Clinical feasibility and performance of 3D-printed vs milled: A comparative study

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마지막으로, 언제나 제 선택을 믿어 주시고 지지해 주신 부모님, 혜훈이 언니, 성훈이 우리 가족과 외할아버지, 그리고 하늘나라에서 기뻐하고 계실 외할머니, 할머니, 할아버지께도 마음 깊이 감사와 사랑을 전합니다.

처음 시작했던 열정과 여러분께 받은 사랑을 잊지 않고, 다시 나누는 사람이 되겠습니다. 이 논문을 저에게 도움을 주신 모든 분께 바칩니다.

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(Directed by Professor Jae-Sung Kwon, M.D., Ph.D.)

In recent years, interest in 3D printing technology has been increasing rapidly in the field of dental prosthetics. This study compared and evaluated the clinical suitability, aesthetics, and patient satisfaction of zirconia crowns produced using 3D printing and traditional milling methods. This study was conducted on 10 adult patients, and both 3D printing crown (AM) and milling crown (SM) were applied to each patient, and their suitability, aesthetics, and patient satisfaction were evaluated.

As a result of the study, there was no significant difference in the inner fitness, periodontal response test, aesthetics, and patient satisfaction of the crown produced by the two manufacturing methods, and it was proved that there was no statistical difference between the two methods in all clinical indicators. This means that 3D printing is clinically not different from the milling method in the production of dental prosthetics.

This study suggests that 3D printing technology can be an alternative that can be practically used clinically in the field of dental prosthetics. However, several limitations should be considered in generalizing the results of the study. The subjects of this study were all single units, and the follow-up period was 1 month per crown. In the future, long-term prognosis evaluation of prosthetics for various cases is needed. These efforts are expected to make an important contribution to technological progress in the field of prosthetics in the future.

Keywords: 3D printing, Zirconia crowns, Additive manufacturing, Subtractive manufacturing, Clinical trials, 3D Printed Zirconia

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I. INTRODUCTION

In recent years, the field of dental prosthetics has experienced rapid technological advancements, particularly with the advent and growth of 3D printing technology. This innovation has garnered significant attention due to its potential to revolutionize dental practices (Kim et al., 2021; Camargo et al., 2022). Compared to traditional Computer-Aided Design - Computer-Aided Manufacturing (CAD-CAM) milling methods, 3D printing offers numerous advantages, providing greater flexibility and material efficiency.

CAD-CAM technology, while streamlining the traditional prosthetic fabrication process by utilizing advanced oral scanning techniques, still faces limitations in terms of material wastage and time efficiency. In contrast, 3D printing builds prostheses layer by layer through the photopolymerization of liquid resin, significantly reducing material waste and allowing for the production of highly intricate structures that would be difficult or impossible to achieve with conventional milling (van Noort, 2012; Oropallo & Piegl, 2015; Srinivasan et al., 2021).

Materials used in CAD-CAM systems, such as ceramics, resin, and metals, have also evolved. Ceramic blocks, in particular, have become a material of choice for prosthetic applications due to their high strength, durability, and aesthetic qualities. Zirconia, a ceramic material known for its superior strength and biocompatibility, has gained particular attention for dental restorations (Oropallo et al., 2015). The milling process allows these materials to be precisely shaped into prosthetic forms with remarkable precision. However, one of the major drawbacks of milling is the considerable time required for shaping the blocks, coupled with the fact that this process le/6ads to significant material waste (Srinivasan et al., 2021).

As a response to the limitations of CAD-CAM milling, 3D printing has emerged as a promising alternative, particularly in shaping complex ceramic structures. This technology has been applied across a wide range of ceramic materials, such as structural ceramics, electronic ceramics, and bioceramics, to name a few. The application of 3D printing in bioceramics has drawn significant interest due to its ability to create customized, patient-specific dental restorations (Abdelkader et al., 2024). The stereolithography (SLA) method, which forms structures by layering photopolymer resin, was one of the earliest 3D printing techniques and has since paved the way for other additive manufacturing (AM) processes (Huang et al., 2020). Over the years, 3D printing has transcended its original industrial applications and established itself as a critical tool in both the dental and medical fields.

In dental applications, SLA uses lasers to precisely cure liquid resin layer by layer, while Digital Light Processing (DLP) employs a digital light source to cure an entire layer of resin at once. This results in faster production speeds without compromising the precision required for dental prostheses (Kadry et al., 2019). Fused Deposition Modeling (FDM), another prevalent 3D printing technique, utilizes thermoplastic filaments to construct objects layer by layer, offering a more cost-effective solution. FDM has found widespread use across industries due to its versatility and affordability. Each of these 3D printing technologies, distinguished by their materials and methods, plays a crucial role in the production of highly precise and complex prostheses, particularly in dental and medical fields where accuracy is paramount.

Despite these advancements, the use of 3D printing in dental applications has remained predominantly focused on resin-based materials. The 3D printing of ceramic restorations, such as zirconia crowns, has not yet been widely adopted in clinical practice (Lee et al., 2017; Jiaxiao et al., 2023). This limitation may stem from the inherent characteristics of ceramic materials, which are more difficult to manipulate, and the complexity of the polymerization process required in 3D printing ceramics (Lim et al., 2023; Kim et al., 2023).

Nonetheless, the potential benefits of 3D printing in dentistry are undeniable. In particular, advancements in gradation technology, as explored in this study, have the potential to revolutionize the field by enabling the replication of the natural color variations found in teeth. This would allow for different colors to be printed at the tooth base and incisal edges, providing an aesthetic precision that cannot be achieved with conventional single-color printing methods (Lee et al., 2021).

Existing literature indicates that zirconia crowns produced through traditional milling techniques exhibit superior mechanical properties compared to those fabricated using 3D printing methods (Revilla-Leon et al., 2021). However, recent studies have shown that 3D-printed 3 mol % yttria-stabilized tetragonal zirconia polycrystals (3Y-TZP) possess bending strengths exceeding 800 MPa, making them suitable for clinical use (Revilla-Leon et al., 2022; Osman et al, 2017). Nevertheless, 3Y-TZP materials are often criticized for their aesthetic limitations (Rues et al., 2023). To address these issues, 5Y-TZP was developed, offering improved translucency. However, this material has been reported to exhibit insufficient flexural strength and fracture toughness (Kwon et al., 2018). Positioned between these two materials is 4 mol % yttria-stabilized zirconia (4Y-TZP), which balances the strength of 3Y-TZP and the aesthetics of 5Y-TZP, making it a suitable option for the production of monolithic zirconia crowns (Kwon et al., 2018). While much research has focused on 3Y-TZP and 5Y-TZP, there is still a relative scarcity of studies investigating the clinical performance and aesthetic properties of 4Y-TZP-based prosthetics. This highlights the need for further research into the clinical applicability of 4Y-TZP in dental restorations.

Bernardo Camargo and colleagues found no significant difference in the internal fit between 3D-printed zirconia crowns and those produced using milling methods (Camargo et al., 2022). However, their study was non-clinical and focused exclusively on 3Y-TZP materials. In a separate study by Andrew B. Cameron et al., it was reported that the angle at which the crown is printed can influence the fidelity and surface roughness of the final prosthesis, suggesting that the printing angle may play a role in determining the final fit (Cameron et al., 2024). Nevertheless, like the Camargo study, this research was limited to 3Y-TZP materials, which are aesthetically limited. Furthermore, direct comparisons of ceramic-based 3D printing technologies have been largely restricted to in vitro studies (Refaie et al., 2023; Wu et al., 2021; Rues et al., 2023; Lee et al., 2017), and clinical comparisons remain scarce (Su et al., 2023). Although ceramics are widely used in dentistry due to their aesthetic appeal, biocompatibility, and durability (Derafshi et al., 2017; Su et al., 2023), systematic clinical studies are essential to fully understand the impact of ceramic manufacturing processes on the final quality and performance of prosthetic restorations.

Despite the increasing demand for customized dental prosthetics, ceramic materials present challenges for patient-specific fabrication due to their inherent properties and the limitations of conventional manufacturing processes like CAD-CAM milling. While CAD-CAM technology has streamlined prosthetic production, it often leads to substantial material waste and high costs, particularly with ceramic materials. Furthermore, most clinical research has focused on resin-based 3D printing applications, leaving the clinical performance of ceramic prostheses underexplored. Given these limitations, there is a pressing need to evaluate the clinical reliability and functionality of 3D-printed ceramic prostheses to determine their viability as a practical alternative to traditional methods. This study aims to address the existing research gap by evaluating the clinical applicability of various ceramic materials and 3D printing techniques in comparison to conventional milling

Therefore, this study aims to evaluate the clinical efficacy of AM 4Y-TZP prostheses and milled prostheses by assessing fit, clinical outcomes such as the gingiva index (GI), bleeding of probing (BOP), probing depth, plaque index (PI), and color stability. The hypotheses of this study are as follows: First, there will be no difference in marginal and internal fit between crowns fabricated using the milling method and those fabricated using the 3D printing method. Second, the method of zirconia crown fabrication will not affect color stability, periodontal response, or patient satisfaction.

II. MATERIALS AND METHODS

1. Patient recruitment

All procedures of this study were conducted in accordance with the principles of the declaration of helsinki and approved by the Seoul national university dental hospital clinical trial ethics committee (Approval No. CDE222). the study involved 10 patients who visited the dental hospital and required crown prosthetic treatment. all participants provided written informed consent prior to their participation. Inclusion criteria included adults aged 20 years and above, individuals without systemic diseases, those who signed the clinical trial consent form, and patients needing crown treatment. exclusion criteria were pregnant or breastfeeding women, patients with uncontrolled systemic diseases, individuals suspected of having psychiatric disorders, patients with temporomandibular joint disorders that could complicate opening or closing the mouth during treatment, and those deemed inappropriate for participation in the clinical trial by the investigator. the abutment teeth requiring crown treatment were prepared with a chamfer margin design. impressions were taken after gingival retraction using gingival retraction cord to manage any potential inaccuracies caused by saliva and bleeding, using honigum light impression material (Dental Material-Gesellschaft mbH). The acquired impressions were used to create study models, which were then scanned using a tabletop scanner (T500; Medit Corp, Seoul, Korea) and converted into stereolithography (STL) format. The crowns were designed using dental CAD software (Exocad Dental CAD; exocad GmbH). A spacer of 0.017 mm was applied starting from 2 mm above the margin. The crowns for the Subtractive Manufacturing (SM) group were milled from zirconia blocks (Natura M1; Dmax Corp) using a milling machine (ZX-5SD; Manix Dental). The patient information is as follows. The average age of the patients was 51.1 years, with a distribution of 6 males and 5 females. The shades of the treated teeth ranged from A2 to A3.5, and the treated tooth locations included 3 maxillary molars, 5 mandibular molars, 1 maxillary premolar, and 1 mandibular premolar (Table 1).

Table 1. Patient demographics and prosthetic details

Age	Color information	Tooth number
40	A3	36
34	A3	16
51	A3	25
31	A3	45
51	A3.5	47
67	A3	47
53	A3	46
44	A3.5	36
75	A3.5	26
65	A3.5	27

2. Specimen preparation

The AM group fabricated crowns using an in-house DLP printer. The same design data as the SM group was used for crown production (Figure1). Pre-processing was conducted using Veltz Build Processor 1.5.5 (Hephzibah Corp), arranging the geometric crown data, generating supports, and slicing with a layer thickness of 50 μm. Crowns were printed using an in-house paste, with a composition of zirconium oxide 84-90 %, hafnium oxide 1-3 %, yttrium oxide 6.5-7.5 %, aluminum oxide ≤ 0.5 %, acrylic binder 2.5-3.5 %, and other trace elements ≤ 0.5 %. by adjusting the discharge quantity of A1 and A3 shaded pastes for each layer, a natural color gradation was achieved through continuous tonal variation. Unhardened excess paste was cleaned with 90 % alcohol and dried. the debinding process to remove the binder involved a slow temperature increase to 1,000 °C, followed by gradual cooling. Sintering was then performed at 1,450 °C for 20 hours (Figure 2).

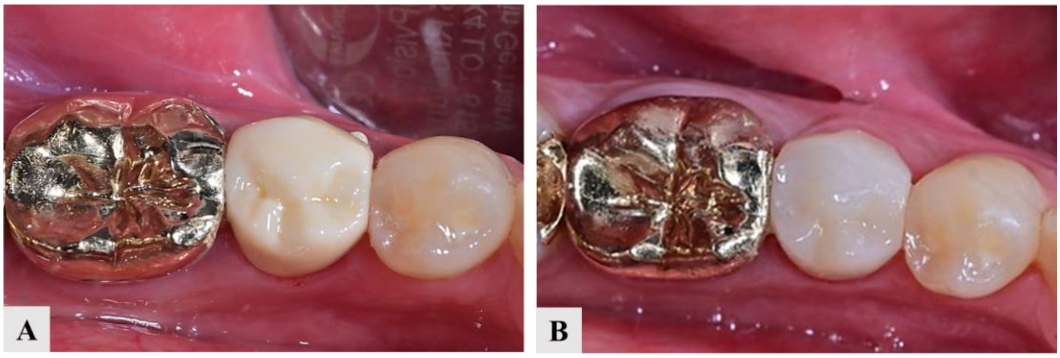

Figure 1. Zirconia crown set within the patient's intraoral space (A) Printed gradation crown (AM), (B) Milled crown (SM).

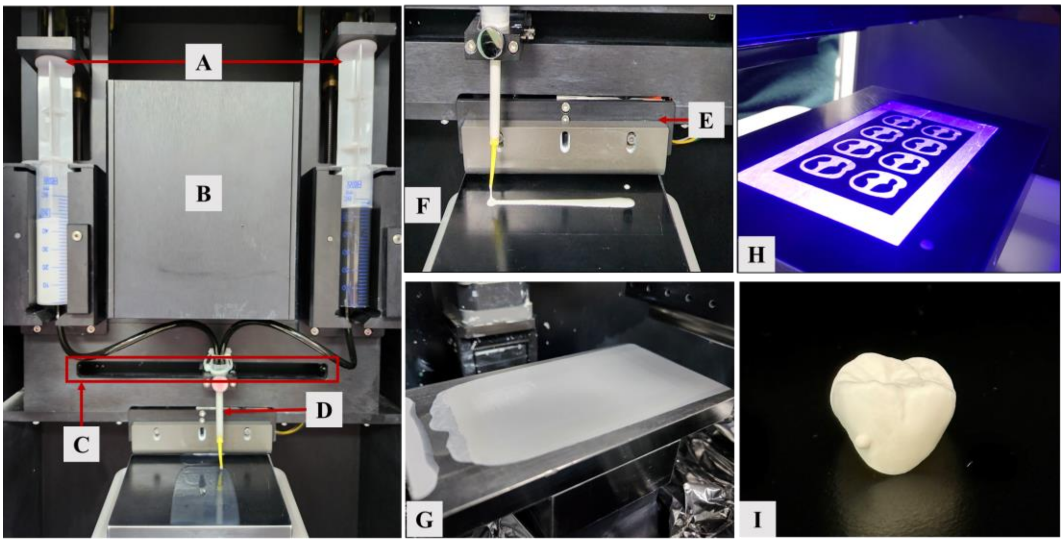

Figure 2. Customized top-down DLP 3D printer for gradation crown fabrication (A) Dual suspension extruder, (B) DLP engine, (C) Suspension supply system via stepper motor, (D) Static mixer, (E) Doctor blade, (F) Extruded prepared suspension onto the platform, (G) Slurry spreading, (H) Exposure of a layer of the prepared prosthetic model, (I) Printed gradation crown.

3. Internal fit evaluation -*invitro*

To evaluate the fit of crowns from each group, a replication technique using fit checker (Fit Checker II; GC Corp), light-body silicone (Exafine Light Body; GC Corp), and putty was employed (Figure 3). the replica specimens were sectioned into two parts—mesial-distal and buccal-lingual—to measure the thickness of the silicone film at the marginal, axial wall, line angle, and occlusal positions, resulting in 16 measurements per specimen (Figure 4). images were captured using a stereomicroscope at 30x magnification (SMZ-168; Motic) and analyzed with image analysis software (Image J; NIH).

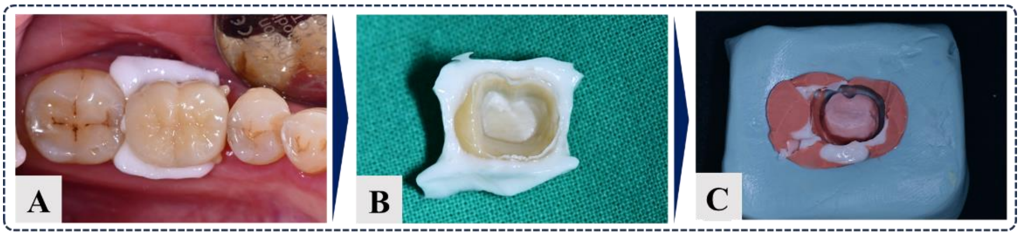

Figure 3. Replica technique method for measuring internal gaps (A) After filling the crown with Fit Checker (Fit Checker II; GC Corp), it is fitted onto the abutment tooth and allowed to cure according to the working time, (B) The hardened fit checker and crown are then removed, (C) To create a replica, light body silicone (Exafine Light Body; GC Corp) is injected to preserve the shape of the fit checker, and a support base made of heavy body silicone completes the replica.

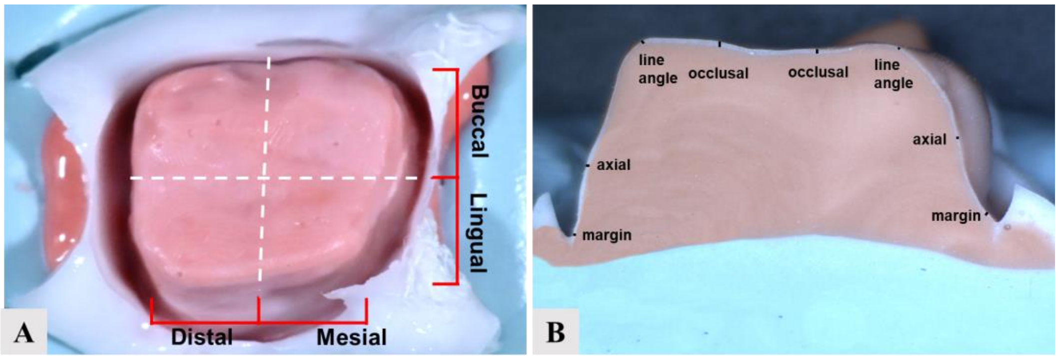

Figure 4. Specimen sectioning and measurement locations (A) Lines indicate the sections of the specimen, (B) Measurement locations within the divided sections.

4. Clinical assessment

This study used a crossover approach to compare the clinical use of crowns between two groups, with participants receiving crowns from both the additive manufacturing (AM) and subtractive milling (SM) groups. Clinical examinations, including the GI, BOP, plaque, probing depth, and color stability, were conducted at three time points: baseline (T1), 2 weeks after placement (T2), and 4 weeks after placement (T3).

The process involved first placing the AM group crown, followed by clinical evaluations at T1, T2, and T3. After the final evaluation for the AM crown at 4 weeks, it was removed and replaced with the SM group crown, with clinical evaluations conducted at the same time points.

The GI was assessed on two surfaces of the relevant tooth (mesial and lingual) using a scoring system from 0 to 3. The BOP index was evaluated based on the presence or absence of bleeding 30 seconds after periodontal probing. A modified plaque index was used with scores of 0 or 1. Probing depth was measured by inserting a probe with consistent pressure (20-30 g) parallel to the tooth's long axis, taking measurements at six points per tooth (mesial, central, and distal on both buccal and lingual sides) (Figure 5).

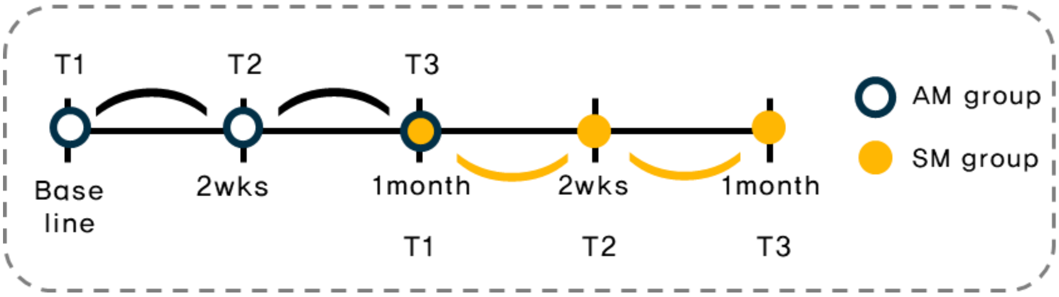

Figure 5. The timeline diagram represents the study's clinical assessment schedule. T1 represents the initial clinical assessment conducted at the time of crown placement, T2 corresponds to the follow-up clinical assessment performed 2 weeks after placement, and T3 marks the final clinical assessment and satisfaction survey conducted 4 weeks post-placement. The empty circle indicates the periodontal evaluation time point for the AM group, the orange circle represents the periodontal evaluation time point for the SM group, and overlapping circles signify the transition from the AM group to the SM group.

5. Color Stability

Color stability of the crowns was examined using a color measurement device (VITA Easyshade® V; VITA Zahnfabrik GmbH) at the buccal midline, and changes in L*, a*, b* values before and after the experiment were analyzed.

6. Participants completed a satisfaction survey

Following the 4-week application period for each group, participants completed a satisfaction survey based on their experiences. Questions 1 to 4 pertain to the functional aspects of the prosthesis, while questions 5 to 7 address its aesthetic characteristics.

7. Statistical analysis

Statistical analyses were performed using statistical software (IBM SPSS Statistics, v25; IBM Corp). The Levene test was used to evaluate the equality of variances, and the Shapiro-Wilk test was applied to assess the normality of each variable. The Wilcoxon signed-rank test was conducted to evaluate differences between two groups, while the Kruskal-Wallis test was used to analyze changes over time within each group. A significance level of 0.05 was applied, and a P-value less than 0.05 was considered statistically significant

III. RESULTS

1. Internal fit evaluation

In this study, a total of 10 participants (6 males and 4 females) were included, and 20 crowns were fabricated, with each participant receiving both an AM group crown and an SM group crown for the necessary restorative areas. To compare the fit of the two groups, the replica technique was employed. Replica specimens were measured at 8 points in the buccal-lingual section (left-margin, axial, line angle, occlusal, right-margin, axial, line angle, occlusal) and 8 points in the mesial-distal section (left-margin, axial, line angle, occlusal, right-margin, axial, line angle, occlusal), totaling measurements at 320 points. The comparison of all internal measurement points of the AM group with those of the SM group showed no statistically significant differences across all measured areas (Table 2).

Table 2. Evaluation results of internal fit of crowns using replicas

	AM	SM	*p*-value (Wilcoxon signed rank test)
	Median[Q1-Q3]	Median[Q1-Q3]	
Margin	84.50[59.50-133.00]	90.50[58.25-167.00]	0.82
Axial	107.50[60.25-154.25]	119.50[60.50-182.00]	0.22
Line angle	145.50[103.75-226.75]	155.00[77.50-259.50]	0.27
Occlusal	190.50[108.75-320.00]	256.50[164.00-346.50]	0.32

AM, Additive Manufacturing; SM, Subtractive Manufacturing; p-value<0.05

2. Clinical assessment

On the day of fitting (T1), two weeks after fitting (T2), and one month after fitting (T3), clinical evaluations were conducted for the gingival index (GI), bleeding on probing (BOP), probing depth, and plaque index (PI). At each time point, there were no statistically significant differences in any of the clinical evaluation parameters between the AM group and the SM group. Furthermore, there were no statistically significant differences in the clinical outcomes over time within each group (Table 3).

Table 3. Clinical assessment results according to time changes

		AM	SM	***p*-value (Wilcoxon signed rank test)**
		Median[Q1-Q3]	Median[Q1-Q3]	
GI	T1	0.00[0.00-0.21]	0.00[0.00-0.00]	0.11
	T2	0.00[0.00-0.04]	0.00[0.00-0.00]	0.18
	T3	0.00[0.00-0.00]	0.00[0.00-0.00]	0.32
	p-value (Kruskal-wallis)	0.20	0.37	
BOP	T1	0.17[0.17-0.5]	0.00[0.00-0.50]	0.50
	T2	0.00[0.00-0.25]	0.00[0.00-0.37]	0.66
	T3	0.00[0.00-0.25]	0.00[0.00-0.25]	0.32
	p-value (Kruskal-wallis)	0.07	0.97	
Probing	T1	2.5[2.00-2.87]	2.00[2.00-3.08]	0.72
	T2	2.00[2.00-3.08]	2.00[2.00-3.08]	1.00
	T3	2.00[2.00-3.08]	2.00[2.00-3.08]	1.00
	p-value (Kruskal-wallis)	.75	1.00	
PI	T1	0.00[0.00-0.17]	0.00[0.00-0.00]	0.26
	T2	0.00[0.00-0.00]	0.00[0.00-0.08]	0.29
	T3	0.00[0.00-0.04]	0.00[0.00-0.00]	0.57
	p-value (Kruskal-wallis)	0.5	0.32	

3. Color stability

Using the measured L*, a*, and b* values, color changes were assessed, and no statistically significant differences were observed over time (Table 4).

Table 4. Assessment of color changes (L, a*, b*) over time

		AM	**SM**
		Median[Q1-Q3]	Median[Q1-Q3]
L*	T1	71.25[66.68-79.10]	74.60[69.18-78.18]
	T2	7.25[65.20-78.60]	7.35[62.55-74.28]
	T3	7.25[65.68-81.]	69.25[64.75-73.05]
	p-value (Kruskal-wallis)	0.88	0.12
*a**	T1	3.10[2.35-5.05]	1.[.4-1.925]
	T2	3.50[2.85-3.95]	1.20[.90-1.93]
	T3	3.50[2.65-4.55]	1.15[.80-1.88]
	p-value (Kruskal-wallis)	0.87	0.60
*b**	T1	33.10[24.18-36.33]	24.70[22.53-29.58]
	T2	32.50[27.58-38.25]	25.30[21.33-3.10]
	T3	32.50[27.95-36.50]	25.40[23.55-28.13]
	p-value (Kruskal-wallis)	0.96	0.95

4. Participants completed a satisfaction survey

To assess the clinical utility of the AM group in this study, a survey was conducted. questions 1 through 4 addressed functionalities, while questions 5 through 7 focused on aesthetics. Statistical analysis revealed no significant differences between the AM group and SM group for any survey question (Table 5).

Table 5. Survey results on satisfaction with crown use by group

Item	AM group	SM group	*p*-value (Wilcoxon signed rank test)
1. No discomfort with prostheses	4.70(±0.67)	4.90(±0.32)	0.32
2. Comfortable chewing during meals after prosthesis placement	4.80(±0.42)	4.50(±1.27)	0.66
3. Food rarely gets stuck between teeth after meals	4.30(±1.16)	4.70(±0.67)	0.16
4. Don't often bite cheeks due to prosthesis	5.00(±0.00)	5.00(±0.00)	1.00
5. Prosthesis color is similar to natural teeth	3.90(±1.45)	4.70(±0.48)	0.14
6. Prosthesis shape is similar to natural teeth	4.30(±1.34)	4.50(±0.97)	1.00
7. Don't worry about smiling because of prosthesis	4.80(±0.63)	5.00(±0.00)	0.32
Total	4.54(±0.97)	4.76(±0.69)	0.07

IV. DISCUSSION

This study aimed to explore the clinical applicability of 3D-printed crowns by evaluating the fit of the final prosthesis. The results showed that the marginal fit for the AM group and the SM group was 110.81±73.25 μm and 117.34±83.97 μm, respectively, with no significant difference observed. These findings are consistent with previous studies comparing the marginal fit of milled and 3D-printed zirconia crowns (Lee et al., 2017; Rues et al., 2023; Wu et al., 2021) and fall within the clinically acceptable maximum marginal gap of 120 μm proposed by McLean et al. In contrast, in an in vitro study by Ashraf Refaie et al., the marginal fit of printed prostheses was inferior to that of milled prostheses. This discrepancy may be due to the optimization of the 3D printing process. For instance, software settings, such as print parameter configuration, can affect the internal fit of the final prosthesis. However, the marginal fit reported in that study also remained within the clinically acceptable range of 120 μm. Based on the results of this study, there was no significant difference in the marginal and internal fit between crowns fabricated by milling and 3D printing, and therefore, the first hypothesis of this study was not rejected.

Differences in prosthesis fabrication methods may manifest in periodontal tissue responses. The marginal gap, surface roughness, and surface energy may lead to plaque accumulation around the prosthesis, increasing the risk of various periodontal health issues (Lee et al., 2021). This study employed a crossover design, applying crowns from both groups to patients for four weeks each, and examined periodontal responses such as GI, BOP, probing depth, and plaque index. The results showed no significant differences between the AM and SM groups. Previous studies comparing printed and milled zirconia crowns (Lee et al., 2017; Rues et al., 2023; Refaie et al., 2023; Wu et al., 2021) were mostly conducted in vitro. In contrast, this study investigated the effect of crowns from both groups on periodontal responses in a clinical environment. The manufacturing method of zirconia crowns may affect the shape and characteristics of the surface (Refaie et al., 2023). However, in this study, the differences in fabrication methods did not affect the periodontal examination results. While previous studies on printed crowns reported that surface roughness was statistically significantly higher than that of milled crowns, this study found no difference in the plaque index between the milled and printed groups (Cho et al., 2023). This suggests that the surface roughness of the printed crowns has minimal impact on periodontal health in the oral cavity, or that the difference is not substantial enough to affect it. Periodontal outcomes may be more influenced by the patient's oral hygiene habits than by the manufacturing characteristics of the prosthesis.

The lack of difference between restorations fabricated by 3D printing and CAD-CAM in this study can be attributed to factors highlighted in previous research. Refaie et al. reported that both 3D printing and milling methods produced marginal gaps within clinically acceptable limits (Refaie et al., 2023). This suggests that both methods can create precise restorations using advanced technology. Additionally, Stefan Rues et al. found similar clinical outcomes for crowns made by both methods, indicating that both technologies provide accurate internal fit. These results suggest that the advancements in fabrication processes and materials allow for consistent and precise restorations in both 3D printing and CAD-CAM. Therefore, the lack of clinical differences observed in this study aligns with these technological advancements.

The color system recognized by the International Commission on Illumination (CIE) is based on the CIE color system, which was initially developed in 1931 by the CIE and further improved in 1976. This color system measures L*, a*, and b* values to calculate color difference (ΔE*), using this value as a standard for color stability. As the ΔE* value increases, color stability decreases. In this study, the color difference between L*, a*, and b* values measured at T1 and T3 showed ΔE = 5.3 in the AM group and ΔE = 5.2 in the SM group. Previous clinical studies identifying color showed ΔE = 5.5~6.8, similar to the results of this study (Johnston et al., 1989; Douglas et al., 2007). For dental restorative materials, ΔE* values of 3.3 or less are considered acceptable, whereas ΔE* values of 3.7 or more are regarded as noticeably problematic. This difference may be attributed to the fact that this study is a clinical trial. The large range of color difference observed in clinical trials can be explained by the potential of edge loss. In the complex intraoral environment, when using instruments to measure the color of prostheses, the sensor of the measuring device may not accurately detect the edges of the prosthesis, leading to inaccurate measurements. Especially since teeth or prostheses have geometrical shapes such as maximum convexity and ridges, the measuring tip may not fully contact the surface being measured, which can result in uncontrolled light during measurement.

While this study evaluated the color stability of zirconia crowns over a relatively short period, it provides quick insights into long-term color changes and valuable data for assessing the initial aesthetic performance of crowns. Furthermore, by emphasizing the initial color retention of zirconia crowns, this research contributes to increased reliability and patient satisfaction in clinical settings. Additionally, this is one of the first studies to clinically verify color changes in zirconia crowns.

The clinical utility of the crowns was evaluated through a satisfaction survey conducted among the study participants. Specifically, the survey comprised questions 1-4 evaluating the comfort of use of the crowns and questions 5-7 assessing aesthetic satisfaction. These items aimed to directly measure the comfort in daily life and the perception of the aesthetic attributes of the crowns. The analysis revealed no statistically significant differences between the AM group and SM group across the items. On average, the AM group showed a satisfaction score of 4.54, while the SM group scored 4.76, suggesting no significant differences in the comfort or aesthetic properties between the two manufacturing methods.

The findings of this study suggest no clinical differences between the two manufacturing technologies. However, several limitations must be considered before generalizing the results, particularly the small sample size of 10 participants, which limits statistical power and warrants cautious interpretation of the findings. Thus, further studies involving larger cohorts and longer follow-up periods are needed to more robustly support the findings of this study. Future research should also include long-term assessments of the functionality and durability of crowns, which would provide more reliable information for clinical decision-making.

V. LIMTATION

This study has several limitations that should be considered when interpreting the findings:

1. Sequence bias: The study design involved sequential placement of milling and 3D-printed zirconia crowns on the same tooth of the same patient, with each method evaluated for one month. This may have introduced a potential bias favoring the group applied first, as the patient's adaptation to the initial crown could influence the response to the subsequent crown.

2. Short observation period: The observation period for each crown type was limited to one month. This short duration may not have been sufficient to fully assess long-term outcomes such as crown durability, periodontal response, or patient satisfaction.

3. Limited sample size: The study included a small number of participants, which may reduce the generalizability of the results. Future studies should aim to recruit a larger sample size to validate these findings and increase statistical power.

Despite these limitations, this study provides valuable preliminary insights into the clinical feasibility of 3D-printed zirconia crowns compared to traditional milling methods. Future research addressing these limitations will help build upon the results presented here.

VI. CONCLUSIONS

This study compared the clinical application of zirconia crowns fabricated using additive manufacturing (AM) and subtractive manufacturing (SM) techniques:

1. Internal fit: Both AM and SM methods produced zirconia crowns with comparable internal fits, all within clinically acceptable margins.

2. Periodontal Response: No significant differences were observed in clinical periodontal parameters between crowns fabricated by the AM and SM methods.

3. Color stability: The color stability (ΔE*) of crowns from both methods showed no significant variation, demonstrating similar short-term aesthetic performance.

4. Patient satisfaction: Patient satisfaction was high for both groups, with no significant differences in comfort or aesthetic appeal.

In conclusion, zirconia crowns fabricated using the AM technique demonstrated clinical outcomes comparable to those produced by the SM method. Both techniques achieved clinically acceptable internal fit, similar periodontal responses, and short-term color stability (ΔE*) without significant differences. Patient satisfaction regarding comfort and aesthetics was equally high. Additionally, the AM technique offers greater material efficiency by minimizing waste, underscoring its potential as a viable and sustainable alternative to traditional milling for zirconia crown fabrication.

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ABSTRACT (KOREAN)

3D 프린팅 방식과 밀링 방식의

임상적 타당성 및 성능 비교 연구

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정 혜 민

최근 수년간 치과 보철 분야에서는 3D 프린팅 기술에 대한 관심이 급증하고 있다. 본 연구는 3D 프린팅과 전통적인 밀링 방식을 이용하여 제작된 지르코니아 크라운의 임상적 적합성과 심미성 및 환자 만족도를 비교 평가하였다. 이 연구는 10 명의 성인 환자를 대상으로 수행되었으며, 각 환자에게 3D 프린팅 크라운 (AM)과 밀링 크라운 (SM)을 모두 적용하고, 이에 대한 적합도, 심미성, 환자 만족도를 평가하였다.

연구 결과, 두 제작 방식으로 제작된 크라운의 내면 적합도와 치주반응 검사, 심

미성, 환자 만족도에서 유의미한 차이가 나타나지 않았으며, 모든 임상 지표에서 두 방식이 통계적으로 차이가 없음을 입증하였다. 이는 3D 프린팅이 치과 보철물 제작에 있어서 밀링 방식과 임상적으로 차이가 없다는 것을 의미한다.

본 연구는 3D 프린팅 기술이 치과 보철 분야에서 실제 임상적으로 활용 가능한 대안이 될 수 있음을 시사한다. 하지만 연구의 결과를 일반화하는 데에는 몇 가지 제한점을 고려해야한다. 본 연구의 대상은 모두 하나의 치아 (single unit)였으며, 추적 관찰 기간은 각 크라운당 1개월이었다. 향후는 다양한 증례를 대상으로 한 보철물의 장기적인 예후 평가가 필요하다. 이러한 노력은 향후 보철 분야에서의 기술 진보에 중요한 기여를 할 것으로 기대된다.

핵심되는 말: 3D 프린팅, 지르코니아 크라운, 적층 제조, 절삭 제조, 임상시험, 3D 프린트 지르코니아