Accuracy of mandibular removable partial denture frameworks fabricated by three techniques

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Accuracy of mandibular removable partial denture frameworks fabricated by three techniques

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먼저, 늦깎이 대학원생이 된 저를 따뜻하게 맞아 주시고, 논문이 온전히 완성되기까지 지도와 격려를 아끼지 않으신 김지환 교수님께 진심 어린 감사의 마음을 전합니다. 그리고, 논문 시작부터 끝까지 여러 모로 많은 도움을 주신 오경철 교수님께 깊은 감사를 드립니다. 또한, 바쁘신 가운데에도 심사를 통해 소중한 가르침을 주신 이현종 교수님, 신유석 교수님, 송제선 교수님께 심심한 감사의 마음을 전합니다. 심준성 교수님을 비롯한 모든 보철과 교수님들께 아울러 감사드리며, 실험을 도와준 윤상혁 선생님, 박예슬 선생님에게도 고마운 마음을 전합니다.

코로나가 한창일 무렵, 어린 나이에 고국으로 돌아와 사춘기에 접어들기까지 여러 모로 쉽지 않았을 상황 속에서 엄마가 없는 시간들마저 잘 견디며 성장해 준 사랑하는 두 아들, 수호와 태호에게 이 논문을 선사하고 싶습니다. 그리고, 언제나 묵묵히 자신의 일을 하며 아내의 재도약을 지지하고 응원해 주는 인생의 동반자인 남편, 저를 이 세상에 있게 해주시고 지금의 저로 성장하기까지 늘 뒤에서 든든한 버팀목이 되어 주신 부모님, 살아 계셨다면 누구보다 기뻐하셨을 시부모님과 이 기쁨을 함께 하고 싶습니다.

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ABSTRACT

Accuracy of mandibular removable partial denture frameworks fabricated by three techniques

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(*Directed by Prof. Jee-Hwan Kim, D.D.S., M.S.D., Ph.D.*)

The purpose of this study was to evaluate the accuracy of metal frameworks for mandibular removable partial dentures (RPDs) fabricated using three techniques via digital superimposition.

A mandibular dentiform of Kennedy Class II modification 1 was prepared with rest seats and guiding planes on the left second premolar, right first premolar, and right second molar. Thirty master casts were fabricated using repetitive impressions of the prepared dentiform and were divided into three groups. Thirty RPD frameworks for each master cast were manufactured using three different methods: selective laser melting (SLM)-based metal 3D printing (SLM group), digital light projection-based resin 3D printing and subsequent casting (RPC group), and conventional lost-wax casting (CON group; n=10). The master casts were scanned twice after the preparation and after attaching silicone using the frameworks. The two scan files were superimposed using metrology software, and the thicknesses of the silicone material were measured at eight areas: three rests, four tissue stops, and a lingual bar. The internal discrepancies of each component and overall were compared among the three groups. Statistical analysis was conducted using SPSS Statistics (Version 23.0, IBM Corp, Somers, NY, USA). One-way ANOVA and a post-hoc Tukey's multiple comparison tests were performed to determine differences among the three groups ($\alpha = 0.05$).

The following results were obtained. The RPC group exhibited significantly higher overall internal discrepancies than the SLM and CON groups ($P=0.001$ and $P=0.019$, respectively). The SLM and CON groups exhibited statistically insignificant differences in terms of overall internal discrepancies ($P=0.633$) and the lowest mean internal discrepancy at rests ($P=0.010$, $P<0.001$) and tissue stops ($P=0.001$, $P=0.025$), respectively. The lingual

bars of the three groups indicated no statistically significant differences in terms of internal discrepancies.

Within the limitations of this study, it can be concluded that SLM-fabricated RPD frameworks have overall similar accuracy to those of conventional cast RPD frameworks. A combined method of resin 3D printing and casting showed inferior accuracy; however, all frameworks in the three groups were clinically acceptable.

Keywords: accuracy, removable partial denture framework, selective laser melting, superimposition, 3D printing

Accuracy of mandibular removable partial denture frameworks fabricated by three techniques

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I. INTRODUCTION

The manufacturing methods of metal frameworks for removable partial dentures (RPDs) have recently transitioned from conventional lost-wax techniques to computer-aided design/computer-aided manufacturing (CAD/CAM) techniques, specifically metal three-dimensional (3D) printing. Considering the history of manufacturing methods of RPD metal frameworks, the transition to the current direct 3D-printed RPD frameworks provides an innovative path. Fauchard first reported the use of metal structures in an RPD in 1728, whereby he used metal labial and lingual bars to connect two carved ivory blocks (Becker, Kaiser, Goldfogel 1994, Girardot 1941). In the late 1890s, over 160 years later, the lost-wax casting technique which has been used since ancient times was introduced in dentistry. However, it comprised complex procedures: the making of a refractory cast, waxing up, investing, and casting, thus requiring enormous labor and time (Ucar Y 2009, van Noort 2012, Venkatesh, Nandini 2013). Moreover, distortion of the wax pattern on a refractory cast causes inaccuracies in the RPD frameworks, possibly hindering the overall success of the RPD treatment (Diwan R 1997). However, the lost-wax casting technique were used to fabricate RPD frameworks for over a century until CAD/CAM technology was introduced. The emergence of CAD/CAM technology in dentistry in the 1970s brought revolutionary changes in the manufacturing methods, from inlays to RPD frameworks (Azari, Nikzad 2009, Beguma, Chhedat 2014, Dawood et al. 2015, Lima et al. 2014, Rekow 1987).

The early CAD/CAM method involved milling, which is a subtractive technique. However, it had several disadvantages: wear of cutting tools, limitation of complicated shapes or undercut areas, waste of cutting chips, long processing time, and shrinkage during processing (Bae et al. 2017, Suzuki et al. 2021). The 3D printing technology has replaced the milling method as it bypasses these limitations. It is an additive manufacturing (AM) technique that produces 3D objects by adding materials in layers, rendering it highly efficient in manufacturing complex-shaped objects (van Noort 2012). Currently, there are several 3D printing technologies, such as stereolithography (SLA), digital light projection (DLP), selective laser sintering (SLS), and selective laser melting (SLM), depending on the materials used and the sources of energy. The ones used in this study are selective laser melting (SLM) and digital light projection (DLP) (Azari, Nikzad 2009, Beguma, Chhedat 2014, Kessler, Hickel, Reymus 2020, Koutsoukis et al. 2015, Lima et al. 2014).

SLA was the first 3D printing technique patented in the 1980s and has been used to manufacture various objects. It involves using ultraviolet lasers to polymerize resin in layer thicknesses ranging from 10 to 100 μm (Barazanchi et al. 2017, Tregerman et al. 2019). Further, DLP, which was invented by Larry Hornbeck of Texas Instruments in 1987 (Revilla-Leon, Ozcan 2019), has a resolution and use range similar to that of SLA; however, it is faster than SLA as the projecting light can cure an entire layer at once (Snosi et al. 2021, Tregerman et al. 2019). DLP is considered in the same AM category as that of SLA by the American Section of the International Association for Testing Materials (Revilla-Leon, Ozcan 2019); however, the primary difference between the two methods is the light source, wherein the image is created by an arc lamp or micro-mirrors. The number of micro-mirrors corresponds to the resolution of the projected image in DLP. (Revilla-Leon, Ozcan 2019) SLA was first used to print resin sacrificial patterns for RPD frameworks from 3D CAD models in the early 2000s; however, the method still required casting processes (Williams RJ 2004). Later, directly printing metal RPD frameworks using an SLM 3D printer became possible, thereby eliminating the complex conventional casting processes, except for finishing and polishing (Bibb, Eggbeer, Williams 2006, Williams et al. 2006).

SLM involves melting metal powder using a high-energy laser beam and fusing and solidifying it in layers according to CAD information (Koutsoukis et al. 2015, Tregerman et al. 2019). SLM and SLS principles are similar; however, Koutsoukis et al. (Koutsoukis et al. 2015) mentioned that the primary difference between the two methods is the material used; the terms SLS and SLM are preferred for ceramics/polymers and metals, respectively. Suzuki et al. (Suzuki et al. 2021) stated that various materials, including metals, could be used in SLS, and the difference was the method of manipulating the powder. SLM involves melting the powder, and SLS entails sintering it. Similarly, Alageel et al. (Alageel et al. 2018) stated that SLM involved the full melting of metal powder, while SLS involved its partial melting. In this study, the term SLM implies the metal 3D printing technique.

The use of SLM-fabricated RPD frameworks has increased recently; however, conventional casting techniques remain time- and labor-consuming. To generalize using convenient metal 3D printed frameworks, the properties of 3D printed chrome-cobalt (Co-Cr) alloy should be proven, and the accuracy of the frameworks should be comparable to that of conventional cast frameworks. Several studies have reported that SLM-fabricated Co-Cr alloys have more homogeneous microstructures than cast Co-Cr alloys, which enhance their mechanical properties (Hong et al. 2020, Koutsoukis et al. 2015, Lapcevic et al. 2016, Souza Curinga et al. 2023, Stamenkovic et al. 2023, Zhou et al. 2018). Stamenkovic et al. (Stamenkovic et al. 2023) evaluated the microstructure and mechanical properties of 3D-printed Co-Cr alloys through the tensile test, and concluded that laser melting and sintering of dental Co-Cr alloys provided RPD frameworks with favorable mechanical properties compared to conventional casting of Co-Cr alloys. Hong et al. (Hong et al. 2020) compared mechanical properties of Co-Cr alloys fabricated by casting, milling, and SLM, and SLM group showed finer homogeneous crystalline-microstructure. These results indicate that the SLM manufacturing method has the potential to replace traditional fabrication methods of dental prostheses made from Co-Cr alloys.

Regarding the accuracy of metal 3D printed RPD frameworks, recent studies concluded that RPD frameworks fabricated by SLM and conventional cast RPD frameworks have similar accuracy within the clinically acceptable range (Ahmed et al. 2021, Carneiro Pereira et al. 2021, Oh, Yun, Kim 2022, Souza Curinga et al. 2023). Although these are clinically acceptable, certain studies have noted that the internal discrepancies of SLM-fabricated RPD frameworks are larger than those of conventionally casted frameworks (Arnold et al. 2018, Soltanzadeh et al. 2019, Ye et al. 2017). Moreover, the studies on mandibular metal 3D printed RPD frameworks are limited. Mandibular RPD frameworks are u-shaped and have a significantly smaller contact area with tissue than maxillary RPD frameworks owing to the absence of a palatal area, where most of the contact with maxillary RPD frameworks is concentrated, which might affect the internal adaptation of the components of RPD frameworks. In addition, despite the various methods employed to investigate the accuracy of RPD frameworks manufactured through

CAD/CAM techniques (Arnold et al. 2018, Forrester, Sheridan, Phoenix 2019, Lee et al. 2017, Negm, Aboutaleb, Alam-Eldein 2019, Oh, Yun, Kim 2022, Soltanzadeh et al. 2019), comparative studies on the three types of fabrication methods using reliable digital measurements are rare. Previous researches predominantly compared metal 3D printing with conventional casting techniques, often relying on point measurements, which have higher contingency compared to area measurements.

In this study, we compared the accuracy of mandibular RPD frameworks fabricated using three methods via digital analysis. The methods evaluated were SLM-based metal 3D printing, DLP-based resin 3D printing followed by casting, and conventional lost-wax casting. The null hypothesis was that there would be no significant differences in the accuracy of the mandibular RPD metal frameworks among the three manufacturing methods.

II. MATERIALS AND METHODS

The overall schematic workflow of this study is presented in **Figure 1**.

1. Preparation of the mandibular dentiform

A partially edentulous, Kennedy Class II modification 1 classified, mandibular dentiform (YS-RPD; M. Tech, Gimcheon, South Korea) was used as a reference model for manufacturing master casts in this study. Three occlusal rest seats and guiding planes were prepared on the left second premolar, right first premolar, and right second molar of the dentiform for fabrication of mandibular RPD metal frameworks according to the preparation principles.

2. Fabrication of 30 master casts and division into three groups

Impression of the prepared dentiform was taken repeatedly over thirty times for fabrication of thirty master casts using vinyl polysiloxane impression material (Aquasil XLV; Dentsply Sirona, Konstanz, Germany). The type 4 ultrahard die stone (Snow Rock Gypsum; DK Mungyo Co., Gimhae, South Korea) was mixed and poured following the instructions of the manufacturer. The casts were trimmed after complete hardening.

Thirty master casts were divided into three groups according to the fabrication method of RPD metal frameworks. Ten master casts were used for the fabrication of direct metal

3D printed RPD frameworks (**SLM group**), another 10 were used for the fabrication of 3D printed resin-cast RPD frameworks (**RPC group**), and the remaining 10 were used for the fabrication of conventional lost-wax cast RPD frameworks (**CON group**). The number of samples was determined based on other studies that conducted similar experiments. The three different manufacturing methods are described in detail in Section II-4.

3. Verification of the master casts trueness

First, the prepared dentiform was scanned using a tabletop scanner (T500; Medit, Seoul, South Korea), and the scan data were saved as a reference file in standard tessellation language (STL) **(Figure 2)**. Subsequently, the thirty master casts were scanned using the same tabletop scanner and saved as STL files.

To prove that the master casts of the three groups did not differ, every STL file of the thirty master casts was superimposed individually over the reference file. The trueness of each master cast was verified using the local best-fit alignment function of the metrology software (GOM Inspect 2018; Hotfix 3, Rev. 1114010, Carl Zeiss GOM Metrology GmbH, Braunschweig, Germany).

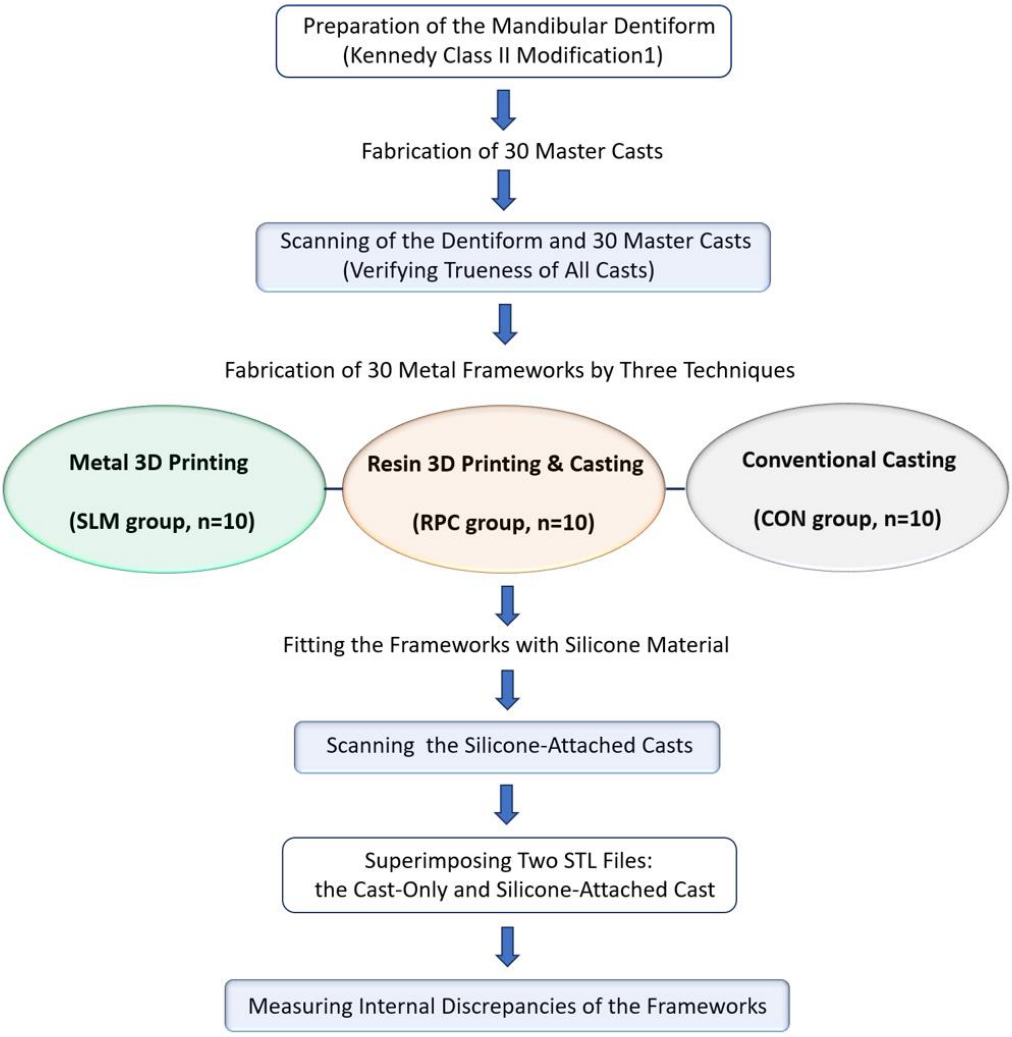


Figure 1. Overall schematic workflow of this study.

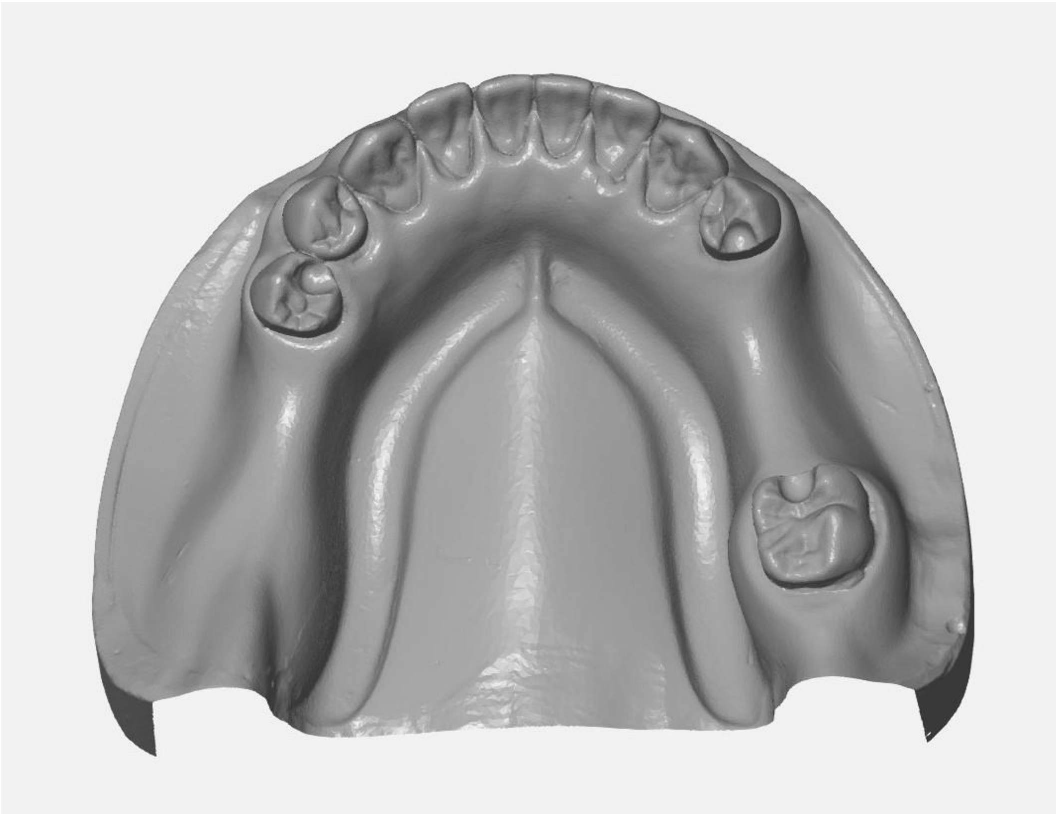


Figure 2. Screenshot of the standard tessellation language (STL) file of the mandibular Kennedy classification II, modification 1 dentiform used in this study. Rest seats and guiding planes were prepared on the left second premolar, right first premolar, and right second molar.

4. Fabrication of mandibular RPD metal frameworks by three techniques

All the 30 RPD frameworks were designed identically to have a lingual bar as a major connector, an I -bar type clasp on the left second premolar, and basic C clasps on the right first premolar and second molar. The details of the 3D printers, CAD software, and materials used for three groups are presented in **Table 1**.

4.1 SLM group - Metal 3D printing

The RPD metal frameworks of the SLM group were designed with CAD software (Dental system 2019; 3Shape A/S, Copenhagen, Denmark) after electronic surveying, and the virtual RPD frameworks were printed out directly via the SLM technology-based metal 3D printer (NCL-M2150X; Nanjing Chamlion Laser Technology Co., Nanjing, China) using CoCr alloy powder (ChamTiger; Shinseki International Inc., Seoul, South Korea). The support-attached 3D printed RPD metal frameworks underwent heat treatment and were polished after removing the supports (**Figure 3A, 4A**).

4.2 RPC group - Resin 3D printing and casting

Fabrication of the RPD metal frameworks of the RPC group was implemented through combined process of resin 3D printing and casting. First, the RPD frameworks were designed identically with the SLM group using the same CAD software. The virtual RPD frameworks were printed out as resin sacrificial patterns with the DLP technology-based resin 3D printer (Pro3D printer SRP1902A; SprintRay Inc., CA, USA) and 3D-printable resin material (S-plastic cast 2.0; Graphy Inc, Seoul, South Korea). Subsequently, the 3D printed resin frameworks were invested and casted using same material and manner with the CON group (**Figure 3B, 4B, 4C**).

4.3 CON group - Conventional casting

Finally, for the CON group, the framework design was drawn on each master cast with a pencil. After wax relief process on the 10 master casts, impressions were taken individually with reversible hydrocolloid material (Polyflex; Dentsply Sirona, Konstanz, Germany) to fabricate refractory casts (rema Exakt; Dentaurum GmbH, Ispringen, Germany). Wax patterns of the RPD framework were created on the refractory casts and multiple sprues were added. It was invested with a phosphate-bonded investment material (BC-VEST P-Plus; Bukwang, Busan, South Korea) and casted using Co-Cr alloy (Zaire Partial Denture Alloy, Neodontics Inc., USA) (**Figure 3C, 4D**).

4.4 Finishing and polishing

Finishing and polishing were performed on the thirty RPD metal frameworks to be adapted to the corresponding master casts paying attention to avoid damaging the intaglio surface of the frameworks. Designing procedures were implemented by an experienced prosthodontist, and all laboratory procedures were performed by an experienced board-certified dental laboratory technician.

Table 1. Description of the main hardware, software, and materials used in this study.

Item	**Type**	**Description**
Metal 3D printer	SLM	NCL-M2150X (Nanjing Chamlion Laser Technology Co., Nanjing, China)
Resin 3D printer	DLP	Pro3D printer SRP1902A (SprintRay Inc., Los Angeles, CA, USA)
Printing software		Dental System 2019 version 19.3.0 (3Shape A/S, Copenhagen, Denmark)
Metal powder	CoCr	ChamTiger (Shinseki International Inc., Seoul, South Korea)
Resin powder		S-plastic Cast 2.0 (Graphy Inc., Seoul, South Korea)
Cast alloy	CoCr	Zaire Partial Denture Alloy (Neodontics Inc., Sun Valley, CA, USA)
Tabletop scanner		T500 (Medit Inc., Seoul, South Korea)
Metrology software		GOM Inspect 2018 (Hotfix 3, Rev. 1114010, Carl Zeiss GOM Metrology GmbH, Germany)

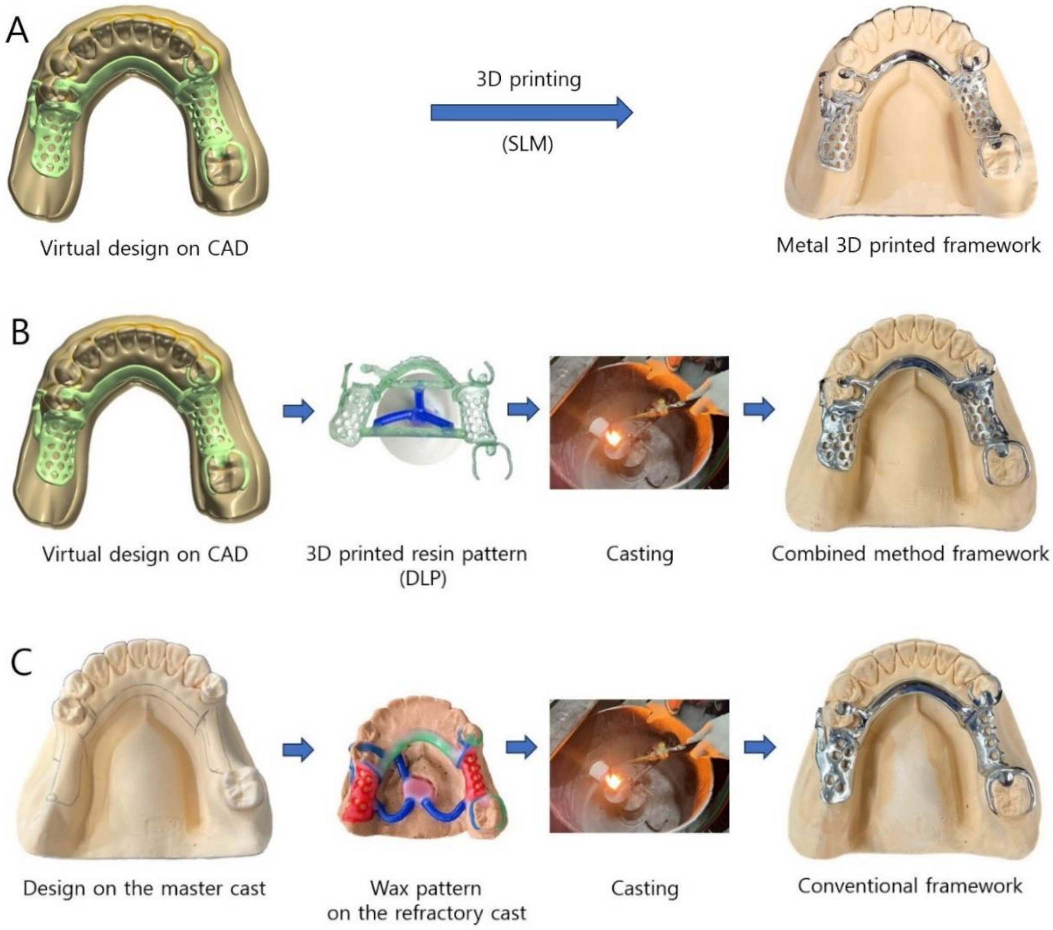


Figure 3. Three fabrication methods for removable partial denture metal frameworks. (A) Selective laser melting (SLM) technology-based metal 3D printing (SLM group), (B) digital light projection (DLP)-based resin 3D printing and subsequent casting (RPC group), and (C) conventional lost-wax casting (CON group).

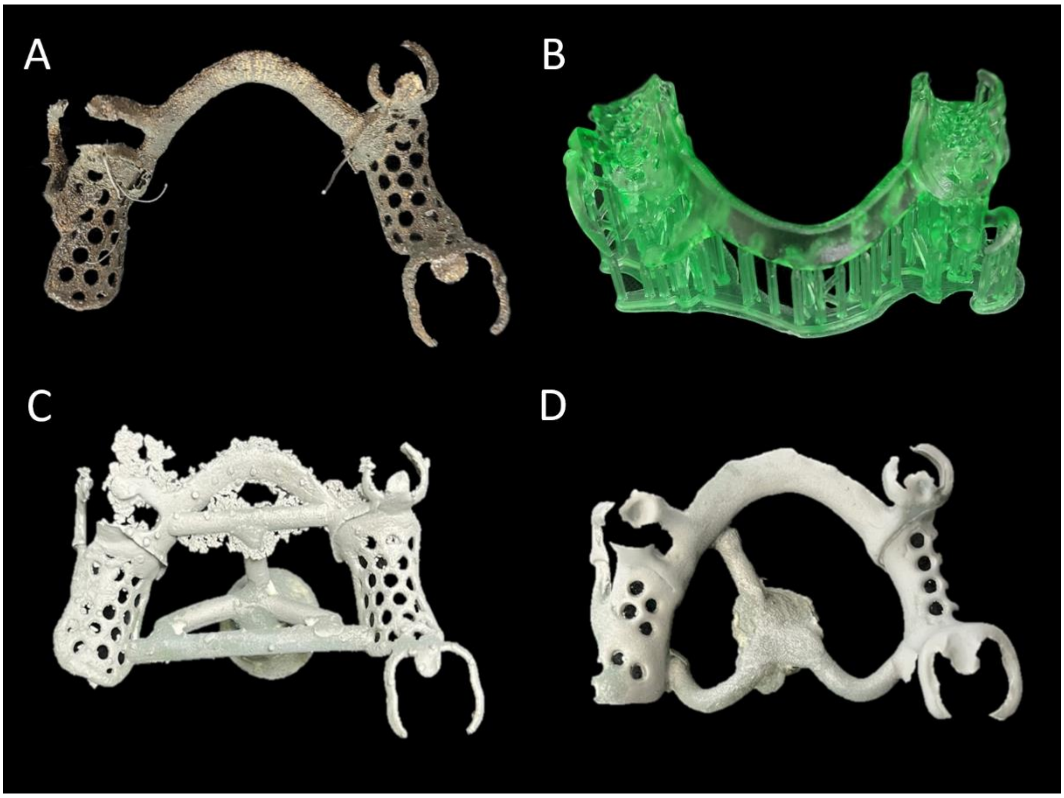


Figure 4. Three kinds of mandibular RPD metal frameworks prior to finishing and the 3D printed resin pattern. (A) Metal 3D printed RPD framework, (B) 3D printed resin pattern for RPC group, (C) 3D printed resin-cast RPD framework, and (D) conventional casted RPD framework.

5. Fitting the RPD metal frameworks with silicone material

Each RPD metal framework was fitted onto the corresponding master cast with silicone material. Before fitting, the intaglio surface of the framework was coated with a thin layer of petroleum jelly (Vaseline, Unilever, Greenwich, USA) to avoid attachment of the silicone material to the framework, and very thin adhesive liquid (polyether adhesive, 3M ESPE, USA) was applied to the rest seats, tissue stops, and major connector area of the master cast to avoid detachment of the silicone material from the cast while removing the framework. Vinyl polyether silicone material (Fit Checker Advanced; GC Corp., Tokyo, Japan) was mixed according to the manufacturer's instructions and applied to the intaglio surface of the rests, tissue stops, and a major framework connector. The framework was immediately fitted onto its corresponding master cast, and hand pressure was applied until the silicone hardened. Subsequently, the framework was carefully removed, leaving the silicone material intact on the master casts **(Figure 5A**). If any gap between the silicone material and the measurement area of the master cast was detected, the processes were repeated from the step of applying petroleum jelly after cleaning the master cast with steam.

6. Scanning of the silicone material-attached master casts

The silicone-remained master casts were scanned using the same tabletop scanner, and the scan data were saved as STL files (**Figure 5B**). All scanning procedures were performed without a powder coating.

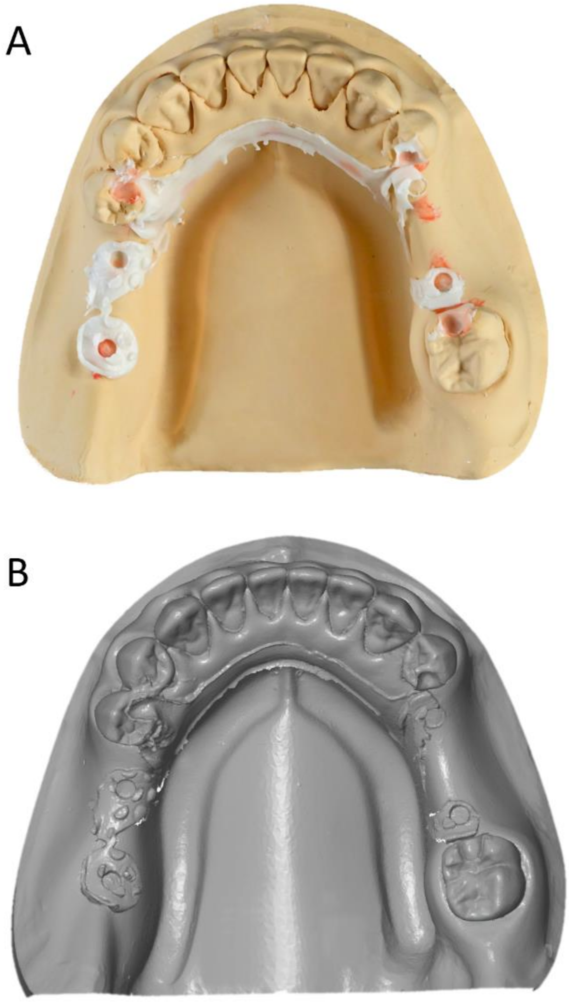


Figure 5. (A) The silicone-attached master cast and (B) screenshot of the STL file of the same master cast.

7. Measurement of internal discrepancies of the RPD metal frameworks

The two types of STL files were opened in the metrology software (GOM Inspect 2018, Carl Zeiss GOM Metrology GmbH, Braunschweig, Germany); one was the STL file of the master cast only, and the other was the STL file of the silicone material-attached master cast. The two STL files were superimposed using a local best-fit alignment function to measure the thickness of the silicone material, which represented the internal discrepancy of the framework (**Figure 6A**). The mean deviation values in eight areas of the RPD framework were digitally measured: three rests (35R, 44R, and 47R), four tissue stops (36T, 37T, 45T, and 46T), and a lingual bar (**Figure 6B**). The borderlines of the area to be measured were manually created in each master cast following a certain standard to ensure designation consistency. The border lines of the rest areas were selected 0.3 mm below the margin of the rest seat preparation, and lower circular lines were selected for the tissue stop areas. For the lingual bar, the horizontal border lines were selected 0.3 mm below the upper and lower imprinted edges, and the perpendicular border lines were selected at the distal sides of the left and right canines. Each selected patch was inspected through the "surface comparison on actual" function of the metrology software and was visualized by color mapping function and the tables presenting the mean and maximum deviation values of the spot (**Figure 6C**).

The internal discrepancies at rests, tissue stops and lingual bars (IDR, IDT, and IDL, respectively) and the overall internal discrepancies (IDOs) of three groups were calculated based on the mean deviation values of the tables in the 3D metrology software.

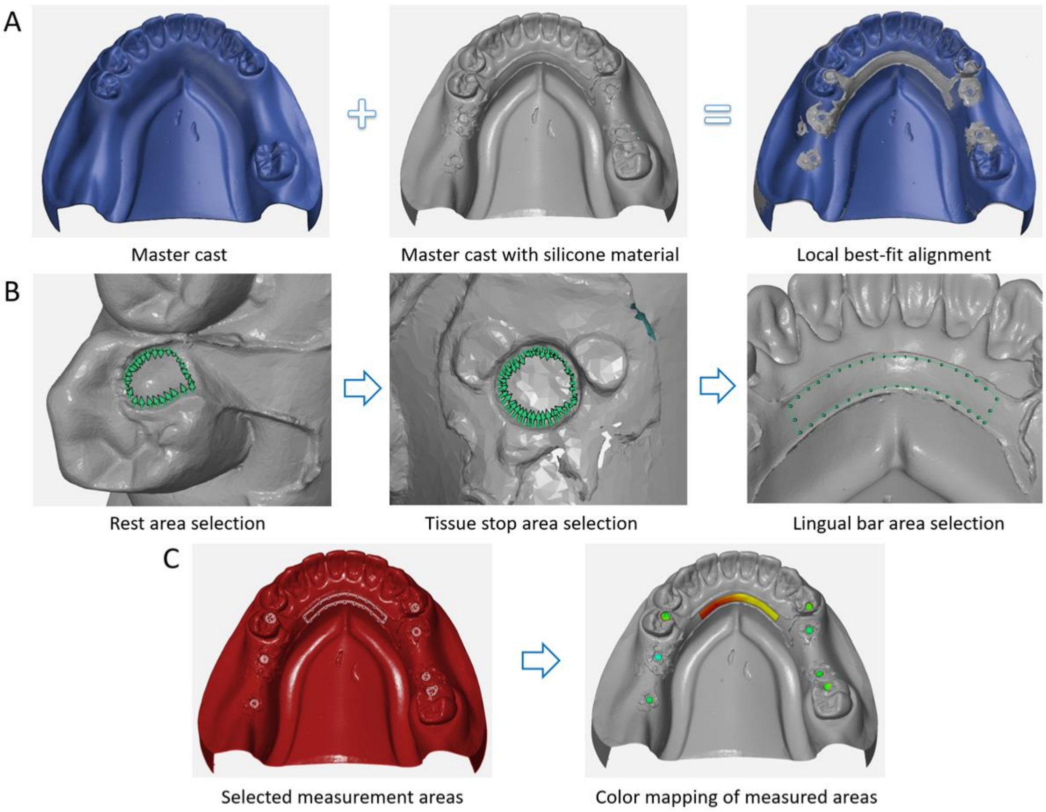


Figure 6. Screenshots of measurement procedures on the 3D metrology software. Thickness of the imprinted silicone material representing internal discrepancy was measured through superimposition of the two standard tessellation language (STL) files: the cast only and the cast with silicone material. (A) Superimposition of the two STL files by local best-fit alignment function of the metrology software, (B) manual selection of each measurement area, and (C) selected border lines at eight measurement areas (three rests, four tissue stops, and one lingual bar area) and color mapping of the areas (green represents good fit, yellow to red represents positive error, blue represents negative error).

8. Statistical analysis

A sample size of 10 per group was determined based on the statistical significance level set at α=0.05 with effect size of 0.6. The Shapiro-Wilk test was performed to examine the normality and all data followed normal distribution ($P > 0.05$). One-way analysis of variance and a post-hoc Tukey's multiple comparison test were performed to determine differences between the three groups ($\alpha = 0.05$). The data were analyzed using statistical software (SPSS Statistics version 23.0, IBM Corp, Somers, NY, USA) and the graphs were created using the analysis graphing software (GraphPad Prism 10, Boston, MA, USA).

III. RESULTS

The IDO, IDR, IDT, and IDL of the mandibular RPD metal frameworks in three groups are presented in **Table 2**, and the comparative graphs of the data are presented in **Figure 7**. The regional analysis of the internal discrepancies is presented supplementarily in **Table 3**, **Figure 8, and Figure 9**.

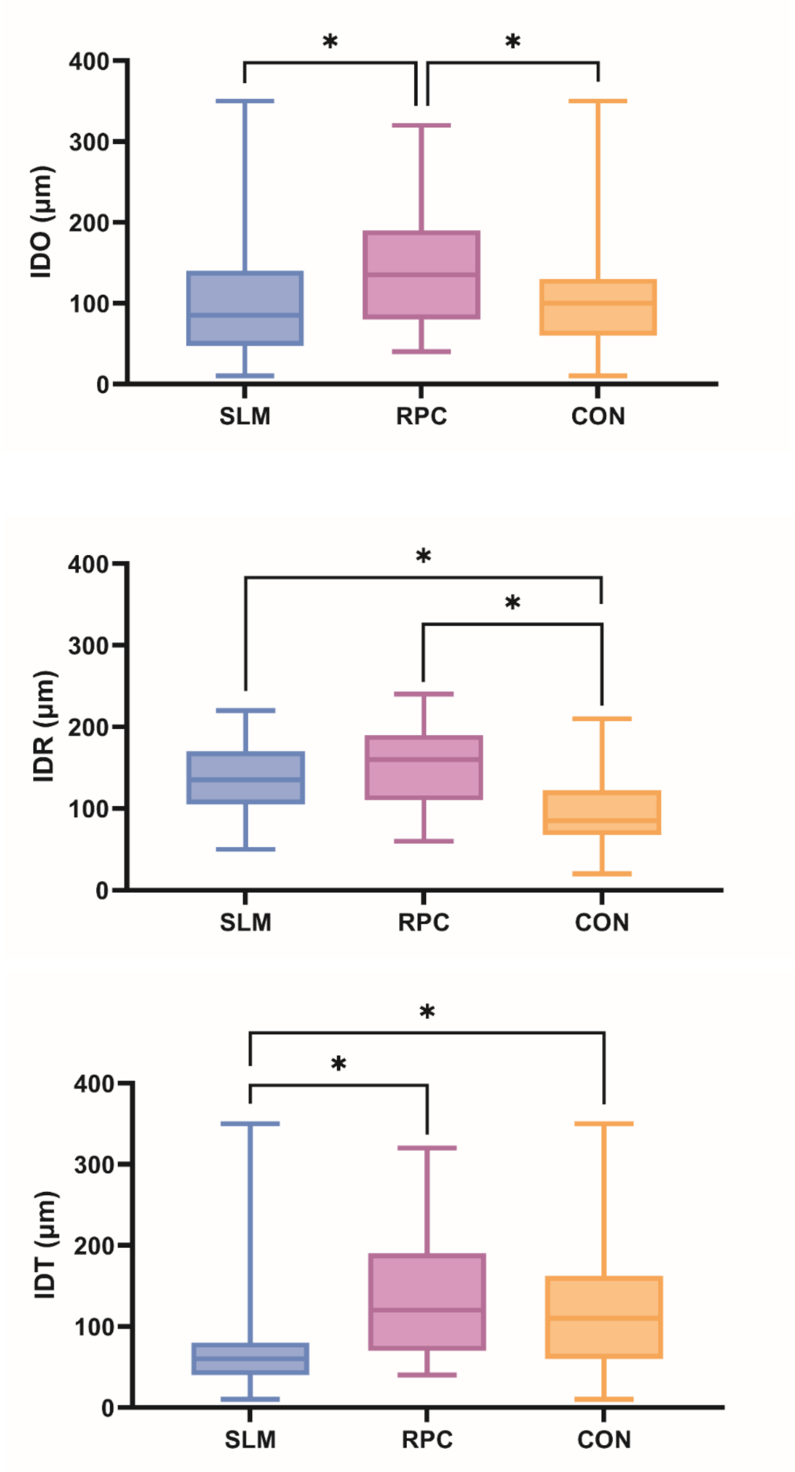
Comparison of internal discrepancies in the mandibular RPD metal frameworks of three groups: SLM, RPC, and CON group

The RPC group showed significantly higher overall internal discrepancies than the SLM and CON groups ($P=0.001$ and $P=0.019$, respectively), and the IDOs of the SLM and CON groups did not differ significantly ($P=0.633$). The CON group showed the lowest mean internal discrepancy at occlusal rests ($P=0.010$, $P<0.001$), whereas the SLM group showed the lowest internal discrepancy at tissue stops ($P=0.001$, $P=0.025$). The RPC group, combined with resin 3D printing and casting, showed the highest internal discrepancies for the rests and tissue stops with significant differences. For the internal discrepancies in lingual bars, no statistically significant differences were found among the three groups.

Table 2. The internal discrepancies (µm) of overall, rests, tissue stops and lingual bars of the mandibular RPD metal frameworks in three groups.

Internal discrepancies(µm) / Group	**SLM**	**RPC**	**CON**
IDO	101.7 ± 68.41^{a} (81.48-121.95)	143.7± 67.29^{b} (123.43-163.99)	112.3 ± 70.09^{a} (88.83-135.74)
IDR	133.0 ± 43.87^{a} (120.92-145.08)	149.0 ± 50.33^{a} (127.09-170.91)	96.3 ± 48.74^{b} (78.02-114.65)
IDT	78.2 ± 74.38^{a} (49.23-107.27)	139.8 ± 78.03^{b} (114.02-165.48)	124.3 ± 81.14^{b} (88.66-159.84)
IDL	127.0 ± 44.48^{a} (95.18-158.82)	135.0 ± 72.91^{a} (82.84-187.16)	150.0 ± 25.81^{a} (131.53-168.47)

The data are expressed as mean ± standard deviation and confidence intervals. IDO, overall internal discrepancy; IDR, internal discrepancy of rests; IDT, internal discrepancy of tissue stops, SLM group, metal 3D printed frameworks; RPC group, 3D printed resin-cast frameworks; CON group, conventional cast frameworks. The default value of 200 µm set for lingual relief in CAD was subtracted from IDL in SLM and RPC groups. Different letters indicate statistically significant differences among the three groups ($P<0.05$).


IDO (μm)
400
300
200
100
0
*
*
SLM
RPC
CON
IDR (μm)
400
300
200
100
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IDT (μm)
400
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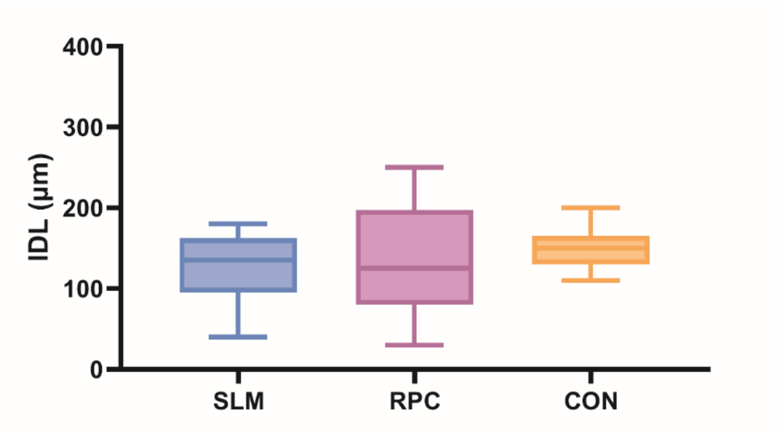

Figure 7. Comparisons of internal discrepancies in mandibular RPD metal frameworks of three groups. (A) Internal discrepancies overall, (B) internal discrepancies at rests, (C) internal discrepancies at tissue stops, and (D) internal discrepancies at lingual bar areas (SLM-selective laser melting-based metal 3D printing, RPC-digital light projection-based resin 3D printing and subsequent casting, and CON-conventional lost wax casting)**.** The asterisks indicate statistically significant differences among the three groups (P<0.05).

Table 3. **The internal discrepancies (μm) at three rests and four tissue stops in mandibular RPD metal frameworks of three groups.**

Internal gap(μm) / Group	SLM	RPC	CON
#35 rest	122 ± 38.23[a]	183 ± 40.83[b]	129 ± 57.62[a]
#44 rest	126 ± 42.47[a]	132 ± 46.61[a]	65 ± 32.40[b]
#47 rest	151 ± 48.86[a]	132 ± 48.94[ab]	95 ± 31.71[b]
#36 tissue stop	59 ± 35.73[a]	87 ± 38.60[ab]	136 ± 50.54[b]
#37 tissue stop	104 ± 50.68[a]	109 ± 65.02[a]	69 ± 36.04[b]
#45 tissue stop	51 ± 28.06[a]	168 ± 55.39[b]	111 ± 58.47[ab]
#46 tissue stop	99 ± 45.54[a]	195 ± 61.39[b]	181 ± 60.33[b]

The data are expressed as mean ± standard deviations. SLM group, metal 3D-printed frameworks; RPC group, 3D-printed resin-cast frameworks; CON group, conventional cast frameworks. Different lowercase letters in the same row indicate statistically significant differences among the groups.

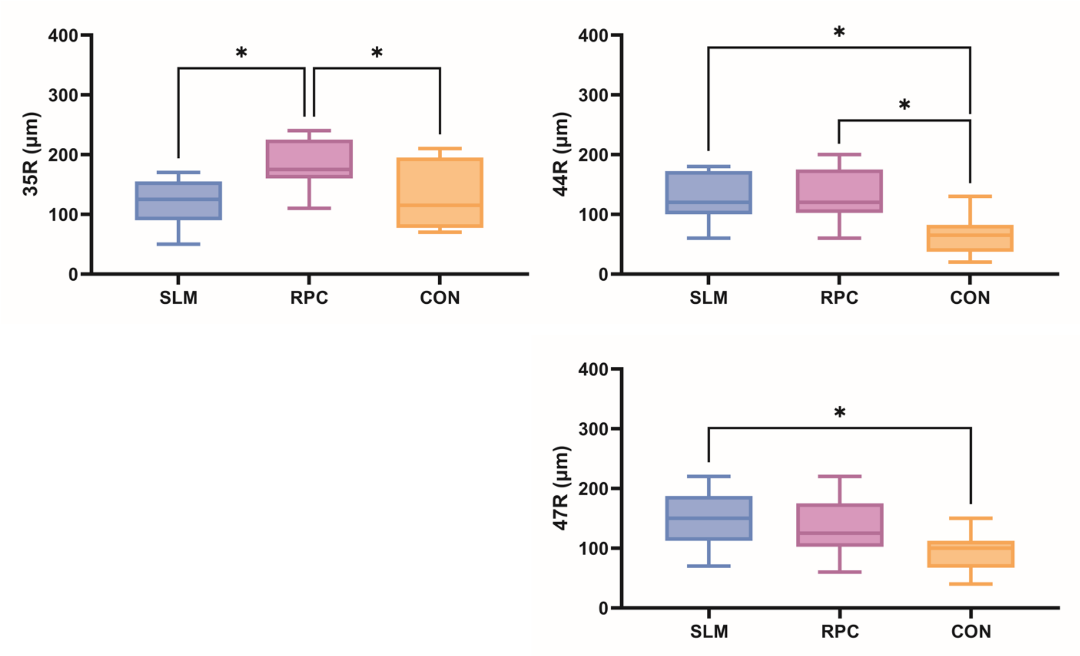

Figure 8. Comparisons of the internal discrepancies at the rests of #35, #44, #47 in mandibular RPD metal frameworks fabricated using three methods (SLM: selective laser melting-based metal 3D printing, RPC: DLP-based resin 3D printing and subsequent casting, CON: conventional lost-wax casting). The asterisks indicate statistically significant differences among the three groups.

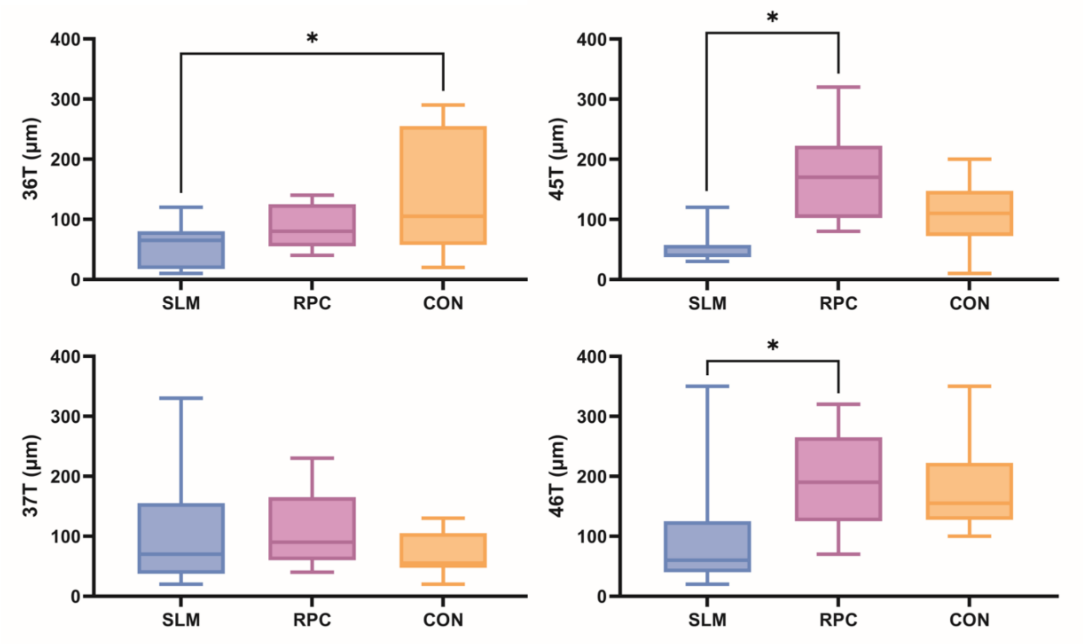

Figure 9. Comparisons of the internal discrepancies at the tissue stops of #36, #37, #45, #46 in mandibular RPD metal frameworks fabricated using three methods (SLM: selective laser melting-based metal 3D printing, RPC: DLP-based resin 3D printing and subsequent casting, CON: conventional lost-wax casting). The asterisks indicate statistically significant differences among the three groups.

IV. DISCUSSION

The null hypothesis was rejected owing to significant differences in the accuracy of the mandibular RPD metal frameworks among the three manufacturing methods. There were no significant differences between the IDOs of the SLM and CON groups, whereas the RPC group showed a relatively higher IDO than the other two groups, which can be ascribed to the higher error tendency of the RPC group. The RPD frameworks of the RPC group were manufactured using a combined method of resin 3D printing and conventional casting, which could be more prone to errors. Although it eliminated the steps of fabricating a refractory cast and waxing, which could result in inaccuracies owing to the physical properties of wax (Diwan R 1997), it was implicated in the errors from the steps of 3D printing of castable resin patterns and in those from the steps of conventional investing and casting. According to Revilla-Leon et al. (Revilla-Leon, Ozcan 2019), discrepancies can be incorporated into each step of a digital dental workflow. The 3D printer parameters, the material used (which has its optimal activation range of wavelength), power, and exposition time for additive manufacturing on the 3D printers can affect the accuracy of the printed objects.

The accuracy of the rests and tissue stops, which are the structural components of the RPD frameworks that directly contacted the tooth or tissue, differed significantly among the three groups in this study. The CON group showed the highest accuracy for the rests, and the SLM group had the highest accuracy for tissue stops. The RPC group had the lowest accuracy for both components. In 2020, Tasaka et al. (Tasaka et al. 2020) reported that the accuracy of mandibular RPD metal frameworks differed depending on the structural components comparing SLS technology-based 3D printing and 3D printed resin pattern-casting, which is consistent with the results of this study. In 2019, Bajunaid et al. (Bajunaid et al. 2019) compared the accuracy of mandibular RPD frameworks fabricated by SLM technology-based 3D printing and conventional casting through measuring four rest zones with a digital microscope. The zones with the highest fit and accuracy among the two groups were different, which is also consistent with the result of present study.

As this study was conducted on the mandibular RPD frameworks, it was also compared with previous studies on the maxillary RPD frameworks. Oh et al. (Oh, Yun, Kim 2022) compared the accuracy of maxillary RPD frameworks under similar conditions with this study, concluding that there were no significant differences among the three groups of SLM, RPC, and CON; however, the IDOs (226.99–365.30 μm) were all higher than those of this study (101.70–143.70 μm). The mean IDR of the three groups in this study was also lower by approximately 110 μm than that of the study of Oh et al. This difference could be ascribed to different factors. First, the palatal contact area was not included in the mandibular RPD frameworks, which can reduce the interferences before the contact of rests and rest seats. In contrast, the maxillary RPD frameworks could have early interferences due to palatal contact of a major connector. Second, the measurement criteria differed. “Point” measurement was employed in the previous study, whereas “area” measurement was employed in this study. The “area” measurement can reduce the contingency of manual designation more than the “point” measurement. Lastly, the use of equipment and metrology software of different manufacturing companies could affect the difference. Chen et al. (Chen et al. 2019) evaluated the adaptation of maxillary RPD metal frameworks fabricated by SLM technique with four types of partially edentulous resin models. They reported that SLM-fabricated RPD frameworks had acceptable accuracies; however, among the frameworks with a large span and more retainers and clasps, conventional casting technique exhibited slightly better fit and accuracy. Moreover, Soltanzadeh et al. (Soltanzadeh et al. 2019) evaluated the accuracy and fit of maxillary RPD frameworks fabricated by conventional casting and 3D printing techniques with stone and 3D printed resin models. Both methods revealed clinically acceptable adaptation (50–311 μm) but the conventional casting groups exhibited better overall fit and higher accuracy. The poorest fit was observed at the anterior palatal straps fabricated using the 3D printing technique.

Studies on 3D printed RPD metal frameworks regardless of maxilla and mandible have previously been conducted. Tregerman et al. (Tregerman et al. 2019) compared the clinical fit of RPD metal frameworks fabricated by three workflows—conventional casting pathway, SLM-3D printing with extraoral scanning of the stone cast, and SLM-3D printing with intraoral scanning—and concluded that the completely digital workflow had the lowest misfit. Almufleh et al. (Almufleh et al. 2018) compared patient satisfaction with

RPDs using frameworks fabricated by conventional casting and SLS-3D printing, revealing that higher satisfaction was achieved with the RPDs obtained using SLS-3D printed frameworks. Peng et al. (Peng et al. 2022) compared the trueness of RPD metal frameworks fabricated by SLM-3D printing and 3D printed resin-casting. The frameworks fabricated by SLM-3D printing exhibited higher trueness than those by the combined method. Summarizing the results of recent studies, SLM-3D printing and conventional casting techniques demonstrated similar accuracies for fabricating RPD metal frameworks within a clinically acceptable range, as evidenced in this study.

For the internal gap between a rest and a rest seat, the mean distance per rest in casted RPD frameworks was reported as 69–387 µm (Stern MA 1985) and 193–203 µm (Dunham et al. 2006). In 2017, Lee et al. (Lee et al. 2017) studied the accuracy of RPD frameworks fabricated through a combined method. The mean IDR of 249.27±134.84 µm, which was higher than previously reported values on casted RPD frameworks, was obtained. Oh et al. (Oh, Yun, Kim 2022) obtained IDRs in the range of 211.91 ± 16.84 to 259.26 ± 45.41 µm without significant differences among the three manufacturing methods. Souza Curinga et al. (Souza Curinga et al. 2023) achieved the IDR range of 20–279 µm for conventional cast frameworks and 30–272 µm for 3D printed frameworks, which did not indicate a significant difference. The IDRs in the aforementioned studies are in the ranged of 20–387 µm, whereas those in this study were lower, indicating the clinically acceptable values.

The internal discrepancies of lingual bars, which are yet to be investigated, were also measured in this study, whereby no significant differences were noted among the three groups. The default value of 200 μm set for lingual relief in CAD was subtracted from the IDLs of SLM and RPC groups because wax relief under a lingual bar was not performed in CON group owing to the absence of undercuts. We also tried to identify specific tendencies depending on the locational factors among three groups, such as tooth-borne area versus tooth and mucosa-borne area; however, it was difficult to find particular trends (**Table 3**, **Figure 8**, **and Figure 9**).

Nonetheless, this study had certain limitations. First, this work was an in vitro study with different conditions than that with an actual patient's oral mucosa. The edentulous area of a patient was covered with elastic soft tissue and saliva, whereas the master cast was not. Thus, there might be differences compared to results obtained from in vivo studies. Second, the finishing and polishing have various influences (Brudvik, Reimers 1992). However, complete adaptation of the RPD framework on the cast is difficult to achieve without finishing and polishing, and an actual RPD framework is fitted into patient's oral cavity after complete polishing. Therefore, the measurement of polished frameworks was considered inevitable and appropriate. To minimize the undesirable effect of finishing and polishing to the result of this study, all 30 frameworks were finished and polished by one experienced board-certified laboratory technician. If the processes were carried out by different technicians, it would be difficult to ensure accurate comparisons among the groups since this study was based on an experiment requiring group comparison under the same conditions. Lastly, the manual designation of the border lines of the measurement areas can affect the measurement values finely. Owing to the nature of digital measurement on the metrology program, the value changes finely each time it is measured depending on the selected location. Therefore, we measured multiple times with careful selection of the border lines.

However, to date, metal 3D printing using SLM technology is the most convenient method for manufacturing RPD frameworks, which can reduce the time and labor required for conventional laboratory processes. To produce more accurate RPD frameworks than conventional cast frameworks, further studies using various metal 3D printers and software are essential. Further, more in vivo studies on the accuracy, fitness, and longevity of metal 3D-printed RPD frameworks are needed until the use of metal 3D-printed RPD frameworks becomes generalized.

V. CONCLUSION

Within the limitations of this study, the following conclusions can be drawn.

1) SLM-fabricated RPD frameworks exhibited overall accuracy similar to those of conventional casted RPD frameworks.

2) A combined method of resin 3D printing and casting showed inferior accuracy. However, all frameworks in the three groups were clinically acceptable.

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국문요약

세 가지 방식으로 제작된 하악 국소의치 금속 구조물의 정확도

연세대학교 대학원 치의학과

<지도교수 김 지 환>

김 수 남

1970 년대부터 발전을 거듭해 온 CAD/CAM 기술은 치과계에 많은 변화를 가져왔으며, 국소 의치의 금속 구조물 제작도 예외는 아니었다. 2000 년대 초반, CAD/CAM 을 이용해 3D(삼차원)로 출력한 국소 의치 금속 구조물의 레진 모형이 전통 방식에서 수작업으로 만들어지던 납형을 대신하는데 성공하였고, 곧이어 컴퓨터 프로그램 상에서 설계한 국소 의치 금속 구조물을 금속 3D 프린팅 기술로 직접 출력하는 단계에 이르렀다. 이는 곧 많은 노동력과 시간이 소요됨에도 한

세기 넘게 사용되어 온 납형 주조 방식의 혁신적인 대안으로 각광받게 되었다. 이에 본 연구에서는 금속 3D 프린팅 방법 (SLM 군), 레진 3D 프린팅/주조 방법 (RPC 군), 전통적인 납형 주조 방법 (CON 군)으로 제작된 하악 국소의치 금속 구조물의 정확도를 디지털 중첩을 통해 비교해 보고자 한다.

먼저 케네디 분류 2 급 1 류의 하악 덴티폼을 준비하여 좌측 제 2 소구치의 근심, 우측 제 1 소구치의 원심, 우측 제 2 대구치의 근심에 교합면 레스트를 형성하고 유도면 설정 후 테이블탑 스캐너로 스캔하여 레퍼런스 파일로 저장하였다. 덴티폼을 반복적으로 인상 채득하고 석고를 부어 30 개의 주모형을 만들고, 완성된 주모형을 스캔한 뒤 각각 레퍼런스 파일에 중첩시켜 모든 주모형이 동일함을 확인하였다. 30 개의 주모형은 10 개씩 세 그룹으로 나누어 세 가지 방식으로 국소의치 금속 구조물을 제작하였으며, 국소 의치의 설계는 모두 동일하게 하였다 (주 연결부는 설측바, 좌측 제 2 소구치에는 I-바 클래스프, 우측 제 1 소구치와 제 2 대구치에는 C-클래스프를 적용하였으며, 양측 무치악부에는 두 개씩 조직부 스탑을 형성). 이후 완성된 각 금속 구조물마다 내면에 실리콘 재료를 얇게 도포하여 해당 모형에 시적한 뒤 빼내어 인기된 실리콘 재료만 남아 있는 모형을 동일한 스캐너로 다시 스캔하였다. 각 모형마다 갖게 된 두 스캔 자료를 중첩하여 총 8 곳(3 개의 레스트, 4 개의 조직부 스탑, 설측바)에서 실리콘 두께를 측정하여 내면 오차를 비교하였다.

그 결과, RPC 군의 내면 오차가 다른 두 군에 비해 유의하게 높은 것으로 나타났고(각 P=0.001, P=0.019), SLM 군과 CON 군은 통계적으로 유의할 만한 차이가 없었다(P=0.633). 국소 의치 금속 구조물의 각 부위별로 비교해 보면 교합면 레스트에서는 CON 군이(P=0.010, P<0.001), 조직부 스탑에서는 SLM 군이 가장 낮은 내면 오차를 보였으며(P=0.001, P=0.025), 설측 바에서는 세 군 모두 통계적으로 유의할만한 차이가 없었다.

결론적으로 금속 3D 프린팅 방식으로 제작된 국소 의치 금속 구조물은 전통적인 납형 주조 방식으로 제작된 금속 구조물과 비슷한 정확도를 보였다. 레진 3D 프린팅/주조 방식으로 제작된 금속 구조물은 가장 낮은 정확도를 보였으나, 세 군 모두 임상적으로 사용 가능한 범위에 있었다.

핵심이 되는 말: 가철성 국소 의치 금속 구조물, 디지털 중첩, 정확도, 선택적 레이저 용융