaluating the fit of the restoration. By paying attention to these factors, dental professionals can achieve accurate and predictable results with digital workflows for indirect restorations.

In a 2019 study published in the Journal of Prosthetic Dentistry, researchers evaluated the marginal adaptation of 3D printed resin crowns using 3D printed models. The study found that the marginal adaptation of the crowns was within clinically acceptable limits, with an average marginal gap of 51.4 µm.[13]

A 2020 study published in the same journal evaluated the marginal adaptation of 3D-printed resin inlays using 3D-printed models. The study found that the marginal adaptation of the inlays was also within clinically acceptable limits, with an average marginal gap of 48.2 µm. [14]

A 2018 study published in the International Journal of Computerized Dentistry compared the marginal adaptation of 3D printed resin crowns using 3D printed models to conventionally fabricated crowns. The study found that the marginal adaptation of the 3D printed crowns was similar to that of conventionally fabricated crowns, with an average marginal gap of 61 µm for both types of restorations.[15]

Overall, these studies suggest that 3D printed restorations using 3D printed models can achieve clinically acceptable levels of marginal adaptation. However, more research is needed to further evaluate the marginal and internal adaptation of multiple digitally printed restorations on a 3D-printed model.

The aim of this study was to evaluate the marginal and internal adaptation of multiple digitally milled restorations on a model created with three different 3D printers.

1- Carbon Digital Light Synthesis (Carbon DLS) is a 3D printer that uses the Continuous Liquid InterfaceProduction (CLIP) process to produce high-quality parts promptly. Dental grade resins can be printed and offer good surface finish and mechanical properties. A major advantage of dental carbon DLS is the rapid production of accurate and consistent parts, enabling efficient production of high-volume restorations efficiently.

2- The Straumann P30 is a 3D printer designed specifically for dental applications, capable of producing high-quality restorations from a variety of materials, including ceramics and polymers. Known for its accuracy and precision, the P30 is ideal for creating complex dental restorations with high-tech designs. Additionally, the P30 is compatible with multiple software and hardware systems, facilitating integration into existing workflows.

3- The Form 3B+ is a versatile 3D printer that can print a variety of dental materials, including biocompatible resin for direct use in the oral cavity. Form 3B+ uses a proprietary Low Force Stereolithography (LFS) process to create high-resolution, precise parts on smooth surfaces. One of the major advantages of Form 3B+ for dental applications is its ease of use and intuitive software that simplifies printing.[16,17.]

In terms of fitting restorations on printed casts, all three of these 3D printers can produce accurate and precise parts, so the quality of the final restoration will likely depend more on the design and manufacturing process than the specific printer used. However, using multiple printers to print and test restorations can help ensure that the final product is of the highest quality and meets the needs of each patient.

II. Research Aims/Hypothesis

The purpose of this in-vitro study was to evaluate and compare the marginal and internal adaptation of multiple milled restorations in the scenario of maxillary veneers, crowns and fixed dental prostheses on alveolar casts fabricated with three different 3D printers. Group A: Carbon (using Carbon Digital Light Synthesis™ or Carbon DLS™), Group B: P30 (manufactured by Straumann), and Group C: Form3B+ (Form 3B+ 3D printer by Formlabs).

NULL HYPOTHESIS

The marginal and internal adaptation of multiple milled restorations with three different 3D printers (Carbon DLS™, P30 manufactured by Straumann, and Form 3B+ by Formlabs) have equal accuracy.

III. Significance

The significance of this study was to evaluate different 3D printing technologies to enhance the precision and reliability of dental prosthetics. By providing a detailed comparison of Carbon DLS™, Straumann P30, and Formlabs Form 3B+ technologies, this research furnishes dental professionals with empirical data essential for selecting the appropriate technology based on specific restoration requirements. The analysis of marginal and internal adaptations helps elucidate how variations in technological application impact the clinical effectiveness and durability of dental prostheses, directly affecting patient satisfaction and clinical outcomes.

By addressing these critical areas, the study not only validates specific 3D printing applications but also promotes continuous improvement in the methodologies and materials employed in dental restoration. It ensures that dental practices can keep pace with the rapid advancements in medical science and technology, thereby enhancing patient care and treatment outcomes.

IV. Materials and Methods

I. Designing the reference cast

A prepared reference cast (K-2- crown and bridge model, Kilgore) was used with tooth preparations for a veneer, two single crowns, and a fixed dental prosthesis, in order to simulate different clinical scenarios of prepared teeth on maxilla that would be restored with multiple restorations (Figure_1).

The typodont included a preparation for a veneer on the left central incisor (tooth #9), two single crowns on the right first molar and the right central incisor (Tooth #3 and #8), and a 3-unit tooth-supported FDP from the left canine to the left second premolar (#11-X-#13) All other teeth in the typodont were intact.

The reference cast was scanned with the intra-oral scanner (Trios4, 3Shape, Copenhagen, Denmark). Based on the manufacturer's instructions, the scanner was calibrated before each scanning[18]. After the scanning was completed, the study's digital model was exported as an STL file (Figure_2).

The STL file was then imported into a Computer Aided Design software (Exocad Rijeka Version 3.1). First, the margins of the teeth preparations were traced. Then the alveolar cast was designed including removable dies and the cast base. The generated data for the digital alveolar cast was exported as STL files to make the design printable (Figure_3).

II. **Printing the Alveolar Cast**

The STL file that has been designed underwent ergo printing using three different 3D printers, Group A: Carbon (using Carbon Digital Light Synthesis™ or Carbon DLS™), Group B: P30 (manufactured by Straumann), and Group C: Form3B+ (Form 3B+ 3D printer by Formlabs) (Figure_4).

After printing, all the alveolar casts were processed and cleaned, followed by treatment based on the manufacturer's instructions for each printer. Once completed, the printed dies were inserted into their sockets passively and evaluated for sufficient retention (Figure_5).

Reference restoration

The PM7 milling system from (Ivoclar USA) was utilized for the fabrication of the dental restorations. This advanced milling technology offers precise and consistent results, ensuring accurate shaping and customization of the restorations. The PM7 system's high-speed capabilities and optimized tooling enable efficient and reliable milling of the Katana Zirconia material[19].

The desired restorations were milled from blocks of Katana Zirconia. The milling process followed the manufacturer's guidelines and parameters for the specific restorations, ensuring optimal fabrication and quality.

After the milling process, each restoration was subjected to thorough quality control measures. This will include a visual inspection for any milling errors, surface roughness, or structural defects. Additionally, precision measuring instruments were employed to evaluate the marginal fit and adaptation of the milled restorations on a reference cast.

Evaluation of the marginal and internal adaptation:

The thickness of the marginal gap and cement space on the incisal, middle, and cervical surfaces of the restorations were measured using a light microscope with 5 X magnification (OLYMPUS SZX16, OLYMPUS) (Figure _6).

To achieve this, a silicon light body impression material (Imprint 3 light body, 3M ESPE) was injected into the accepted restorations as the cementing medium and then placed on their respective models using finger pressure. The restorations were subjected to a constant weight of 5 kg until the material sets. Any excess material beyond the margins was removed using micro brushes. Once the light body material had set, the heavy body silicon impression material (Imprint 3 Heavy Body, 3M ESPE) was injected into the restorations to act as a carrier for the cementation medium during the slicing and measuring procedure. A slice of approximately 1 mm thickness was taken from the center of each specimen and placed under the microscope for measurement at 5X magnification. Four measurements were taken for each specimen at the incisal/occlusal margin for marginal adaptation, cervical, middle, and incisal/occlusal thirds for internal adaptation. All measurements were done blindly by the same operator.

The study was conducted in the Gavel Centeron the 8th floor at Tufts University School of Dental Medicine.

V. Data Analysis

Sample size calculation:

In this research, a convenience sample was used; the samples were derived from a previous study that aimed to evaluate the accuracy of 3D printed alveolar casts fabricated with three different 3D printers from digital scans on a typodont in the scenario of a maxillary veneer, crowns, and fixed dental prostheses. In the prior study, the sample size was calculated using nQuery Advisor software v. 9.1.1.0 (Statistical Solutions Ltd., Cork, Ireland). The Type I error rate was set at 5% and the Type II error rate was set at 20% (i.e., a power of 80%).

Statistical analysis:

Descriptive statistics (means, medians, standard deviations, and interquartile ranges) were calculated. In cases with no significant evidence of non-normality or heteroscedasticity, statistical significance was assessed using one-way ANOVA, with post-hoc tests conducted via Tukey's HSD. In cases with significant evidence of heteroscedasticity but not non-normality, statistical significance was assessed using Welch's ANOVA, with post-hoc tests conducted via the Games-Howell test. In cases with significant evidence of non-normality, statistical significance was assessed using the Kruskal-Wallis test, with post-hoc tests conducted via Dunn's test and the Bonferroni correction. Evidence of non-normality was evaluated using the Shapiro-Wilk test, while evidence of heteroscedasticity was evaluated using Levene's test. The significance level was set at α=.05, with the exception of tests in which the Bonferroni correction was used. SPSS v. 28 (IBM Corp., Armonk, NY, USA) was used in the analysis.

VI. Results

This in vitro study evaluated the marginal and internal adaptation of fixed dental restorations fabricated using three distinct 3D printing technologies: Carbon Digital Light Synthesis™ (Carbon DLS™), Straumann P30, and Formlabs Form 3B+. Adaptations were assessed at various anatomical points on dental crowns, specifically numbered 3, 8, 11, 13, and veneer 9, with detailed measurements taken on both buccal and lingual surfaces across incisal, middle, and cervical regions.

Significant variations in printer performance were observed, especially in the incisal buccal regions of the crowns. Carbon DLS™ consistently demonstrated superior adaptation capabilities, exemplified by its achievement of the smallest mean marginal gaps. For instance, in the incisal buccal region of Crown #3, Carbon achieved a mean marginal gap of 52.3 micrometers, significantly better than the gaps produced by Straumann P30 (80.8 micrometers) and Formlabs (71.3 micrometers), with statistically significant differences noted ($p < .001$) for Carbon vs. P30; $p = .005$ for Carbon vs. Formlabs). This trend of superior performance by Carbon was similarly observed in Crown #8 where it recorded a marginal gap of 53.44 micrometers, markedly smaller than that of P30 (89.72 micrometers) and significantly smaller than Formlabs' gap of 116.4 micrometers.

Across other regions such as the middle buccal and lingual surfaces, and the cervical regions of these crowns, non-significant differences were frequently observed among the printers. These findings suggest that while technological distinctions impact the precision in critical aesthetic zones like the incisal areas, there was often non-significant evidence of differences in less critical areas of the crowns.

Furthermore, the reliability of the Carbon printer in producing precise restorations was reinforced across multiple crowns. For example, in the incisal buccal area of Crown #11, Carbon continued to show significantly smaller marginal gaps compared to its competitors, underscoring its consistent performance.

Parameter	**Group**	**Mean (SD)**	**Median (25th - 75th Percentiles)**	**P-value of Global (Omnibus) Test**	**Significant Post-hoc Tests**
Incisal Buccal Crown #3†	Carbon	52.3 (8.6)	52.1 (45.6 - 54.9)	0.003	Carbon vs. P30 (p <.001) Carbon vs. Formlabs (p=.005)
	P30	80.8 (26.3)	75.7 (67.8 - 90.5)		
	Formlabs	71.3 (9.8)	73.6 (66.1 - 76.4)		
Middle Buccal Crown #3‡	Carbon	44.13 (4.9)	42.9 (41.5-47.6)	0.699	NA
	P30	44.98 (10.6)	46.1(35.1-52-5)		
	Formlabs	45.9 (6.2)	49.6 (42-50)		
Cervical Buccal Crown #3‡	Carbon	32.98 (5.3)	32.9 (28-38.6)	0.676	NA
	P30	33.36 (5.36)	31.8 (29.9-26.8)		

	Formlabs	31.05 (4.2)	32 (28.8-34.3)		
Incisal Lingual Crown #3‡	Carbon	45.12 (6.8)	49.9 (38.4-50)	<.001	Carbon vs. P30 (p<.001) Carbon vs. Formlabs (p =.014) P30 vs. Formlab (p=.015)
	P30	89.08 (13.1)	87.3 (80-97)		
	Formlabs	61.91 (9.8)	57.5 (55-73)		
Middle lingual Crown #3‡	Carbon	45.92 (10.5)	45.9 (43.4-48.6)	0.059	NA
	P30	54.97 (11.93)	53.1 (44.3-65.9)		
	Formlabs	44.8 (4.2)	43.4 (42.5-44.8)		
Cervical lingual Crown #3‡	Carbon	35.82 (5.2)	36.4 (32.6-39)	0.818	NA
	P30	35.73 (3.1)	35.9 (33-38)		
	Formlabs	37.6 (4.3)	36.1 (34.8-38.7)		
Incisal Buccal Crown #8‡	Carbon	53.44 (12.4)	49.9 (44.5-57)	<.001	Carbon vs. P30 (p=.009) Carbon vs. Formlabs (p <.001) P30 vs. Formlab (p=.025)
	P30	89.72 (12.5)	89 (86.5-95.3)		
	Formlabs	116.4 (19.7)	112.4 (100.4-126.9)		
Middle Buccal Crown #8‡	Carbon	43.6 (7.2)	44.9 (41.9-47.2)	<.001	Carbon vs. Formlabs (p <.001) P30 vs. Formlab (p <.001)
	P30	45.5 (10.7)	45.9 (36.7-54.2)		
	Formlabs	47.2 (5.9)	47.7 (71.9-77.7)		
Cervical Buccal Crown #8‡	Carbon	41.44 (7.7)	39.5 (37.4-41.9)	0.681	NA
	P30	37.62 (6.22)	9.5 (29.3-42)		
	Formlabs	39.9 (5.6)	42.3 (34.2-45)		
Incisal lingual Crown #8	Carbon	64.34 (12.5)	65.5 (51.3-76)	0.077	NA
	P30	78.3 (19.7)	72.9 (63.9-95)		
	Formlabs	81.03 (17.43)	78.5(66.5-98)		
Middle lingual Crown #8†	Carbon	59.11 (11.3)	49.2 (40-56.6)	<.001	Carbon vs. Formlabs (p <.001) P30 vs. Formlabs (p=.004)
	P30	54.7 (11.04)	54.2 (44.7-59.7)		
	Formlabs	70.42 (6.99)	69.7 (67.5-72)		

Cervical Lingual Crown #8‡	Carbon	41.34 (4.3)	40.8 (37.7-50)	0.009	Carbon vs. Formlabs (p=.003) P30 vs. Formlabs (p=.031)
	P30	39.8 (8.7)	38.4 (34.9-43.4)		
	Formlabs	51.43 (17.6)	46.5 (43.5-95.8)		
Incisal Buccal Bridge #11‡	Carbon	58.44 (8.33)	59.4 (50.2-69.8)	<.001	Carbon vs. P30 (p=.013) Carbon vs. Formlabs (p <.001)
	P30	48.20 (11.34)	87.2 (81.6-98.5)		
	Formlabs	74.71 (12.2)	70.3 (65.4-97.4)		
Middle Buccal Bridge #11‡	Carbon	61.6 (7.6)	61 (55.2-73.3)	0.312	NA
	P30	57.62 (20.8)	54.8 (43.8-105.3)		
	Formlabs	61.04 (10.04)	57.8 (53.3-78)		
Cervical Buccal Bridge #11‡	Carbon	49.8 (5.92)	50.2 (45.4-60.5)	0.153	NA
	P30	56.7 (20.14)	49.9 (37.6-91)		
	Formlabs	44.96 (10.12)	42.9 (39.3-63.3)		
Incisal lingual Bridge #11 ψ	Carbon	44.24 (4.95)	43.3 (41.7-52.2)	<.001	Carbon vs. P30 (p<.001) Carbon vs. Formlabs (p=.004)
	P30	93.41 (17.8)	97.6 (76.9-124.5)		
	Formlabs	70.8 (6.06)	71.4 (65.2-79.8)		
Middle lingual Bridge #11ψ	Carbon	42.73 (5.72)	42.5 (37.3-51.5)	<.001	Carbon vs. P30 (p <.001) Carbon vs. Formlabs (p=.013)
	P30	73.2 (21.7)	70.9 (53.8-107.8)		
	Formlabs	59.44 (11.4)	62.5 (51.1-76.3)		
Cervical Lingual Bridge #11‡	Carbon	35.51 (3.62)	36.5 (33.6-38.8)	0.038	Carbon vs. P30 (p=.017) Carbon vs. Formlabs (p=.046)
	P30	59.97 (16.82)	43.2 (37.3-78.9)		
	Formlabs	32.61 (8.81)	42.4 (36.5-58)		
Incisal Buccal Bridge #13 ψ	Carbon	63 (4.84)	62.9 (61.2-69.8)	<.001	Carbon vs. P30 (p <.001) P30 vs. Formlabs (p=.019)
	P30	102.06 (23.8)	113.6 (87.5-128.3)		
	Formlabs	66.02 (1.31)	66.3 (64.7-66.8)		

Middle Buccal Bridge #13 ‡	Carbon	68.1 (20.3)	68.8 (54.5-80.8)	0.588	NA
	P30	70.6 (15.7)	71.4 (55.5-81.9)		
	Formlabs	80.4 (24.08)	72.9(67-82.3)		
Cervical Buccal Bridge #13†	Carbon	43.12 (4.02)	43.3 (39.6-46.3)	0.037	Carbon vs. Formlabs (p=.060) P30 vs. Formlab (.011)
	P30	46.3 (9.6)	45.2 (40.9-49.2		
	Formlabs	38.2 (5.2)	39 (34.9-42.6)		
Incisal lingual Bridge #13‡	Carbon	48.42 (3.6)	48.8 (45.6-50.6)	<.001	Carbon vs. P30 (p <.001) Carbon vs. Formlabs (p=.001)
	P30	86.99 (15.6)	83.3 (72.6-101)		
	Formlabs	76.81 (11.43)	72.8 (70.5-83.6)		
Middle lingual Bridge #13‡	Carbon	47.8 (11.84)	45.9 (38.6-54.7)	0.046	Carbon vs. P30 (p=.110) P30 vs. Formlabs (p=.015)
	P30	57.83 (14.18)	52.6 (45.7-71.7)		
	Formlabs	42.97 (4.7)	44.8 (37.9-46.3)		
Cervical Lingual Bridge #13‡	Carbon	44.7 (2.5)	45.2 (42.3-45.9)	0.010	Carbon vs. Formlabs (p=.007) P30 vs. Formlabs (p=010)
	P30	44.95 (7.4)	45.4 (39.6-50.5)		
	Formlabs	37.6 (6.5)	36.6 (33.9-37.7)		
Incisal Buccal Veneer #9‡	Carbon	71.6 (13.5)	73.3 (66.3-80.4)	0.128	NA
	P30	69.2 (15.06)	67.8 (55.5-79.4)		
	Formlabs	81.2 (14.82)	77 (75.2-78.5)		
Middle Buccal Veneer #9‡	Carbon	54.3 (4.31)	54.2 (51.5-57.5)	0.033	Carbon vs. P30 (p=.017) P30 vs. Formlabs (p=.035)
	P30	70.84 (21.23)	67.5 (57.1-75.2)		
	Formlabs	56.44 (11.4)	54.6 (52.8-57.3)		
Cervical Buccal Veneer #9‡	Carbon	53.92 (6.5)	50.7 (49.5-59.9)	0.092	NA
	P30	51.7 (6.5)	49.9 (41.9-60.4)		
	Formlabs	46.63 (14.85)	46.4 (40.8-49.6)		

Footnotes:
† One-way ANOVA (with Tukey's HSD in post-hoc tests)
‡ Kruskal-Wallis test (with Dunn's test and the Bonferroni correction in post-hoc tests)
ψ Welch's ANOVA (with the Games-Howell test in post-hoc tests)

VII. Discussion

Advancements in 3D printing are reducing the need for traditional dental impression methods. This simplification is making it easier for dentists to adopt digital workflows, thereby making 3D printing a more convenient option for dental procedures.[20] The objective of this in vitro study was to assess the marginal and internal adaptation of multiple zirconia milled restorations on a model created with three different 3D printers: (Carbon DLS™, P30 manufactured by Straumann, and Form 3B+ by Formlabs). The null hypothesis was that the marginal and internal adaptation of multiple milled restorations with three different 3D printers have equal accuracy.

The findings from this in-vitro study highlight significant technological disparities among three distinct 3D printing systems, namely Carbon Digital Light Synthesis™ (Carbon DLS™), Straumann P30, and Formlabs Form 3B+, which directly influence the precision and success of dental restorations. Notably, Carbon DLS™ demonstrated consistently superior performance, particularly in the incisal buccal regions, achieving the smallest mean marginal gaps compared to the other systems. For instance, in the incisal buccal region of Crown #3, Carbon DLS™ recorded a mean marginal gap of 52.3 micrometers, significantly narrower than that of Straumann P30 at 80.8 micrometers and Formlabs Form 3B+ at 71.3 micrometers. This result not only supports the hypothesis that differences exist but also underscores the potential of high-precision printers to enhance outcomes in critical aesthetic zones of dental restorations.

The similar performance of the printers in many of the less critical areas such as the middle region suggests that modern 3D printing technology can reliably meet clinical standards for these areas. However, the exceptional results achieved by Carbon DLS™ in more demanding incisal regions point to its suitability for complex restorative challenges where marginal adaptation plays a crucial role in the longevity and success of the restorations. This differentiation in performance across various crown regions emphasizes the need for dental practitioners to consider the specific capabilities of 3D printing technologies when selecting a printer for different types of dental restorations.

Furthermore, this study's results encourage a deeper investigation into the factors contributing to the superior performance of Carbon DLS™. Potential areas of exploration could include the unique printing mechanisms employed by Carbon, such as the layering techniques and resin properties, which may offer insights into achieving optimal outcomes. Such findings could propel further advancements in 3D printing technology, enhancing its application in prosthodontics.

Additionally, while the study focused on zirconia as the material of choice, the diverse responses of different dental materials to 3D printing processes also warrant further exploration. Understanding these material-specific responses could guide the development of printing settings and protocols, potentially broadening the application of 3D printing technology in dental restoration beyond zirconia.

Previous studies that have evaluated the accuracy of 3D-printed casts are limited. An in-vitro study evaluating the precision of casts generated by various 3D printing methods found that the DLP 3D printer yielded final models comparable in accuracy to those produced by traditional methods[24]. Another study concluded that Digital Light Processing (DLP) 3D printers exhibited superior capabilities in producing crowns with improved marginal and internal fit compared to Stereolithography (SLA) 3D printers[25]. In another study, it was determined that conventional gypsum stone casts exhibited greater accuracy in full arches and prepared teeth compared to digitally fabricated stone casts and 3D printed photopolymer casts[26]. Multiple studies have examined the marginal discrepancy values of crowns, revealing notable differences between conventional metal crowns and CAD-CAM crowns. Conventional metal crowns typically exhibit mean marginal discrepancies below 50 μm[27], whereas CAD-CAM crowns display higher mean discrepancies ranging from 49 to 83 μm[28]. However, there is a lack of consensus regarding the clinically accepted value for marginal fit in crown restorations. The findings of these studies suggest that an open margin of 100 μm to 120 μm is clinically acceptable[29]. Assessing the marginal fit of crowns presents challenges. While the replica technique has been validated for this purpose, it has limitations and can be sensitive to technique variations. One drawback is its reliance on a limited number of measurement points for each restoration, potentially failing to capture the full circumferential fit of a crown accurately. Nevertheless, its widespread use in prosthodontics facilitates comparisons across studies. seating of all crowns was done using firm finger pressure, a common practice in dental settings. However, this method lacks reproducibility across cases, introducing potential inaccuracies.

Furthermore, the use of a typodont within a laboratory setting, although a controlled and consistent environment, does not fully mimic the complex and dynamic conditions present in actual dental practices. This study's findings, while indicative of controlled conditions, fall short of capturing the biological factors and unique patient-specific circumstances that affect restorations in vivo. These conditions are significant determinants of a restoration's success.

The study's focus on three types of 3D printers—Carbon DLS™, Straumann P30, and Formlabs Form 3B+—although providing valuable insights, may limit the broader applicability of the results. The dental industry utilizes a wide array of 3D printing technologies, each with unique processing capabilities. Consequently, the findings here may not translate across the spectrum of available printing technologies, which could differ in their adaptation outcomes.

Another aspect that needs attention is the reliance on digital impressions and STL file processing. While these digital tools offer unprecedented precision and ease of use, they are not immune to errors. Software algorithms and hardware performance can introduce minute but significant discrepancies, which, although small, can affect the final fit of a dental restoration. Such potential deviations emphasize the need for continuous refinement of digital tools and techniques in dental practices.

The study relies on a convenient sample size derived from a previous study, which may limit the generalizability of the findings. All measurements were performed by the same operator, which could introduce bias into the results. Future studies should aim for a larger and more diverse sample size to enhance the reliability and generalizability of the findings. Conducting multicenter studies involving multiple operators and institutions could help mitigate single-operator bias and increase the external validity of the findings.

VIII. Conclusion

This study has conclusively demonstrated significant disparities in the marginal and internal adaptations of dental restorations produced using three different 3D printing technologies: Carbon Digital Light Synthesis™ (Carbon DLS™), Straumann P30, and Formlabs Form 3B+. Notably, Carbon DLS™ emerged as the superior technology, particularly excelling in the incisal buccal regions of dental crowns. This area is critically important for both aesthetic appeal and functional integrity of dental restorations, as it is highly visible and subject to significant mechanical stress. Carbon DLS™'s ability to consistently achieve the smallest marginal gaps in these regions highlights its advanced precision and reliability, making it particularly suitable for complex dental restorations that demand high accuracy.

The results of this study have important implications for dental practice, especially in the selection of 3D printing technologies. They suggest that while current 3D printing technologies can generally meet clinical standards for less critical areas of dental restorations, such as the middle and cervical regions, discerning differences in performance in more critical areas can guide practitioners in making more informed choices. Specifically, the superior performance of Carbon DLS™ in achieving excellent marginal adaptation suggests that it could significantly enhance the quality and longevity of dental restorations, thereby improving patient outcomes.

Additionally, the findings from this study encourage dental technology developers to continue refining their products, particularly focusing on enhancing precision in 3D printing technologies that may not currently meet the high standards demonstrated by Carbon DLS™. There is a clear opportunity for the development of new or improved printing techniques that could further minimize marginal discrepancies and improve internal adaptation across all areas of dental crowns.

For future research, it would be beneficial to explore the performance of these 3D printing technologies across a broader range of dental restoration materials and more varied clinical scenarios. Further studies could also investigate the long-term clinical outcomes associated with restorations produced by different 3D printers, potentially influencing both clinical practice and patient care guidelines.

In conclusion, this study not only focuses on the capabilities and limitations of current 3D printing technologies in producing dental restorations but also sets a foundation for future advancements in dental material science and prosthodontic practices. By closely aligning the choice of 3D printing technology with specific clinical needs and restoration requirements, dental practitioners can enhance the efficacy of their interventions and ultimately contribute to the evolution of dental restoration technology.

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Figure 1: Prepared Reference Cast (K-2 crown and bridge model, Kilgore) featuring preparations for a veneer on the left central incisor, single crowns on the right first molar and right central incisor, and a three-unit tooth-supported fixed dental prosthesis.

Figure 2: The 3Shape Trios Intraoral Scanner setup, featuring real-time digital impression capture for dental restoration modeling.

Figure 3: Exocad Dental CAD 3.1 Rijeka software interface, utilized for dental restoration design and modeling.

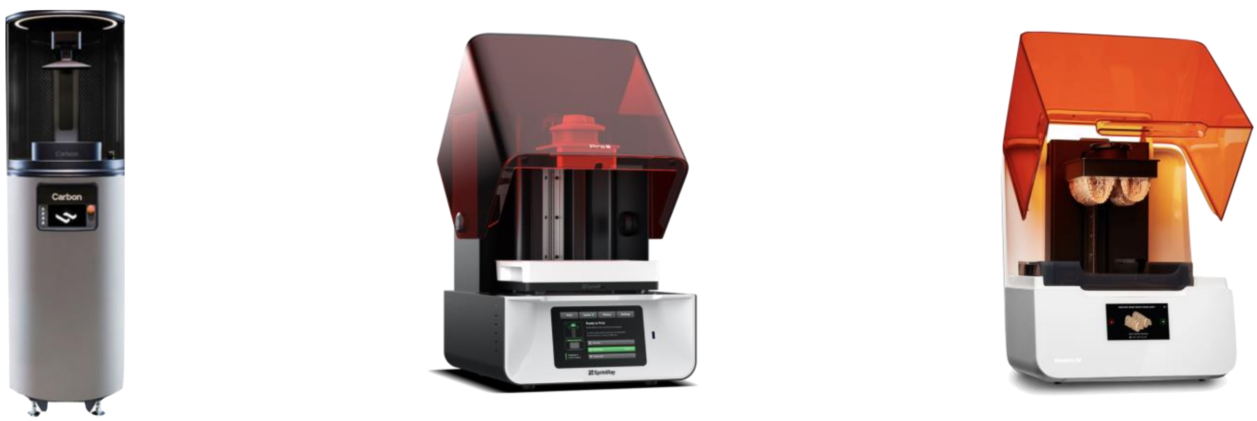

Figure 4: Three 3D printers used for dental restoration fabrication; Group A features Carbon DLS™ technology, Group B is the Straumann P30, and Group C showcases the Formlabs Form 3B+

Figure 5: 3D printed alveolar cast with removable dies, illustrating the precision of digital manufacturing in dental prosthesis creation.

Figure 6: Olympus microscope used for precision measurement at 5X magnification during evaluation.

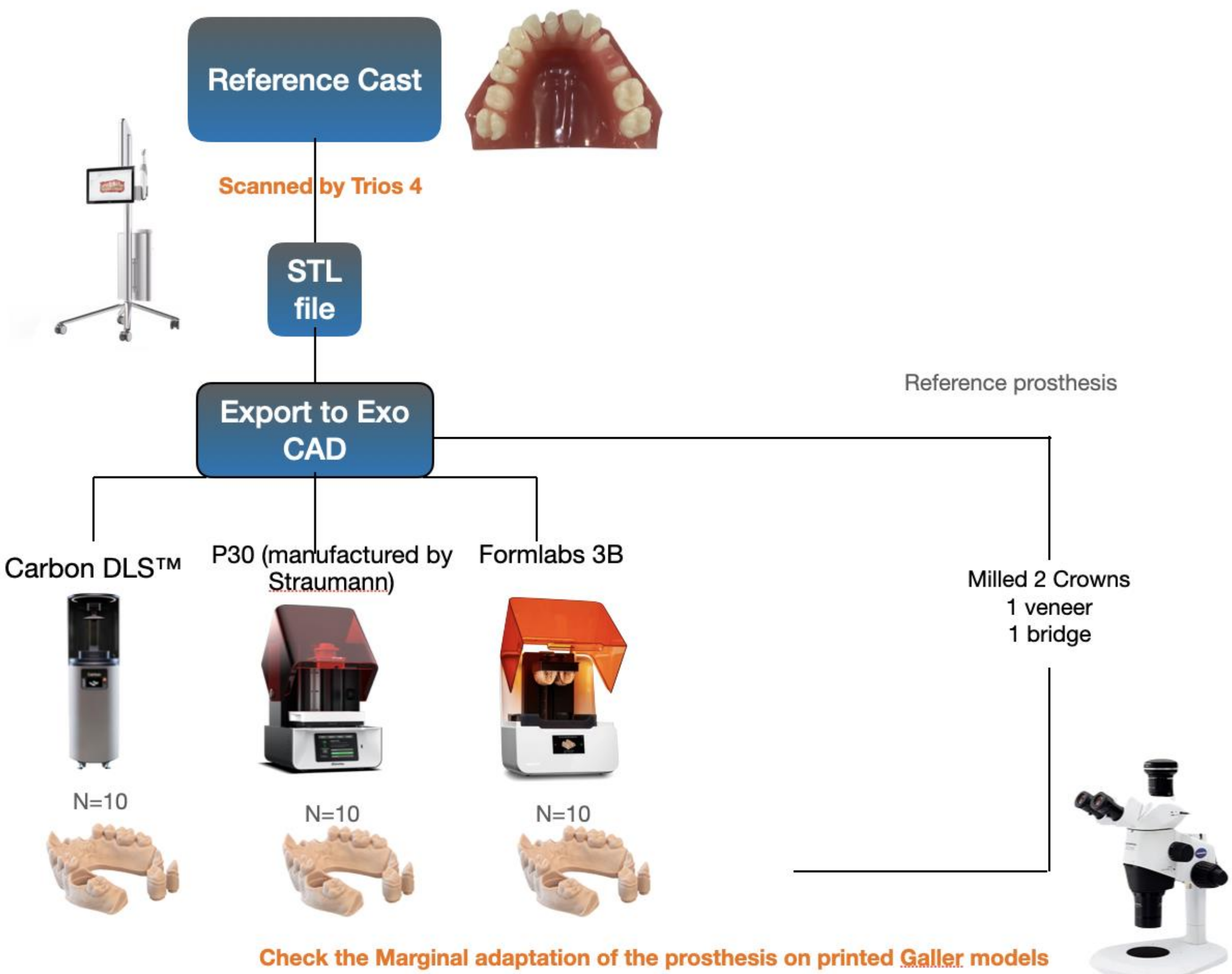

Figure 7 Overview of the study