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저작 재현 과정 중 적층 제조 방식과 대합치의 종류에 따른 레진 크라운의 내마모성

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Wear resistance of dental resin crowns in accordance with different additive manufacturing technologies and abrader types during chewing simulations

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최근 치과 분야에서 레진 크라운 제작은 적층 제조 기술로 많이 활용되고 있다. 또한 지르코니아와 금속 크라운은 다양한 장점으로 수복 및 보철 재료로 사용되어지고 있으며 이에 적층 제조된 레진 크라운에 대합치로 레진 크라운에 마모를 초래할 수 있다. 이에 본 연구는 세 가지 적층 제조 기술로 제조된 치과용 레진 크라운 시편과 지르코니아와 코발트–크롬 합금의 두 가지 대합치로 하여 저작 재현을 수행하였을 때의 내마모성을 연구하였다. 제작방법에 따라 총 3개의 군으로 분류하여 레진 크라운 시편을 준비하였고 대합치로는 지르코니아와 코발트–크롬 합금을 사용하였다. 저작 재현 시험은 수평으로 5 mm, 수직으로 2 mm, 수직하중은 5 kg, 왕복운동빈도는 1.2 Hz로 설정하였고 총 20,000 회 시행하였다.

본 연구 결과, SLA (Stereolithography) 및 DLP (Digital light processing) 레진 시편은 서로 다른 방식으로 생산된 두 샘플 간의 최대 깊이 및 부피 손실량에서 유의미한 차이가 없었으나($p > 0.05$), FDM (Fused deposition modeling) 레진 시편은 다른 두 표본에 비해 최대 깊이 및 부피 손실량이 유의미하게 증가했다($p < 0.05$). 대합치의 종류에 따른 차이의 경우 부피 손실량은 유의미한 차이가 없었으나($p > 0.05$), 코발트–크롬 합금을 대합치로 사용한 경우보다 지르코니아를 대합치로 사용하였을 때 최대 깊이 및 부피 손실량의 편차가 낮게 나타남을 확인할 수 있었다. 이에 임상적으로 대합치의 종류는 레진 크라운에 내마모성에 큰 영향을 주지 않는 것으로 결론을 내릴 수 있었다.

색인단어 : 적층 제조 기술, 코발트–크롬 합금, DLP, FDM, SLA, 치과용 레진 크라운, 지르코니아, 마모저항성

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Introduction

Advances in the digital industry and technology have led to rapid changes in dentistry. Specifically, 3D printing has rapidly emerged as a key additive manufacturing (AM) technology for digital dentistry (1). AM technology has been adopted in a wide range of dental applications, including the production of splints, individual trays, clear aligners, temporary crowns, implant surgical guides, orthodontic appliances, and more (2). In the field of prosthetic dentistry, the adoption of AM technology has particularly stood out in the production of dental resin crowns. These crowns, manufactured using AM technology, offer advantages over conventional methods, including time savings, cost reduction, and decreased labor requirements (3).

The production of dental resin crowns using AM technology primarily involves stereolithography (SLA) and digital light processing (DLP) methods (4), utilizing liquid-based resin materials. In contrast, fused deposition modeling (FDM) employs solid-based resin (5). The SLA and DLP 3D printers have the merit of achieving intricate shapes with rapid processing (6, 7). These techniques use a photopolymer resin in a vat exposed to light-curing material for layering (6, 8). Meanwhile, FDM emits high heat from a nozzle to melt the resin material and extrude it continuously in the form of a filament (9). The main advantage is that objects can be produced quickly, are easy to handle in the clinic, and are compatible with most biomaterial (10). Hence, due to the differences in the characteristics of individual AM technologies, the physical properties of the resin dental crowns produced from each AM method also vary.

Resin dental crowns are often utilized for an extended periods, contingent on patients' oral environments (11). Intraoral wear is influenced by diverse factors, such as the structure of antagonist materials and the restorative material itself (12). Zirconia and cobalt-chrome (CoCr) alloy have recently gained popularity in dentistry due to their superior mechanical properties. These materials can significantly impact the extent of wear and subsequent physical properties when used in opposing prostheses (13, 14).

However, while some comparative studies of the mechanical properties of materials made using conventional milling method have been reported, there is no comparison with the 3D printing method in the existing literature. Additionally, the wear behavior of zirconia and metal restorative materials when opposing 3D printed resin dental crown is not well-known.

Thus, this study was conducted to test the wear resistance of resin crown specimens produced using different AM technologies before and after wear tests. For the wear tests, a chewing simulator was employed, with zirconia and CoCr alloy set as the opposing teeth.

The null hypothesis of this study was that

there would be no differences in the wear resistances of resin crowns printed using various 3D printing methods after undergoing chewing simulation.

Materials and Methods

1. Specimen fabrication

For the resin materials, rectangular parallelepiped-shaped specimens measuring 15 mm × 10 mm × 10 mm (length × width × height) (15) were designed using software (Meshmixer, Autodesk Inc., California, USA). Additive manufacturing was carried out using an SLA printer (Form2, Formlabs, Somerville, MA, USA), a DLP printer (IM110, Carima, Inc., Seoul, Korea), and an FDM printer (CUBICON Single Plus - 320 C, CUBICON Co. Ltd., Seoul, Korea) with resin materials compatible with each printer: High-temp V2 resin (Formlabs, Inc., Somerville, MA, USA), MAZIC D TEMP (Vericom Co., Ltd., Chuncheon-Si, Gangwon-Do, Korea), and Nexway PLA QA2-4 (QUVE Co. Ltd., Seoul, Korea) (Table 1).

SLA is a method in which a light source emitted through a dotted laser point draws an output area and builds up. The specimens were printed with a build angle of 0° orientation with a z-axis layer thickness of 100 μm. After the 3D printing process (Form2, Formlabs, Somerville, MA, USA), the block was detached from the platform and washed for 5 minutes with 100 % isopropyl alcohol to remove excessive resin monomers. In the final stage, the specimens' post-cured temperature was set at 80 ℃ and 120 min using a post-curing machine (Form cure printer, Formlabs, Somerville, MA, USA).

For the DLP samples, the laser was controlled by a digital micro mirror and the entire layer of liquid resin was polymerized at once. Likewise, the specimens were printed with a build angle of 0 orientation with a z-axis layer thickness of 100 μm. After the 3D printing process (Asiga UV Max, Asiga, Alexandria, Australia), the block detached from

Table 1. Chemical composition of resin materials in this study

Resin Product	Resin Manufacturer	Composition	3D Printer	3D Printer Manufacturer
High-temp V2 resin	Formlabs, Inc., Somerville, MA, USA	Urethane dimthacrylate(UDMA) (25-45 %) Acrylated monomer (40-60 %) Photoinitiator (<1.5 %)	Formlabs 2	Formlabs, Inc, Somerville, MA, USA
MAZIC D TEMP	Vericom Co., Ltd., Chuncheon-Si, Gangwon-Do, Korea	Methacrylic oligomer, phosphine oxide	IM110	Carima, Inc., Seoul, Korea
Nexway QA2-4	QUVE Co. Ltd., Seoul, Korea	PLA (Poly lactic acid)	Single Plus-320	CUBICON Co. Ltd., Seoul, Korea

the platform and washed with 100 % isopropyl alcohol to remove excessive resin monomers. In the final stage, the specimen was cured for 15 min using nitrogen chamber (Tera Harz Cure, Graphy Inc., Seoul, Korea).

For FDM samples, the file was transferred to Cubicreator program and printed using an FDM machine (CUBICON Single Plus - 320C, CUBICON Co. Ltd., Seoul, Korea). The specimens were printed with a build angle of 0 orientation with the printing layer thickness was fixed at 200 μm using a 0.4 mm nozzle with an extrusion temperature set at 200 ℃ and a print speed fixed at 60 mm/s. The temperature of the plate was set at 60 ℃ to ensure that the first layer spread enough to create a proper bond with the upper layers according to the manufacturer's recommendation.

Before the wear test, all specimens were dried at a temperature of 37 ℃ for one day. Then, the specimens were polished with silicon carbide paper of grain sizes 220 and 2000 grit on a polishing machine (Ecomet30, Buehler Ltd, Lake Bluff, IL, USA) with water cooling.

2. Abrader specimen fabrication

The abrader, which was mounted on a chewing simulator to apply abrasive force to the specimens, was made of Zirconia or CoCr alloy. It was designed using software (Meshmixer, Autodesk Inc, California, USA) to have a hemisphere with a radius of 1.5 mm connected to a 10 mm cube via a 5 mm long neck. The design was based on the mesio-palatal cusp of the upper molar, the design of which has been used previously (2). The zirconia abraders were fabricated using a dry milling 5-axis milling machine (Arum5x-300 Hoil Dental, England, UK) from a disc-shaped tetragonal zirconia polycrystal-based block (ZirPremium UT+; Acucera Inc., Pochon, Korea) and then sintered. The zirconia abraders surface was polished using a polishing kit (Soft Diamonds Grinding and Buffing Wheels; Asami Tanaka Dental, Friedrichsdorf, Germany). The metal abraders were manufactured with CoCr powder (EOS Cobalt Chrome SP2, EOS GmbH, Krailling, Germany) using a 3D printer (EOSINT M270, EOS GmbH, Krailling Germany) (8). The surface of the CoCr alloy abrader was polished with a brown rubber point (Brownie Polisher PC2, SHOFU, Kyoto, Japan) (16).

3. Chewing simulation

Each resin specimen was placed in the lower holder, and the antagonists were positioned on the upper holder in the wear apparatus. A chewing simulator (Type CS-4.8, SD Mechatronik, Feldkirchen-Westerham, Germany) was employed to conduct the wear test (8). The chewing cycle of the antagonists was set with a 5 mm vertical movement and 2 mm horizontal movement (Figure 1). Each specimen underwent 20,000 cycles at a

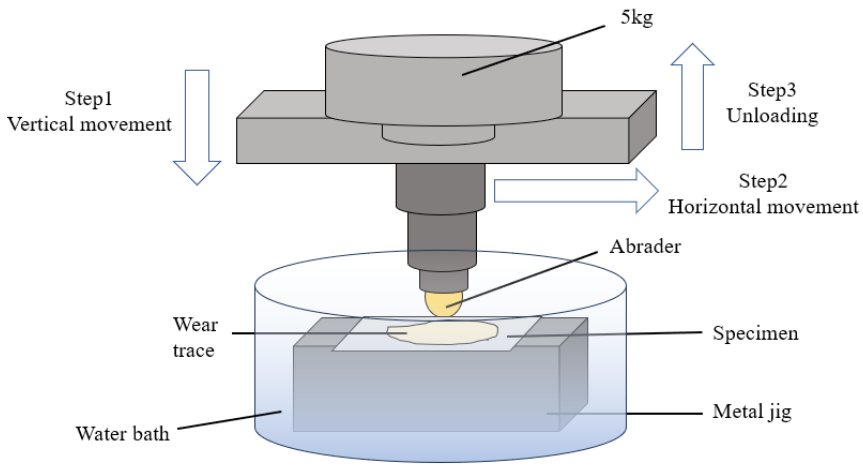

Figure 1. Schematic diagram of chewing simulation

frequency of 1.2 cycles per second and was loaded with a 5 kg weight.

The chewing simulation was conducted without thermocycling and at room temperature (18~20 ℃). Following the chewing simulation, each specimen was air-dried and steam-cleaned to remove any dirt before scanning.

4. Surface wear assessment

1) Quantitative of wear volume loss and maximal depth loss

For the chewing simulations, each specimen was scanned using the Medit T710 model scanner Identica Hybrid; Medit, Seoul, South Korea) with a precision of ± 7 μm. The acquired STL files were then imported into the GOM inspect mesh inspection software (GOM GmbH, Braunschweig, Germany). The STL files taken before wear were designated as the reference, and the best-fit alignment was performed with those taken after wear.

To analyze the worn surfaces, all specimens were trimmed by approximately 2 mm from the worn plane. The amount of volume loss (in mm^3) and depth loss (in mm) were used to calculate the difference between the before and after wear.

2) Qualitative assessment using Field-Emission Scanning Electron Microscopy (FE-SEM)

To analyze the surface wear morphology, a representative specimen was selected for each group. A thin platinum coating was applied to the worn surface, and the specimens were observed using field emission scanning electron microscopy (FE-SEM) (Hitachi S-4700, Hitachi High-Technologies Group, Schaumburg, IL, USA) at magnifications of 50 x and 1000 x after the chewing simulation.

3) Quantitative of abrader wear loss of volume

Using GOM Inspect Mesh Inspection Software (GOM GmbH, Braunschweig, Germany), changes in the STL files of the abraders before and after wear were imported.

Subsequently, the quantification of wear volume loss was measured using GOM Volume Inspect Pro Mesh Inspection Software (GOM GmbH, Braunschweig, Germany), aligned with the abrader before and after the chewing simulations. Then, the abrader was trimmed by approximately 2 mm from the worn plane. The volume loss (in mm^3) was calculated to determine the difference between the conditions before and after wear (Figure 2).

5. Statistical analysis

For the wear test, each specimen underwent 20,000 cycles, and eight abraders were loaded simultaneously. Each abrader's measurements could influence 300,000 cycles.

Statistical analysis of the values from the materials was carried out using statistics software (SPSS, IBM Corp., New York, NY, USA). Tests of normality and equality of variances were applied. The nonparametric Kruskal-Wallis and Mann-Whitney tests by Bonferroni's method were used to analyze the data at a significance level of 5 %.

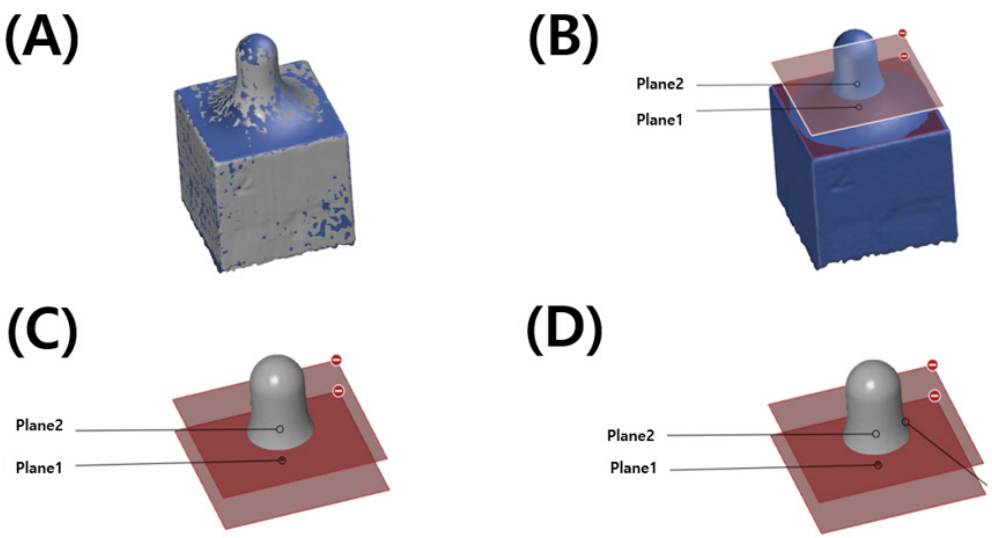

Figure 2. Abrader's wear measurement steps; (A) aligning abraders before and after chewing simulation, (B) cutting 2 mm down from the worn part, (C) cut-out abraders and (D) calculating volume loss by subtracting the abrader's volume, respectively, after the chewing simulations from that of the abraders before the chewing simulations.

Results

1. Quantitative of wear volume loss and maximal depth

The wear volume loss (in mm^3) of the 3D printed specimens is presented (in Table 2 and Figures 3).

The mean ± standard deviation values for wear volume loss against the zirconia abrader were 0.89 ± 0.87 mm^3 for the SLA-printed specimens, 0.96 ± 1mm^3 for the DLP- printed specimens, and 2.97 ± 2.68 mm^3 for the FDM-printed specimens. No significant differences in wear volume loss values were found between the SLA- and DLP-printed specimens ($p > 0.05$). However, the resin specimens fabricated using the FDM printer showed significant differences compared to both the SLA- and DLP- printed specimens ($p < 0.05$).

The mean ± standard deviation values for wear volume loss against the metal abrader were 2.22 ± 1.63 mm^3 for the SLA-printed specimens, 1.82 ± 1.58 mm^3 for the DLP-printed specimens, and 12.24 ± 4.15 mm^3 for the FDM-printed specimens. Similar to the zirconia abrader, the SLA- and DLP-printed specimens showed no significant differences in volume loss ($p > 0.05$), while the resin specimens fabricated using the FDM printer showed significant differences compared to both the SLA- and DLP-printed specimens (p

Table 2. Wear volume loss is expressed as mean ± standard deviations for the specimens.

AM Methods	Wear volume loss (mm^3) in mean ± standard deviation	
	Zirconia abrader	Metal (CoCr) abrader
SLA	0.89 ± 0.87^b	2.22 ± 1.63^b
DLP	0.96 ± 1^b	1.82 ± 1.58^b
FDM	2.97 ± 2.68^a	12.24 ± 4.15^a

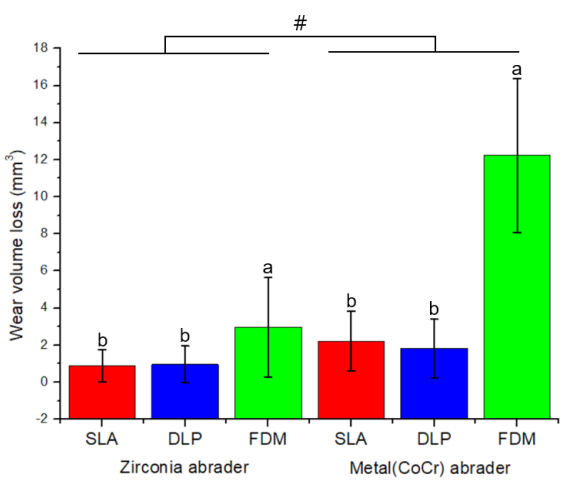

Figure 3. The wear volume loss of the materials against different abraders (zirconia and metal). The same lower case showed no significant difference between the results using three different additive manufacturing (AM) methods ($p > 0.05$). '#' indicates a significantly greater wear volume loss compared to zirconia and CoCr alloy abraders ($p < 0.05$).

〈 0.05).

The same lower case showed no significant difference between results obtained using three different additive manufacturing (AM) methods (p 〉 0.05).

The maximal depth loss (in mm) of the 3D printed specimens is presented (in Table 3 and Figures 4).

The mean ± standard deviation values for maximal depth loss against the zirconia abrader were 0.31 ± 0.11 mm for the SLA-printed specimens, 0.32 ± 0.07 mm for the DLP-printed specimens, and 0.47 ± 0.11 mm for the FDM-printed specimens. No significant differences in the depth loss values were found between the SLA- and DLP-printed specimens (p 〈 0.05). However, the resin specimens fabricated using the FDM printer showed significant differences compared to both the SLA- and DLP-printed specimens (p 〈 0.05).

The mean ± standard deviation values for maximal depth loss against the metal abrader were 2.77 ± 0.32 mm for the SLA-printed specimens, 2.70 ± 0.18 mm for the DLP-printed specimens, and 3.0 ± 0.6 mm for the FDM-printed specimens. Similar to the zirconia abrader, the SLA- and DLP-printed specimens showed no significant differences in depth loss (p 〉 0.05), while the resin specimens fabricated using the FDM printer showed significant differences compared to both the SLA- and DLP- printed specimens (p 〈 0.05).

Table 3. Maximal depth loss is expressed as mean ± standard deviations for the specimens.

AM Methods	Wear maximal depth loss (mm) in mean ± standard deviation	
	Zirconia abrader	Metal (CoCr) abrader
SLA	0.31 ± 0.11[b]	2.77 ± 0.32[b]
DLP	0.32 ± 0.07[b]	2.7 ± 0.18[b]
FDM	0.47 ± 0.11[a]	3.0 ± 0.6[a]

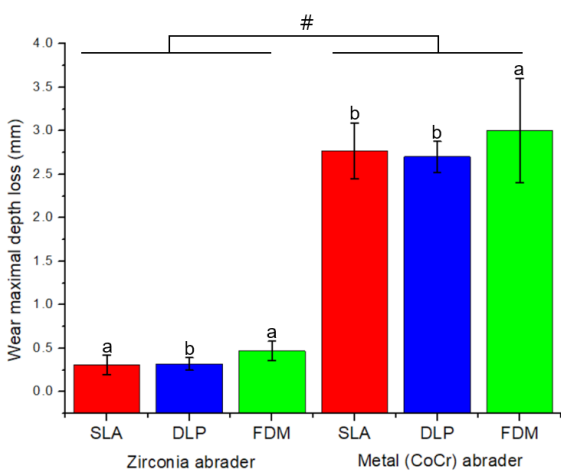

Figure 4. The maximal depth loss of the materials against different abraders (zirconia and metal). The same lower case showed no significant difference between results using three different additive manufacturing (AM) methods (p 〉 0.05). '#' indicates a significantly greater volume loss compared to zirconia and CoCr alloy abraders (p 〈 0.05).

2. Surface wear morphology on the printed resin specimens

The FE-SEM images of the worn surface morphology of the specimens after chewing simulation are shown in Figures 4 and 5. In the SLA resin specimens, small cracks were observed (white arrow in Figures 4(d) and 5(d)). The DLP resin specimens showed more cracks and dented fractures (white arrow in Figures 4(e) and 5(e). However, the FDM resin specimens remarkably exhibited random separations of the layers (Figures 4(c) and 5(c)). Additionally, the surface wear morphology of the three resin materials in contact with the CoCr alloy abrader appeared to be relatively rougher than those in contact with the zirconia abraders (15).

3. Quantitative results for abrader wear loss of volume

In this study, zirconia and metal abraders were used to simulate wear.

Two-body wear tests, loaded with eight antagonist pairs simultaneously, were carried out, allowing each abrader's measurements to influence 300,000 cycles. Table 4 indicates that there was no significant difference in volume loss between the zirconia and CoCr

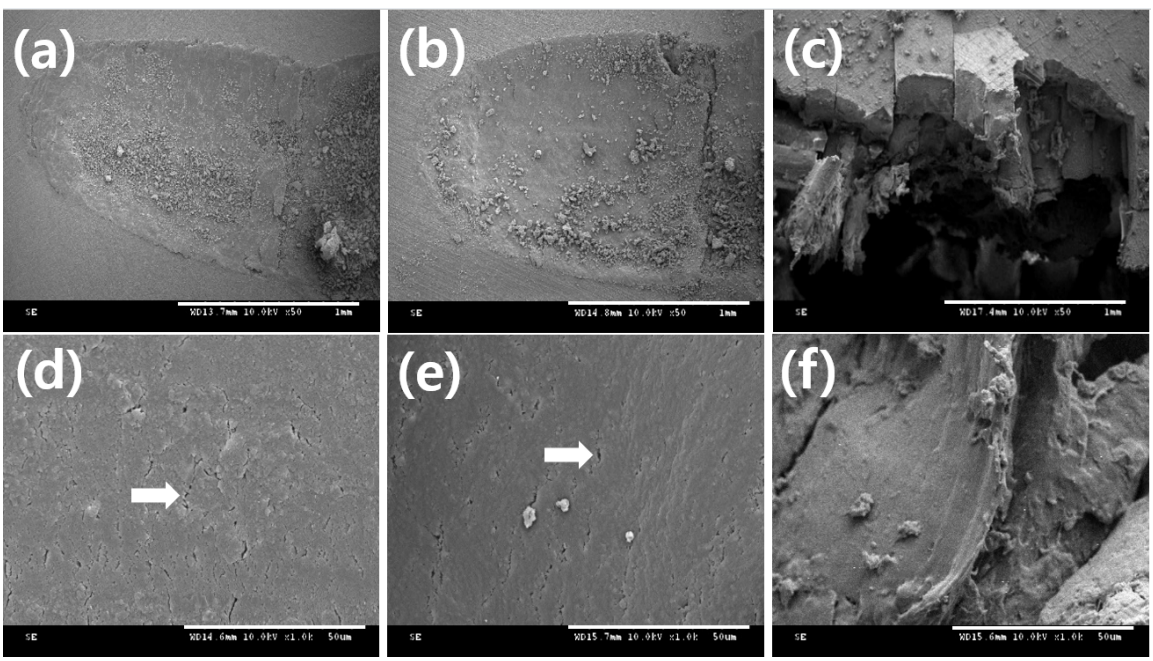

Figure 4. FE-SEM images of the surfaces worn morphology of the materials against the zirconia abrader. (a) SLA-printed resin (original magnification ×50); (b) DLP-printed resin (original magnification ×50); (c) FDM-printed resin (original magnification ×50); (d) SLA-printed resin (original magnification ×1000); (e) DLP-printed resin (original magnification ×1000); (f) FDM-printed resin (original magnification ×1000). The scale bar is 1 mm for (a), (b), and (c). The scale bar is 50 μm for (d), (e), and (f).

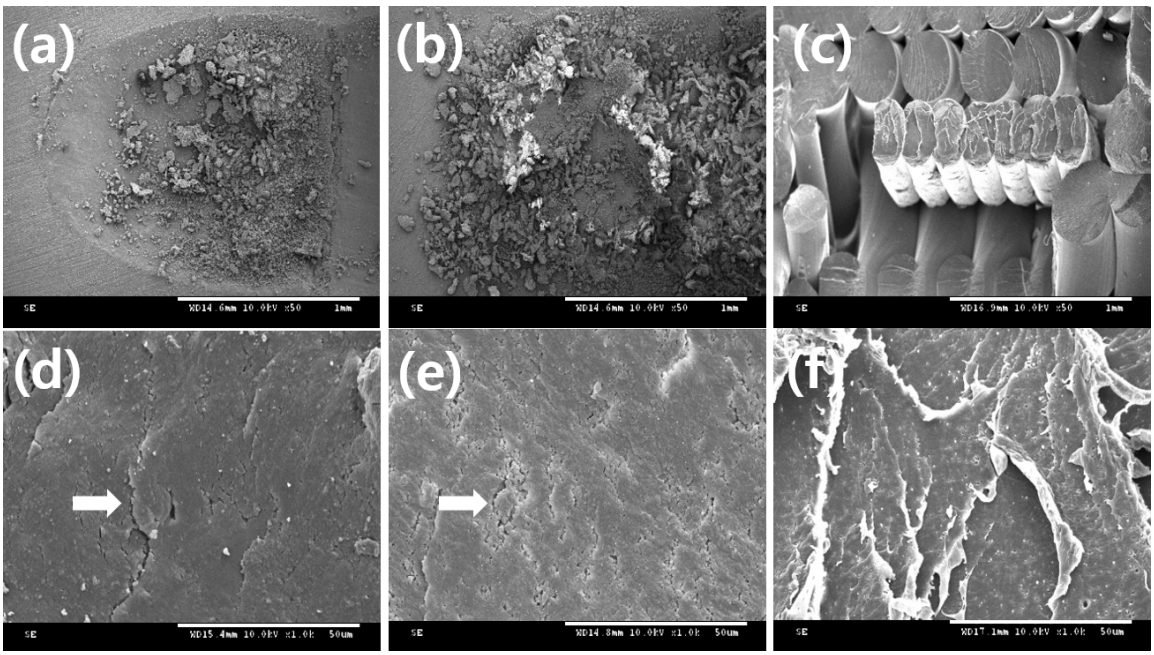

Figure 5. FE-SEM images of the worn surfaces worn morphology of the materials against the Co-Cr abrader. (a) SLA-printed resin (original magnification ×50); (b) DLP-printed resin (original magnification ×50); (c) FDM-printed resin (original magnification ×50); (d) SLA-printed resin (original magnification ×1000); (e) DLP-printed resin (original magnification ×1000); (f) FDM-printed resin (original magnification ×1000). The scale bar is 1 mm for (a), (b), and (c). The scale bar is 50 μm for (d), (e), and (f).

Table 4. Wear volume loss is expressed as mean ± standard deviations for the abraders. The same uppercase letters indicate no significant difference between the zirconia and CoCr alloy abraders ($p > 0.05$).

Abrader wear loss of volume (mm^3) in mean ± standard deviations	
Zirconia abrader	0.17 ± 0.02^A
Metal (CoCr) abrader	0.19 ± 0.02^A

alloy abraders ($p > 0.05$). However, in the case of specimens, wear volume loss and maximal depth loss deviation were generally higher when CoCr alloy was used compared to the use of zirconia as the abrader. In scanning electron microscopy images, the worn surface morphology of the three dental resin materials in contact with the CoCr alloy abraders appeared to be relatively rougher than those in contact with the zirconia abrader.

Discussion

The null hypothesis was that the wear resistance of resin crowns printed using various 3D printing methods would not significantly differ after undergoing chewing simulation.

The results of this study indicate that resin crowns produced from different AM technologies, as well as the choice of antagonists, significantly affect wear resistance. Consequently, the null hypothesis was rejected.

The amount of wear in SLA-type resins was similar to that in DLP-type resins. The wear volume loss and maximal depth loss values exhibited similar patterns. Wear appeared as cracks and dented features in the SEM images. However, in the case of the FDM type, the wear maximal depth loss and wear volume loss values were significantly larger.

Shanmugam et al. have shown that FDM printing has demonstrated its ability to produce polymers compared to conventional methods. However, it is important to note that the formation of porosity and imperfections in FDM-printed polymers is an inevitable characteristic, which could result in failure under loading (17). Furthermore, FDM-printed materials are anisotropic, meaning they do not possess uniform strength throughout due to layer-to-layer adhesion and interlayer voids. Additionally, PLA components printed using an FDM printer often exhibit reduced impact resistance (18); therefore, many cracks and separated layers are present in the SEM images.

For the wear test, the metal used for the antagonists was chosen for its wear resistance and stability. Zirconia also possesses favorable mechanical properties, and monolithic zirconia has been reported to be less abrasive to human enamel than feldspathic porcelain (16). Thus, metal and zirconia abraders were used in this study. Differences in wear appearance were observed between the materials depending on the abraders. There was no significant difference in volume loss between the zirconia and CoCr alloy abraders ($p > 0.05$). However, in the case of the specimens, wear volume loss and maximal depth loss deviation were generally higher when using CoCr alloy as the antagonist compared to when zirconia was used. The worn surface morphology of the specimens in contact with the CoCr abrader appeared relatively rough in the SEM images. This is due to the fact that among the CoCr alloys used in DMLS technique, 'Co' possesses the property of cracking (19).

In this study, the vertical load was maintained at 5 kg during the chewing simulation, equivalent to the masticating force of 49 N. Each specimen was abraded for 20,000 cycles, which is equivalent to one months of chewing from a clinical perspective. However, the limitation of this study is that it has not been simulated in oral environments.

Clinically, the wear resistance of resin dental crown is influenced by oral temperature, humidity, and pH. Temporary restorations can be exposed to the polymer network structure in an aqueous environment (20). Subsequently, water particles fill the empty spaces between micro-gaps (21). The results, which include leaching of the components, degradation of the crosslinked matrix, and hydrolysis in the interphase area, eventually lead to a decrease in mechanical properties (22) over time.

Conclusions

The aim of this study was to examine the wear volume loss and maximal depth loss of various types of 3D-printed resin materials when opposed to either zirconia or metal antagonists. In this study, the wear resistance of materials fabricated using three different types of 3D-printed dental resin material was evaluated. The results showed that dental resin crowns fabricated using SLA and DLP printed materials exhibited similar wear resistance, verifying their clinical feasibility. However, it is worth noting that the FDM printer, while having many advantages, has been associated with poor mechanical qualities in PLA examinations over the last decade (18).

The metal and zirconia used for the antagonists were wear-resistant and dimensionally stable. Future studies are needed to investigate how these physical properties of prostheses manufactured using 3D printing methods may influence the clinical durability of resin crowns produced using different 3D printing methods.

Acknowledgments

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Original Article

Wear resistance of dental resin crowns in accordance with different additive manufacturing technologies and abrader types during chewing simulations

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Recently, dental resin crowns have been widely utilized in various applications through additive manufacturing (AM) technology in dentistry. Additionally, zirconia and metal crowns can be used as restorative and prosthetic materials, benefiting from a variety of advantages. However, the use of these materials may result in wear loss of temporary resin crowns fabricated using AM technology when they are used as antagonists. This study examined the wear resistance of dental resin crown specimens produced using different AM technologies against two common antagonist crown materials: zirconia and metal crown. Three types of dental resin crowns, produced using different methods, were examined: SLA, DLP, and FDM.

The specimens were subjected to a two-body wear test with zirconia and cobalt-chrome alloy as the antagonists under specific conditions (5 mm, 2 mm, 5 kg, 1.2 Hz, 20,000 cycles). The SLA- and DLP-printed resins showed no significant difference in wear volume loss and wear maximal depth loss between the two differently produced specimens ($p > 0.05$). However, the FDM-printed resin showed a significantly increased wear volume loss and maximal depth loss compared to the other two specimens ($p < 0.05$). There was no significant difference in wear volume loss between zirconia and CoCr alloy abraders ($p > 0.05$). However, when examining the resin specimens, wear volume loss and wear depth loss deviation were generally higher when CoCr alloy was used compared to the use of the zirconia alloy as the abrader. In clinical terms, it can be concluded that the type of antagonists does not influence the wear resistance of temporary resin crowns.

Keywords : Additive manufacturing; Co-Cr alloy; DLP; FDM; SLA; Temporary restoration; Zirconia; Wear resistance