Evaluation of full-veneer crowns fabricated with 3D-printable resin material for definitive prostheses : Integration of in vitro and in vivo findings

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Evaluation of full-veneer crowns fabricated with 3D-printable resin material for definitive prostheses : Integration of in vitro and in vivo findings

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This certifies that the Doctoral Dissertation
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감사의 글

본 논문을 완성하는데 있어 아낌없는 격려와 세심한 지도로 저를 이끌어 주신 김지환 지도교수님께 마음 깊이 감사드립니다. 학자로서의 냉철함과 열정뿐만 아니라 온화함과 따뜻함을 통해 교수님께 많은 부분을 배울 수 있었습니다. 완성도 높은 논문이 될 수 있도록 많은 관심을 기울여 주시고 조언을 해주신 오경철 교수님, 바쁘신 와중에도 논문 심사를 맡아 주시고 바른 방향으로 논문이 작성될 수 있도록 귀중한 조언을 해 주신 송제선 교수님, 신유석 교수님, 이현종 교수님께 깊은 감사를 드립니다. 치과의사로서 올곧게 성장할 수 있도록 늘 관심으로 지켜봐 주시고 수련 과정에서 항상 따뜻한 격려와 가르침으로 매일 매일을 밝혀 주셨던 치과보철과 교수님들께도 감사의 마음을 전하고 싶습니다. 연구와 실험에 많은 도움을 주신 강유정 선생님, 박예슬 선생님, 함께 의국 생활을 했던 보철과 동기 및 선후배 선생님들도 감사의 마음을 전합니다. 앞으로도 겸손한 자세로 탐구하며 끊임없이 정진하는 치과의사가 되도록 노력하겠습니다. 언제나 제 곁에서 지켜봐 주시며, 물심양면으로 도움을 주시는 아버지, 어머니, 장인어른, 장모님께도 사랑한다는 말씀과 함께 가슴 깊이 감사드립니다. 그리고 언제나 옆에서 저에게 힘이 되어주고, 저를 응원해주는 사랑하는 아내와 첫째 주원이, 곧 태어날 둘째와 이 기쁨을 함께 나누고 싶습니다.

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ABSTRACT

Evaluation of full-veneer crowns fabricated with 3D-printable resin material for definitive prostheses : Integration of in vitro and in vivo findings

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Despite the popularity of 3D printing methods in dentistry, the application of this technology, particularly in the prosthetic field, has been mainly limited to interim prostheses due to physical limitations such as inadequate physical properties and strength for long-term functionality. Furthermore, the impact of cement space settings on the marginal and internal fits of 3D-printed resin crowns, which are essential for the longevity and success of dental

restorations, has not been thoroughly investigated.

This randomized controlled prospective study evaluated the potential of resin crowns (RCs) as definitive prosthetics by investigating their marginal and internal fit with various cement space settings and comparing the performance of 3D-printed RCs with that of milled zirconia crowns (ZCs) in adult patients requiring single crown restorations over a 1-year period.

A two-part investigation was conducted involving in vitro and in vivo assessments. For the in vitro part, after scanning a prepared typodont left maxillary first molar, a crown was designed with cement spaces of 35, 50, 70, and 100 μm by using a CAD software program. A total of 14 specimens per group were 3D-printed from definitive 3D printing resin. By using the replica technique, the intaglio surface of the crown was duplicated, and the duplicated specimen was sectioned in the buccolingual and mesiodistal directions.

In the clinical phase, adult patients requiring posterior single crown restoration were recruited at Yonsei University Dental Hospital, excluding those with specific health conditions or habits. Fifty-six participants were randomized into two the resin crowns and zirconia crowns groups. Marginal and internal fit were evaluated using the replica technique. Clinical performance, including survival rate, clinical wear of crowns and antagonists, periodontal health, and patient satisfaction, was assessed at multiple follow-ups over 1 year. Crown wear was measured using an analysis software and intraoral scans, comparing between initial and 1-year data.

The in vitro findings indicated that although the median values of the marginal gaps were

within the clinically acceptable limit (<120 μm) for all the groups, the smallest marginal gaps were obtained with the 70 μm setting. For the axial gaps, there was no observed difference in the 35, 50, and 70 μm groups, and the 100 μm group showed the largest gap. The smallest axio-occlusal and occlusal gaps were obtained with the 70 μm setting. Clinically, from the 56 participants with 28 patients in each group (resin crowns and zirconia crowns), the resin crowns demonstrated a 78.6% survival rate compared to 92.9% for zirconia crowns after 12 months, although the comparison was not statistically significant. The last tooth restored was found to be a significant factor that influenced prosthesis survival. Resin crowns exhibited significantly higher wear compared to zirconia crowns, without significant differences in antagonist wear. Both crown types showed clinically acceptable internal fit and marginal gaps, with no significant differences in periodontal and biological responses. Patient satisfaction was similarly high in both groups.

Resin crowns demonstrate potential as a cost-effective and easier-to-manufacture alternative to zirconia crowns, with the recommendation of a 70 μm cement gap setting for optimal fit. However, the higher wear rate of resin crowns necessitates further material development to improve their longevity and performance for definitive prosthetic use.

Keywords: 3D-printed resin crowns; cement gap setting; definitive dental prosthetics; zirconia crowns

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I. INTRODUCTION

With improvements in computer-aided design and computer-aided manufacturing (CAD-CAM) techniques, dental prostheses are being increasingly manufactured using this technology.[1] CAM methods include subtractive and additive manufacturing techniques. The milling method, the most popular in dentistry,[2] requires a dedicated milling bur applied to each block when cutting a prosthesis. However, because of limitations of the milling bur and its fixed thickness, the movement of the milling bur axis limits the reproducibility of complex shapes and prevents precise machining.[3] In addition, milling generates considerable noise, requires a long time, and the debris from the blocks is not reusable.

Additive manufacturing produces less noise, is economical, and faster by eliminating the impression-making step and various drilling processes.[4] In addition, complex shapes can be easily reproduced with this technique with high precision.[5] Three-dimensional (3D) printing methods are recent developments in digital technology that have become popular in dentistry. [6-7] However, 3D printing technology in the prosthetic field has mainly been used for interim protheses due to physical limitations.[8] While efforts have been made to manufacture clinically acceptable definitive protheses using 3D printing, a key challenge lies in achieving adequate physical properties and strength for long-term functionality. The oral cavity environment subjects prosthetics to significant functional stress, which can lead to wear and fracture.[9] It is therefore important to evaluate the physical properties of 3D-printed resin for its use as definitive prosthesis. To that end, recent research has focused on overcoming the limitations of existing 3D-printed resin, which can be only used for temporary prothesis.[10-12] Advancements have been made in developing permanent resin materials that meet flexural strength requirements mandated by the International Organization for Standardization (ISO) standard 10477 for definitive prosthetics.[13] For their successful implementation and definitive use, 3D-printed prostheses must possess accurate marginal and internal fit, in addition to appropriate physical properties.[14-16] Excessive incongruity in the crown margin can increase the rate of cement dissolution, which can induce microleakage and plaque deposition associated with secondary caries, pulpitis, and pathological periodontal conditions.[17-23] Although what is considered an acceptable marginal gap size has varied,[24-28] 120 μm has been considered the clinically acceptable limit of marginal gap,[29-31] a value based on the criteria proposed by McLean and von Franhoufer.[32]

Fusayama et al[33] reported that die spacing is the most widely used method to achieve consistent spacing for luting cement. Using a uniform space reduced the marginal discrepancy of the crown and facilitated complete setting.[34-35] In digital dentistry, the cement gap setting in the CAD software plays the same role as the die spacer. One CAD software program (exocad DentalCAD 2.2, exocad GmbH, Darmstadt, Germany) allows setting the cement gap in the crown intaglio surface design process, and setting no cement gap at a desired distance from the margin. Moreover, an additional cement gap can be included in the axial and radial directions. Currently, rules for setting the optimal values are lacking. [36]

The direct-view, cross-sectioning, and replica techniques have been used for measuring marginal adaptation.[37-39] Laurent et al[40] reported that predictable measurement of the thickness of the cement film layer is possible with the replica technique, regardless of the region of the intaglio surface of the crown (marginal, axial, or occlusal), if an appropriate silicone material is used.

Depending on the manufacturing method (subtractive or additive) and the type of material, the cement space setting impacts the marginal and internal fits differently.[41-45]

Although increasing the cement space can benefit the marginal fit of the restoration,[46-47] an internal space greater than 120 μm can increase the risk of fracture of ceramic restorations.[48] Research on the cement space setting value of prostheses made of 3D-printing-type resin material is lacking. In addition, to the best of our knowledge, in vivo studies on 3D-printed definitive resin crowns (RCs) have not been published. This dissertation is organized into two parts: an in vitro study and an in vivo clinical study. The in vitro part aimed to evaluate how cement gap settings affect the marginal and internal fits of 3D-printed definitive RCs. The in vivo part aimed to compare 3D-printed RCs with zirconia crowns (ZCs) by investigating marginal and internal fit, survival rate, clinical wear of both the crown and antagonist, and patient satisfaction after 1 year. This study would provide a scientific and clinical basis for 3D-printed definitive RCs through a prospective, randomized, non-inferiority, clinical approach. The null hypothesis was that there would be no difference in the marginal and internal gaps of 3D-printed RCs fabricated using the various cement gap settings in the CAD-CAM software system used and there is no difference in survival rate, marginal and internal fit, clinical wear of crowns and antagonists, and patient satisfaction between the 3D-printed RCs and ZCs.

II. MATERIALS AND METHODS

1. In vitro experiments

1.1. Specimen preparation

A typodont tooth (ANA-4 ZP, frasaco GmbH, Tettnang, Germany) was prepared by an operator with more than 20 years of experience in tooth preparation. The prepared tooth was scanned by a dental laboratory scanner (T500, Medit, Seoul, Korea), and a CAD software program (Rhinoceros 5.0, Robert McNeel & Associates, Washington DC, USA) was used to design a die for a replica (Figure 1). The designed die was printed by a metal 3D printer (rainbow Metal Printer, Dentium Co, Seoul, Korea) and 3D printing materials (Ti64 Grade 23, GE Additive, Lichtenfels, Germany) from the standard tessellation language (STL) file (Figure 2).

The printed metal die was sprayed with a powder (Easy scan, Dmax, Daegu, Korea) to prepare the surface and was scanned with an intraoral scanner (TRIOS3, 3Shape A/S, Copenhagen, Denmark). Subsequently, the STL file of the metal die was imported into a CAD software program (exocad DentalCAD 2.2, exocad GmbH, Darmstadt, Germany) to design 3D-printed definitive resin crowns.

The thickness of all crowns was set at approximately 1.0 mm, and the cement space was set at 35, 50, 70, and 100 μm. An experienced operator designed the crowns, and the design was imported into a 3D printer (UNIZ Maker, UniZ Technology, San Diego, CA, USA). Fourteen crowns were arranged on the platform of the 3D printer, and a support was attached perpendicular to the occlusal plane. All crowns were printed with 100 μm layer thickness with a liquid definitive 3D-printing resin (TC-80DP, Graphy Inc, Seoul, Korea) with a DLP-type 3D printer (Sprint Ray Pro 95, SprintRay, Los Angeles, CA, USA). After fabrication, each crown was rinsed with 95% isopropyl alcohol for 5 minutes in an ultrasonic cleaner (Shinhan 200H 3 L, Shinhan-sonic, Incheon, Korea). Subsequently, the outer and intaglio surfaces were post-polymerized for 30 minutes with a polymerizing unit (Cure-M 102H, Sona Global Co Ltd, Seoul, Korea) (Figure 3).

Figure 1. Schematic representation of the prepared tooth and measurements.

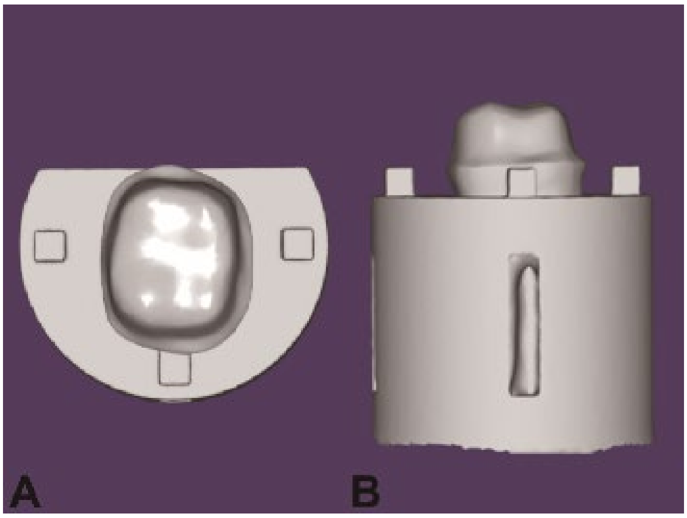

Figure 2. Rendering of scanned prepared tooth using computer-aided design software program. A, Occlusal view. B, Buccal view.

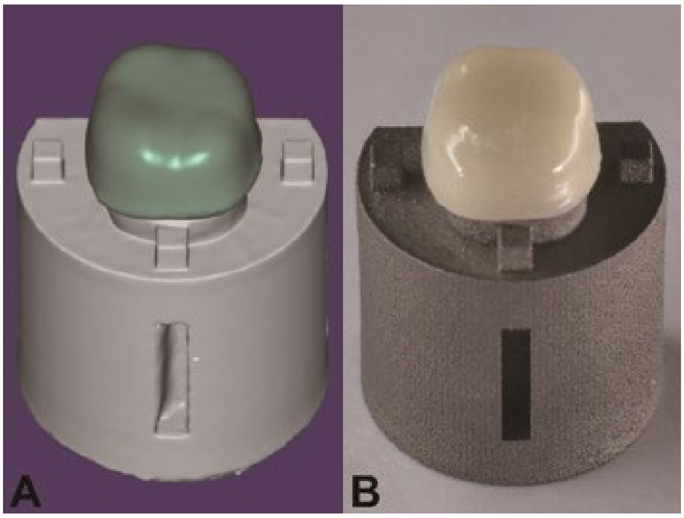

Figure 3. Fabrication of 3D-printed resin crown. A, Virtual crown design. B, 3D-printed resin crown with metal die.

1.2. Measurement the marginal and internal fit

After drying the intaglio surface of the crown, a white silicone impression material (FIT CHECKER, GC America Inc, Tokyo, Japan) was inserted to which an operator applied constant pressure for 2 minutes until the silicone completely polymerized. After which, the crown was carefully separated from the metal die, and the silicone film was examined to ensure complete attachment to the intaglio surface. This step was repeated if tearing or air bubbles were present. The silicone film-lined intaglio surface of the crown was filled with a low viscosity silicone impression material (Aquasil Ultra XLV, Dentsply Sirona, Konstanz, Germany) and the lower part was reinforced with putty (Aquasil Putty, Dentsply Sirona, Konstanz, Germany). Reinforcement with a light body and putty silicone enabled accurate sectioning, and yielded a film that can be used to evaluate internal fit.[40] After polymerization of the light body and putty, the crown was removed.

This process was repeated twice to obtain 2 casts. After segmenting with a sharp scalpel blade (Stainless Sterile blade #11, Paragon, Sheffield, England) at the center for the buccolingual and mesiodistal directions, measurements were obtained at 7 points on each plane, resulting in 14 reference points per crown. The schematic illustration of the replica specimens is presented in Figure 4. To standardize the location of the measuring spots on the whole sample, the marginal gap was measured at a position approximately

100 μm apart from the margin, the axial gap was measured at the center of the axial plane, the axio-occlusal gap was measured at the line angle where the axial plane and the occlusal plane meet, and the occlusal gap was measured at the center of the occlusal plane. A microscope with a ×0.5 lens at ×10 magnification (SMZ-171, Motic, Kowloon, Hong Kong) was used to measure the thickness of the silicone film at 3 points for the marginal, axial, and axio-occlusal planes and the occlusal areas. A cross-section of the replica was made using the Motic Live Imaging Module with a software program (Motic Images Plus 3.0 ML, Motic, Kowloon, Hong Kong) provided by the microscope manufacturer, and the measurement was performed using the “Measure” tool menu in the program. Overall, 42 measurements were obtained for each replica (12 marginal points, 12 axial points, 12 axio-occlusal points, and 6 occlusal points). Each point was measured by one experimenter and the average values of 3 measurements made at each point was recorded (Figure 5).

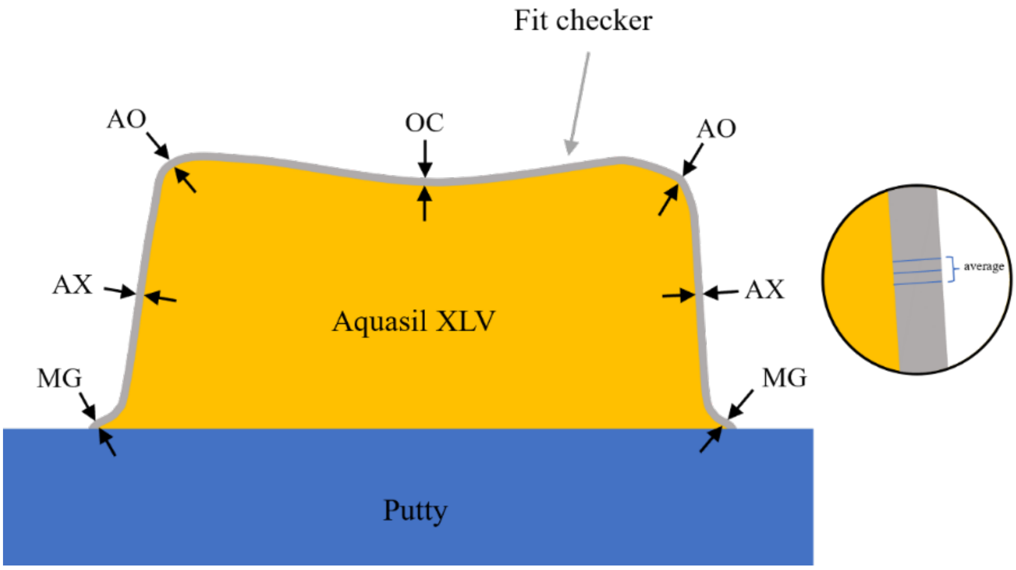

Figure 4. Representative sectional view of simulated cement space with replica technique

AO: Axio-occlusal gap; AX: Axial gap; MG: Marginal gap; OC: Occlusal gap.

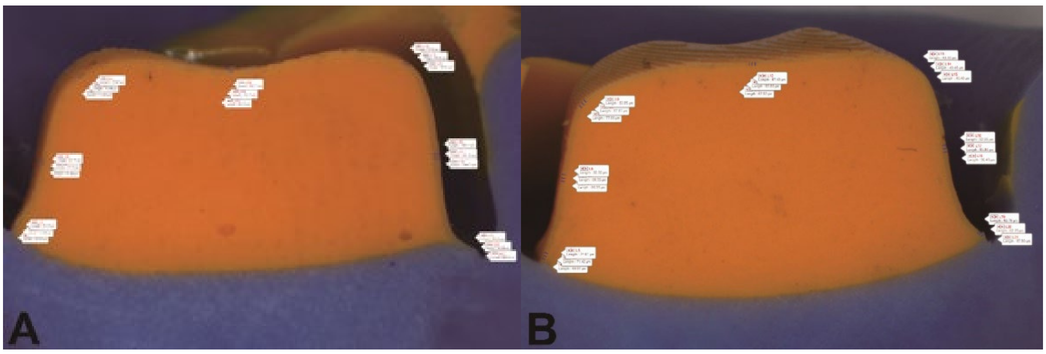

Figure 5. Cross-sectional view of replica specimens with 70 μm cement gap settings. A, Buccolingual section. B, Mesiodistal section.

1.3. Statistical Analysis

All data were analyzed with a statistical software program (IBM SPSS Statistics, v23.0, IBM Corp, Armonk, NY, US). Mean and standard deviation values were calculated from the data measured from the replica specimen. The Shapiro–Wilk test was used to analyze normal distributions. Since it represented content of partial normality, the data of the internal gap in each reference point according to the cement gap setting were conducted using nonparametric analysis with the Kruskal-Wallis test. The Mann–Whitney U post hoc test was used to determine differences between groups (α=.05).

2. In vivo clinical study

2.1. Participants of the clinical study

The study included consenting adult patients requiring posterior single crown restoration under the treatment of the Department of Prosthodontics at Yonsei University Dental Hospital. Exclusion criteria included para-functional habits (e.g., grinding), temporomandibular and other occlusal disorders, inability to read the consent form, uncontrolled systemic disease, active tooth lesions/symptoms requiring repair, allergy to zirconia or resin materials, and any ethical concerns or potential influence on the study results. Written informed consent was obtained from all participants prior to enrollment.

The target number of participants was 30 per group for a total of 60 participants. After obtaining informed consent, participants were randomly assigned to a crown type using a sealed envelope randomization procedure. A double-blinded approach ensured that the participants were unaware of their group assignment. The experimental group received 3D-printed definitive RCs, whereas the control group received milled ZCs. The experimental flow chart of the in vivo study is presented in Figure 6.

The study protocol was reviewed and approved by the Institutional Review Boards of Yonsei University Dental Hospital, Seoul, Korea (IRB no. 2-2020-0048).

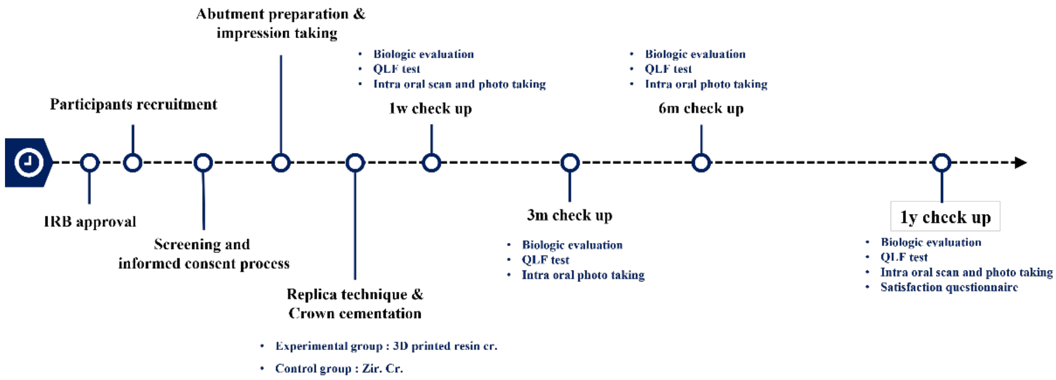

Figure 6. Experimental flow chart of in vivo study design.

2.2. 3D-printed resin crown and milled zirconia crown fabrication

At the initial visit, teeth were prepared, and final impressions were captured using impression material (Monophase Polyether Impression Material, 3M ESPE, St. Paul, MN, US). These impressions were then poured with plaster in the laboratory, creating working models for the study. These stone models were subsequently scanned by a scanner (Identica Hybrid, Medit, Seoul, Korea), and crown designs were produced using the dental design software (exocad DentalCAD 2.2, exocad GmbH, Darmstadt, Germany). Cement gaps of 70 μm and 30 μm were set for RCs and ZCs, respectively.[49]

In the RC group, liquid definitive 3D printing resin (TC-80DP, Graphy Inc, Seoul, Korea) was used to produce 100 μm thick layers of RCs using a DLP-type 3D printer (Sprint Ray Pro 95, SprintRay, Los Angeles, CA, USA). The material comprised of urethane dimethacrylate-based dental resin, phosphine oxides, and pigment. Printed crowns were cleaned using 95% isopropyl alcohol for 5 minutes in an ultrasonic cleaner (Shinhan 200H 3 L, Shinhan-sonic, Incheon, Korea) and post-cured for 30 minutes using a post-curing machine (Cure-M 102H, Sona Global Co Ltd, Seoul, Korea).

In the ZC group, zirconia blocks (Katana Zirconia STML; Kuraray Noritake Dental Inc, Tokyo, Japan) were used to produce ZCs using a milling machine (DWX-51D, Roland DGA Corp., Irvine, CA, USA). The sintering process was completed in a Wieland cube furnace. Crowns were then stained and glazed using IPS e-max stain.

(Crystall/Glaze, Ivoclar Vivadent AG, Schaan, Liechtenstein; and Programat CS, Ivoclar Vivadent AG, Schaan, Liechtenstein) before placement.

2.3. Measurement the marginal and internal fit

At the second visit, a randomly assigned crown was installed prior to cementation, which was done to measure the marginal and internal fit of RCs and ZCs using the replica technique. The replica technique procedure was identical to that of the in vitro experiment. The average values of three measurements at each point was recorded. Once the die has been manufactured using the replica technique, RCs were fixed to the tooth with resin cement (Rely X U200, 3M ESPE, St Paul, MN, US) and ZCs were fixed to the th, 3M ESPE, St Paul, MN, US). Intraoral clinical photo with the prostheses fixed is shown in Figure 7.

Figure 7. Intraoral photo of the prostheses. (A) RC of maxillary right first molar. (B) ZC of maxillary left first molar

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

2.4. Follow up evaluation

At the third visit, the prostheses and surrounding teeth were scanned using an intraoral scanner (TRIOS 3, 3Shape A/S, Copenhagen, Denmark) to evaluate clinical wear. Additionally, for biological evaluation, the Quigley-Hein Plaque Index, gingival index, probing depth, and bleeding on probing were evaluated. A fluorescence images were obtained using an intraoral capture-type QLF device (Q-ray penC, AIOBIO, Seoul, Korea) to evaluate plaque deposits and cracks on the crown.

The fourth and fifth visits were regular checkups every 3 and 6 months, respectively. These visits included the same biological evaluation and fluorescence tests performed during the initial one-week follow-up.

At the sixth visit, which was 1 year later, biological evaluation and fluorescence tests were performed. In addition, an intraoral scan was performed to evaluate wear and compare findings with baseline results. Participants were also instructed to complete a satisfaction questionnaire on masticatory ability and crown esthetics.

2.5. Evaluation of the degree of clinical wear

The degree of clinical wear was evaluated using an analysis software (GOM Inspect) by comparing the intraoral scan files obtained at crown installment and 1 year later. (Figure 8) Superimposition was based on the non-occluding buccal and lingual surfaces of the prostheses, which were unaffected by wear. The wear after one year of function was evaluated by vertical height and volume by isolating only the occlusal surface area. Vertical height was measured as the average height difference of the superimposed intraoral scans in the occlusal surface area, and volume was measured by multiplying the ver by the area. Similarly, antagonist wear was analyzed using clinical photographs and scan data to identify occlusion patterns and separate the contact area. Clinical performance was assessed using the modified California Dental Association (CDA) criteria to analyze the survival rates of the crowns.

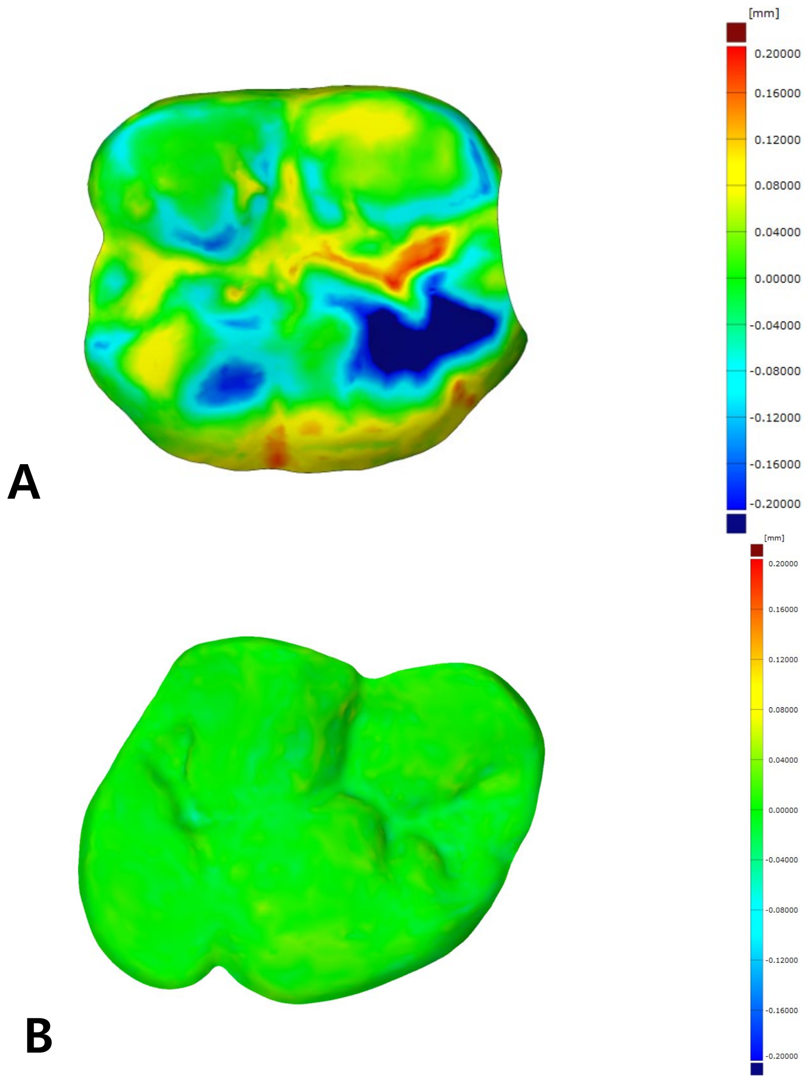

Figure 8. Evaluation of clinical wear by comparing the intraoral scan files using an analysis software (GOM Inspect) (A) RC. (B) ZC

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

2.6. Statistical Analysis

Means and standard deviation values were calculated from the measured data, and the Shapiro–Wilk/Kolmogorov-Smirnov test was performed to evaluate normality. Survival rates between prostheses were analyzed using log-rank (Mantel–Cox). For internal fit data, non-parametric Mann-Whitney U tests were used for analysis at each reference point according to the cement gap setting. For clinical wear data of crowns and antagonists after 1 year, the Mann-Whitney U test and t-tests were utilized due to the partial normality of the data. For questionnaire responses, the Mann-Whitney U test was performed for each item of the questionnaire. All statistical analyses were conducted using a statistical software (SPSS Ver. 23.0, SPSS Inc, IBM Corp, Armonk, NY, US), and statistical significance was set at $\alpha=0.05$.

III. RESULTS

1. In vitro findings

The result of the Kruskal–Wallis test indicated that the cement space values significantly affected the marginal, axial, axial-occlusal, and occlusal gaps ($P<.05$). The median and interquartile range for marginal, axial, axio-occlusal, and occlusal gaps for all 14 crowns with cement space at 35, 50, 70, and 100 μm are shown in Figure 7. The 70 μm cement space group with the smallest marginal gap (81.0 ±35.7 μm) was significantly different compared with the other groups (P=.002). The 100 μm group with the largest axial gap (127.1 ±63.1 μm) was significantly different compared with the other groups (P<.001). The 70 μm group with the smallest axio-occlusal gap (78.0 ±27.6 μm) was significantly different compared with the other groups (P<.001). The 70 μm group had the smallest occlusal gap (103.5 ±41.7 μm), which was not significantly different from that of the 100 μm group (P=.084); the 35 and 50 μm groups showed a significantly larger occlusal gap from that observed in the 70 μm group (P<.001 and P=.002).

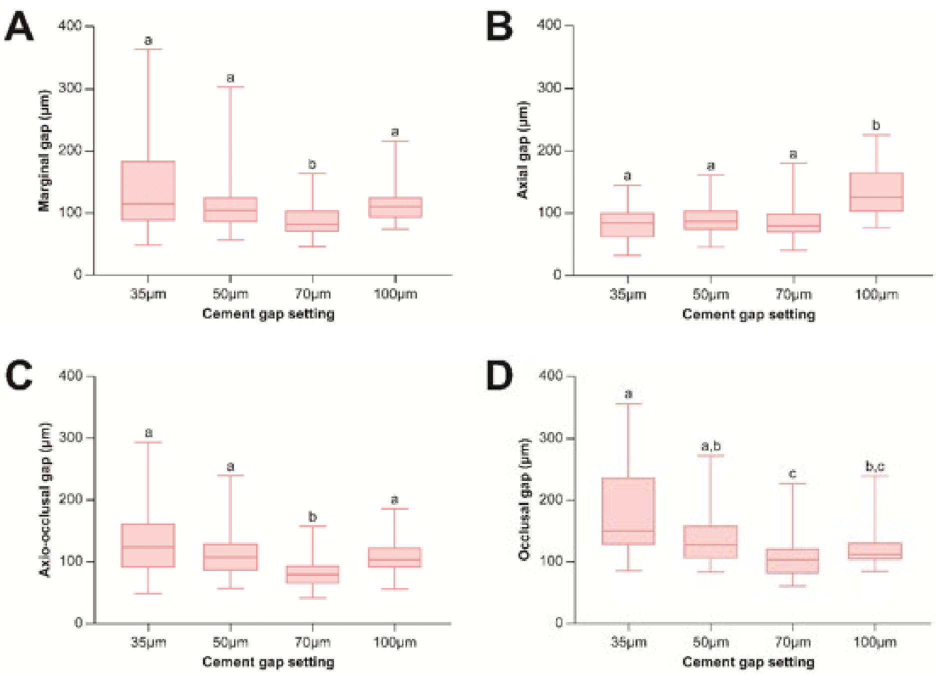

Figure 9. Median values of margin, axial, axio-occlusal, and occlusal gaps in 4 different cement space settings (35, 50, 70, and 100 μm). A, Marginal gap; B, Axial gap; C, Axio-occlusal gap; D, Occlusal gap. Different subscript letters indicate significant difference between groups according to Mann–Whitney U test (P<.05).

2. In vivo clinical findings

Between February 2021 and March 2022, 61 adult patients requiring single crown restoration for their premolar or molar teeth were screened by the Department of Prosthodontics at Yonsei University Dental Hospital, Republic of Korea. Five patients were excluded due to the inclusion/exclusion criteria or declining participation. Thus, only 56 patients were enrolled, with 28 patients receiving RCs (eight premolars and 20 molars) and 28 patients receiving ZCs (seven premolars and 21 molars). Occlusal pressure measurements using the indicated film (Dental Prescale II; GC Corporation, Tokyo, Japan) demonstrated no significant differences between the two groups. Characteristics of the included patients and teeth are summarized in Table 1. The follow-up period for this study was 12 months, and no patients were lost during this period. Regarding restoration survival, six failures in the RC group and two failures in the ZC group were observed due to restoration fractures. The 1-year survival rate of the RC group was 78.6% and that of the ZC group was 92.9%, although the difference was not statistically significant. Prosthesis survival rate and failure time at the 1-year follow-up period are presented in Tables 2 and 3. Interestingly, seven of the eight restoration fractures occurred in the last restored tooth. An overall significant difference in fracture rate was observed based on whether the tooth was the last to be restored. On group comparisons, this significant difference was shown in the RC group, while no significant difference was observed in the ZC group (Table 4).

While no significant differences were observed in the marginal and axial gap regions, the RC group exhibited a smaller internal gap in the axial and occlusal regions (Table 5). Clinical wear of prostheses and antagonists were for survival analysis are presented in Table 6. On comparison, the RC group (n=22) demonstrated significantly higher wear (approximately 6.5x in height and 9x in volume) compared to the ZC group (n=26). No significant differences were noted in the wear for matched antagonists (Table 7).

No significant differences were noted in periodontal health and biological parameters between the two groups (Table 8). Cracks and fractures were evaluated with the fluorescence test using QLF device. RCs exhibited weak cracks on the occlusal surfaces, with evident plaques on the tooth surface. Conversely, ZCs displayed smooth smooth surfaces with no fractures or cracks. Patient satisfaction was surveyed with eight questions on prosthetics (scored 1-5), showing slightly higher scores for ZCs compared to RCs, although the difference was not statistically significant (Table 9).

Table 1. Decriptive analysis of the included patients and their teeth.

		RC	ZC	All Data
Patient's Age	Years	56.8 ±16.8	53.0 ±13.7	54.9 ±15.3
Gender	Female	14	14	28
	Male	14	14	28
Arch Location	Upper	18	15	33
	Lower	10	13	23
Type of tooth	Premolar	8	7	15
	Molar	20	21	41
Occlusal pressure	MPa	30.84 ±4.44*	30.54 ±5.79*	30.69 ±5.10

"*" represent no significant difference between the groups ($p > 0.05$)

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

Table 2. Comparison of 1-year survival rates between prostheses.

	RC	ZC	Total	*p*-value
Survival	22 (78.6%)	26 (92.9%)	48 (85.7%)	.124
Fail (fracture)	6 (21.4%)	2 (7.1%)	8 (14.3%)	
Total	28 (100.0%)	28 (100.0%)	56 (100.0%)	

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

Table 3. Comparison of failure time between prostheses during the 1-year follow-up duration.

	No. of failure case	Reason of failure	Tooth No.	Failure time after placement	Management
RC	6	fracture	#47	1 months	Remaking and placement the zirconia crown in the usual way
			#27	4 months	
			#14	5 months	
			#47	6 months	
			#26	7 months	
			#27	12 months	
ZC	2	fracture	#47	7 months	
			#47	10 months	

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

Table 4. Correlation between restoration fracture and "last tooth restored" status.

Total	Last molar		Total	*p*-value
	absence	presence		
Survival	36 (97.3%)	12 (63.2%)	48 (85.7%)	.001
Fail (fracture)	1 (2.7%)	7 (36.8%)	8 (14.3%)	
Total	37 (100.0%)	19(100.0%)	56 (100.0%)	

RC	Last molar		Total	*p*-value
	absence	presence		
Survival	18 (94.7%)	4 (44.4%)	22 (78.6%)	.002
Fail (fracture)	1 (5.3%)	5 (55.6%)	6 (21.4%)	
Total	19 (100.0%)	9 (100.0%)	28 (100.0%)	

ZC	Last molar		Total	*p*-value
	absence	presence		
Survival	17 (100.0%)	9 (81.8%)	26 (92.9%)	.068
Fail (fracture)	0 (0.0%)	2 (18.2%)	2 (7.1%)	
Total	17 (100.0%)	11(100.0%)	28 (100.0%)	

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

Table 5. Comparison of marginal and internal fit between prostheses.

	RC (μm)	ZC (μm)	*p*-value
Marginal	70.09±36.52	72.92±33.11	.167
Axial	89.28±40.50	80.35±33.75	.082
Axial-occlusal	92.37±43.68	122.16±55.23	.000
Occlusal	116.71±63.09	178.79±58.83	.000

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

Table 6. Comparison of 1-year clinical wear between prostheses.

i) total

	RC	ZC	*p*-value
Vertical height of wear (mm)	0.092 ±0.070	0.014 ±0.008	.000
Volume of wear (mm^3)	4.311 ±3.683	0.472 ±0.309	.000

ii) premolar

	RC	ZC	*p*-value
Vertical height of wear (mm)	0.077±0.069	0.016±0.012	.005
Volume of wear (mm^3)	2.521±3.547	0.307±0.246	.005

iii) molar

	RC	ZC	*p*-value
Vertical height of wear (mm)	0.101±0.072	0.014±0.007	.000
Volume of wear (mm^3)	5.275±3.509	0.520±0.315	.000

iv) last molar

	RC	ZC	*p*-value
Vertical height of wear (mm)	0.141±0.103	0.014±0.005	.091
Volume of wear (mm^3)	6.575±4.234	0.495±0.161	.064

		premolar	molar	*p*-value
Vertical height of wear (mm)	RC	0.077±0.069	0.101±0.072	.310
	ZC	0.016±0.012	0.014±0.007	.937
Volume of wear (mm^3)	RC	2.521±3.547	5.275±3.509	.021
	ZC	0.307±0.246	0.520±0.315	.864

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

Table 7. Comparison of 1-year antagonist wear between prostheses.

i) total

	RC	ZC	*p*-value
Vertical height of wear (mm)	0.025±0.017	0.033±0.022	.488
Volume of wear (mm^3)	0.814±0.533	1.240±1.159	.624

ii) premolar

	RC	ZC	*p*-value
Vertical height of wear (mm)	0.030±0.023	0.020±0.009	.463
Volume of wear (mm^3)	0.633±0.580	0.471±0.173	.605

iii) molar

	RC	ZC	*p*-value
Vertical height of wear (mm)	0.023±0.013	0.036±0.024	.323
Volume of wear (mm^3)	0.919±0.498	1.445±1.227	.648

		premolar	molar	*p*-value
Vertical height of wear (mm)	RC	0.030±0.023	0.023±0.013	.464
	ZC	0.020±0.009	0.036±0.024	.159
Volume of wear (mm^3)	RC	0.633±0.580	0.919±0.498	.496
	ZC	0.471±0.173	1.445±1.227	.056

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

Table 8. Comparison of 1-year periodontal health and biological evaluation between prostheses.

i) Quigley Hein Plaque Index

	1w	1y	*p*-value
RC	0.48±0.59	0.52±0.59	.705
ZC	0.32±0.62	0.32±0.45	.763
p-value	.137	.304	

ii) Gingival index

	1w	1y	*p*-value
RC	0.35±0.57	0.48±0.67	.405
ZC	0.36±0.83	0.44±0.84	.608
p-value	.505	.482	

iii) Probing depth

	1w	1y	*p*-value
RC	2.54±0.66	2.78±0.60	.110
ZC	2.33±0.68	2.71±1.05	.006
p-value	.197	.230	

iv) BOP

	1w	1y	*p*-value
RC	1.48±1.73	1.78±1.62	.559
ZC	1.12±1.11	1.36±1.37	.364
p-value	.769	.516	

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

Table 9. Comparison of 1-year patient satisfaction responses between prostheses.

	RC	ZC	*p*-value
Anatomical form	4.45±0.80	4.52±0.71	.861
Color	4.36±0.95	4.56±0.65	.680
Height	4.45±0.74	4.60±0.71	.408
Chewing ability	4.45±0.80	4.56±0.71	.500
Pronunciation	4.55±0.67	4.52±0.83	.736
Discomfort	4.23±1.07	4.44±0.87	.428
Life satisfaction	4.41±0.67	4.52±0.66	.523
Overall satisfaction	4.27±0.77	4.60±0.58	.131

Abbreviations: RC, 3D-printed resin crown; ZC, zirconia crown.

IV. DISCUSSION

The in vitro part of this study evaluated the effect of cement gap settings on marginal fit and internal gap of 3D-printed definitive resin crowns. The 70 μm cement gap setting group had a significantly better fit in the marginal, axio-occlusal, and occlusal areas. Therefore, the null hypothesis was rejected.

The occlusal gap was generally larger than the marginal and axial wall gaps. However, even with a large gap, the occlusal area can be completely filled with cement during crown seating. However, the retention may decrease if the gap is large, and microleakage and cement washout may occur at the margin and axial wall.[23] In the 35 and 50 μm groups, interference at the axial wall is expected, likely inhibiting complete seating and increasing the marginal gap.

Previous studies that evaluated the marginal and internal gaps of 3D-printed resin crowns based on the cement space setting are sparse.[36] Therefore, a direct comparison of the results of the present with previous studies is not feasible. Nevertheless, the findings can be compared with the results of previous studies on different cement space settings for crowns of other materials. Grajower and Lewinsteine[41] determined that the optimal cement space was 50 μm: 30 μm for the cement material and a decrease in friction due to surface roughness and 20 μm to provide for potential distortion in the manufacturing process. Kale et al[42] examined the effect of the cement gap setting value on the marginal gap of zirconia crowns and concluded that the marginal discrepancy decreased when the cement space is increased from 30 to 50 µm. Nakamura et al[43] measured the marginal gap of CEREC 3 standardized crowns according to 3 different cement space settings and reported that, with the luting space set at 10 µm, the mean value of the marginal gap is significantly larger than that with the luting space set at 30 µm or 50 µm. Sultan et al[44] concluded that the smallest mean marginal gap of resin-ceramic implant prostheses was when the luting space was set at 60 µm. According to Özçelik et al,[45] the marginal gap is smallest for polymethyl methacrylate interim CAD-CAM crowns when the digital cement gap value is set at 20 µm at the margins and 60 µm at the other intaglio surfaces. Depending on the material, the cement space should vary according to the processing method. For 3D-printed resin crowns, the intaglio surface is manufactured in a stepwise manner, owing to the nature of the additive manufacturing process, requiring a larger cement space. When printing, the stacking height also has an effect, and in the present study, the layer thickness was set at 50 µm. At the corresponding lamination height, a cement gap of 70 µm resulted in a uniform fit.

The marginal gap size in all the cement gap settings (35, 50, 70, and 100 µm) was lower than 120 µm, which has been considered to be the maximum clinically acceptable marginal gap size.[32] However, the clinically acceptable size for the marginal gap depending on the crown material and manufacturing techniques has not been established. An acceptable discrepancy in the marginal gap size of the crown is 50 to 200 µm.[24-27] A recent study[27] determined that the best fit for ceramic prosthesis was between 7.5 and 206.3 µm; however, a consensus remains to be established. It is unclear whether the criteria of a 120-µm marginal gap size are applicable in the 3D printing of the resin crown that is manufactured differently from previous methods.[24-28] A direct comparison between various studies is difficult because of the diversity of the crown materials, CAD-CAM environment, lack of consistency in defining a marginal fit, and use of different methods to measure the marginal fit.[28]

The replica technique is a nondestructive, accurate, and reliable evaluation method. Rahme et al[37] reported that the sectioning and silicone replica techniques produce similar measurements of the marginal gap of Procera ceramic crowns. However, in the replica technique, the crown margin is difficult to distinguish from the finishing line, and the silicone film might tear when the crown is removed.[38] In addition, incorrect plane sectioning can result in the over- or under-estimation of measurements.[39]

Limitations of the present study included the small sample size and the in vitro design being different from those in actual clinical practice. The clinical environment may induce thermo-mechanical fatigue, and the effects on the marginal and internal gaps depend on the abutment condition and type of preparation. [50-51] Additional research regarding the crown thickness, printing method and materials, thickness of printing layers, surface roughness, and adhesive method is required for sustainable application in clinical practice.

The in vivo part of this study compared 3D-printed RCs to traditional ZCs in single crown restorations in terms of marginal and internal fit, survival rate, clinical wear of prothesis, periodontal health, and patient satisfaction after 1 year. The results suggest that the physical properties of RCs require further improvements, particularly in survival rate and clinical wear. Therefore, the null hypothesis of this study was rejected.

Interestingly, the last tooth restored was found to be a significant factor that influenced prosthesis survival. For the 1-year survival rate of the RC group, 44.4% of the last teeth survived, while 94.7% of non-last teeth survived. It should be noted that the term “last tooth restored” and not “second molar” was used, since not all second molars were the last tooth to be restored, as seen in cases of missing posterior detention. The lower survival rate of the last tooth restored is most likely due to its position in the posterior teeth, which is closer to the center of the rotational axis of the masticatory muscle, the position where the biting force acts most strongly.[52]

Therefore, when considering the clinical application of RCs, the position of the tooth that is last to be restored should be a critical factor. Table 3 exhibits a noticeable trend showing that fractures tend to occur later for ZCs compared to RCs. This trend is likely due to the higher wear observed in RCs. The mean occlusal pressure of patients whose prosthesis fractured during the follow-up period was 31.78±5.61 MPa, which was not significantly different from the mean occlusal pressure of 30.51±5.06 MPa of patients with surviving prosthesis (*P*=.521).

According to in vitro results, a 70 μm cement gap setting is recommended for optimal marginal and internal fit of 3D-printed RCs.[49] Following these recommendations, 70 μm cement gaps must be incorporated in the CAD of RCs.

Regarding marginal and internal fit, no significant differences were observed between the RC and ZC groups, both of which showed clinically acceptable values of <120 μm.[32] Large marginal gaps in prostheses can increase the risk of cement washout and subsequent microleakage, negatively impacting restoration prognosis. This study showed that both the RC and ZC groups achieved marginal gap results within the range of 120 μm, suggesting their potential for clinical use. Moreover, the axio-occlusal and occlusal gaps were smaller in the RC group, likely due to the inherent characteristics of the manufacturing method. In subtractive manufacturing, a milling bur is used to fabricate the restoration. As such, the diameter of the bur and the range of the cutting movement can affect the accuracy.[53-54] While a statistically significant difference in the internal gap was observed, it is considered clinically insignificant.

Regarding clinical wear evaluation after 1 year, the RC group demonstrated significantly more wear in terms of vertical weight and volume compared to the ZC group. This trend held true in patients when divided into premolar and molar restorations. In contrast, no significant differences were observed in the wear of antagonists between the two. Excessive wear of the prosthetic occlusal surfaces can cause occlusal perforation, potentially leading to secondary dental caries. Close monitoring is therefore necessary during follow-ups of RC restoration. Although antagonist wear did not differ significantly, severe wear that was only observed in RCs suggest loss of occlusal function and weakened occlusal force. The high degree of wear may also be attributed to the characteristics of the resin products used in this study. Recent studies have explored the incorporation of fillers and other methods to improve the physical properties and strength of RCs. With the rapidly evolving use of the 3D printing resin market, it is important to acknowledge that advancements may have occurred since the selection of materials for this study. Exploration with a broader range of materials may yield more favorable results.

Despite the insights offered in this study, certain limitations should be acknowledged. First, only one type of 3D printing resin was studied. Second, multiple doctors were included in the clinical aspect of the study. Third, since the study focused on the molar region, physical properties were deemed more important and the evaluation of esthetic properties was excluded. Future research should explore the esthetic properties of RCs, which are also a significant factor to consider. Additionally, long-term follow-up studies utilizing various types of 3D printing resin under the evaluation of a single doctor would clarity the findings of our study.

V. CONCLUSION

Based on the findings of this in vitro and in vivo study, the following conclusions were drawn:

1. A 70 µm cement gap setting is recommended as the optimal marginal and internal fit for 3D-printed definitive resin crowns.
2. Overall, excluding wear, 3D-printed resin crowns were found to be non-inferior to zirconia crowns, supporting the clinical utility of 3D-printed resin.
3. 1-year wear evaluation showed that 3D-printed resin crowns had significantly higher vertical and volume wear compared to zirconia crowns.
4. These findings imply that 3D-printed resin crowns require further material reinforcements, such as the incorporation of fillers, before they can be considered as a viable option for definitive prosthetics.

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ABSTRACT (KOREAN)

최종 보철물용 레진 3D 프린팅 소재로 제작한 전부 전장관의 평가: 실험 및 임상 연구의 결과

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신 희 도

치과 분야에서 3D 프린팅 방법이 널리 사용되고 있음에도 불구하고, 특히 보철 분야에서는 장기적인 기능을 위한 부적절한 물성 및 강도와 같은 물리적 한계로 인해 주로 임시 보철물로 제한되어 왔다.

본 연구는 실험실 연구 및 임상 연구 두 부분으로 나누어 연구를 진행하였다. 실험실 연구에서는 다양한 시멘트 공간 설정에 따른 레진 크라운의 변연 및 내부 적합성을 조사하였다. 모형상에서 치아 삭제가 된 좌측 상악 제 1 대구치를 스캔한 후 CAD 소프트웨어 프로그램을 사용하여 35, 50, 70, 100 μm 의 시멘트 공간으로

크라운을 디자인하였다. 그룹당 총 14 개의 시편을 최종 3D 프린팅 레진으로 3D 프린팅하였다. Replica 기법을 사용하여 크라운의 음각 표면을 복제하고 복제된 시편을 협설 및 근원심방향으로 단면화하였다.

무작위 대조 전향적 임상 연구에서는 1 년 동안 단일 크라운 수복이 필요한 성인 환자를 대상으로 3D 프린팅 레진 크라운을 밀링 지르코니아 크라운과 비교함으로써 최종 보철물로서 레진 크라운의 가능성을 평가하였다. 연세대학교 치과병원에서 특정 건강 상태나 습관이 있는 환자를 제외한 구치부 단일 크라운 수복이 필요한 성인 환자를 대상으로 모집하였다. 56 명의 참가자를 무작위로 레진크라운과 지르코니아 크라운 두 그룹으로 나누었다. Replica 기법을 사용하여 내부 적합성을 평가하였다. 1 년 생존율, 크라운 및 대합치의 임상적 마모, 치주 건강, 환자 만족도 등 임상적 성과는 1 년에 걸쳐 여러 차례 추적 관찰을 통해 평가하였다. 크라운 마모는 구강 내 스캔의 초기 데이터와 1 년 데이터를 비교하여 분석 소프트웨어를 사용하여 측정하였다.

실험실 연구 결과, 모든 그룹에서 변연 간격의 중앙값이 임상적으로 허용 가능한 한계(120 µm 미만) 내에 있었지만, 70 µm 설정에서 가장 작은 변연 간격이 나타났습니다. 측벽 갭의 경우 35, 50, 70µm 그룹에서 관찰된 차이는 없었으며 100µm 그룹이 가장 큰 값을 보였다. 가장 작은 측벽-교합면 간격 과 교합면 간격은

70μm 설정에서 얻었다. 임상 연구 결과, 56 명의 참가자 중 각 그룹(레진크라운, 지르코니아 크라운)에 28 명의 환자가 배정되었고, 12 개월 후 레진크라운 그룹은 78.6%의 생존율을 보인 반면 지르코니아 크라운 그룹은 92.9%의 생존율을 보였지만 통계적으로 유의미한 비교는 아니었다. 최후방 치아로 수복된 경우가 보철물 생존율에 영향을 미치는 중요한 요인으로 밝혀졌다. 레진 크라운은 지르코니아 크라운에 비해 유의하게 높은 마모를 보였으나 대합치 마모에는 큰 차이가 없었다. 두 크라운 유형 모두 치주 및 생물학적 반응에서 유의미한 차이가 없이 임상적으로 허용 가능한 내면 간격과 변연 간격을 보였다. 환자 만족도는 두 그룹 모두 비슷하게 높았다. 레진 크라운은 최적의 적합도를 위해 70μm 의 시멘트 공간이 권장되며, 지르코니아 크라운에 비해 비용 효율적이고 제조하기 쉬운 대안으로서의 가능성을 보여주었다. 그러나 레진 크라운의 마모율이 높기 때문에 안정적인 최종보철물로서의 사용을 위해 물성을 개선하기 위한 추가적인 소재 개발이 필요하다.

핵심되는 말: 3D 프린팅 레진 크라운, 시멘트 공간값, 지르코니아 크라운, 최종 보철물