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# A comparative study of accuracy in dental CAD softwares on designing a fixed partial denture

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# A comparative study of accuracy in dental CAD softwares on designing a fixed partial denture

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# 감사의 글

보통의 경우 보다 10년 이상 늦게 시작한 대학원 공부는 어려운 점도 많았지만, 배움의 끈을 놓지 않도록 해준 것과 배움의 중요성을 다시금 생각해볼 수 있도록 하여준 것만으로도 너무나 유익한 시간이었습니다. 그리고 박사과정에서 막연하게나마 느낄 수 있었던 디지털 치의학의 변화는 놀라웠고, 앞으로 발전하게 될 그 방향과 한계는 짐작할 수 없을 것 같았습니다.

지난 4년 여간의 박사과정 동안 학문적인 지도뿐만이 아니라 어려운 일이 있을 때마다 배려해주신 문홍석 지도교수님께 깊은 감사를 드립니다. 불쑥 연락 드려도 마다하지 않으시고 기꺼이 상담해주셨던 김지환교수님과 김종은교수님과 모든 보철과 교수님들께 머리 숙여 감사를 드립니다. 그리고 귀중한 조언으로 논문을 보다 가치 있게 만들어 주셨던 보존과 신유석 교수님과 생체재료학교실 권재성교수님께 다시 한번 감사를 드립니다. 여러 가지 문제가 있을 때 해결책을 알고 있는 오경철교수님께도 특별한 감사를 드립니다.

수련기간 동안 부족한 저를 참아주시고 이끌어 주신, 은사 인하대병원 치과 오남식과장님께 심심한 감사를 드립니다. 치과병원 업무를 가르쳐 주신 중앙보훈병원 치과병원 장영일원장님께도 감사의 인사를 드립니다.

마흔이 훌쩍 넘은 막내아들을 네 살 배기처럼 아껴주시는 아버지와 어머니께 사랑과 존경을 드립니다. 자주 찾아 뵙지 못해도 이해해 주시고 사랑해주시는 장인어른, 장모님께 사랑과 존경을 드립니다. 모두 건강하시고, 하루하루가 행복하시길 기도 드립니다.

1인 3역을 하느라 항상 수고가 많은 나의 반쪽, 아내 아미씨와 언제 봐도 자랑스러운, 내 삶의 축복 주영이, 민영이, 준영이 그리고 윤영이에게

사랑한다는 말을 전하고 싶고, 앞으로는 더 많은 시간을 함께하겠다는 약속을 드립니다.

지금까지 인도하셨고, 영원히 선한 인도자가 되실 나의 예수님으로 인하여, 내 삶의 주인 되시는 하나님께 사랑과 감사와 영광을 올려드리며 박사 논문을 마무리하고자 합니다.

2019년 6월

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# Abstract

## A comparative study of accuracy in dental CAD softwares on designing a fixed partial denture

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In the manufacture of dental prostheses, computer-aided design/computer-aided manufacturing (CAD/CAM) methods offer numerous advantages compared to traditional methods. However, like traditional methods, there is potential for error at each stage, and the sum of these errors is the error in the final prosthesis. Meanwhile, error testing at each stage is relatively underdeveloped for CAD/CAM methods. In particular, there have been almost no experimental studies on the validation of CAD software.

Therefore, in this study, we aimed to test the accuracy of CAD software, in terms of trueness and reproducibility, in the stage of fixed prosthesis design. Trueness was defined as the concordance between the values for the internal clearance set by the operator and the internal clearance of the CAD prosthesis implemented in CAD software. Reproducibility was defined as the concordance in three-dimensional (3D) shape between the intaglio surfaces of prostheses designed identically in different CAD software. There was a total of nine test groups, corresponding to three types of CAD software and three values set for the internal clearance. The 3D analysis software was used to calculate the internal clearance error for the CAD prostheses and the 3D concordance of the intaglio surfaces of the CAD prostheses.

Statistical analysis was performed using two-way ANOVA, and there were significant differences between the groups in trueness and reproducibility ($p<0.05$). For Exocad®, using an internal clearance of 120 μm, the mean error was 22 μm, with errors of 3 μm or less at the margins, axial walls, and occlusal surfaces. Dental Designer™ showed errors of 1 μm or less at the margins, axial wall, and occlusal surface. The inLab16® software showed mean errors of -5 μm at the mesial axis margin, -6.7 μm at the distal axis margin, -16.5 μm at the mesial axial wall, 7.8 μm at the distal axial wall, 3.2 μm at the occlusal surface of #24, and -5.2 μm at the occlusal surface of #26.

The root mean square error (RMSE) of each group showed significant differences depending on the type of CAD software and the internal clearance ($p<0.05$). At the internal clearance set of 40 μm, 80 μm, and 120 μm, the mean RMSE for Exocad was 85 μm, 115 μm , and 127 μm, respectively, for Dental Designer™ it was 270 μm, 292 μm, and 319 μm, respectively, and for inLab16 it was 183 μm, 194 μm, and 171 μm, respectively.

Within the limitations of our study, the following conclusions were obtained: 1. The accuracy of the CAD software varied depending on the dental CAD software type and the internal clearance(IC) parameter. 2. According to the internal clearance of CAD prostheses at the margins, axial walls, and occlusal surface, DentalDesigner™ showed the best trueness, followed by Exocad, then inLab16. The internal clearance of CAD prosthesis of inLab16 presented greater difference between mesial and distal side of the abutment model than Exocad and Dental Designer. 3. According to the RMSE between CAD prostheses of same condition, Exocad showed the best reproducibility, followed by inLab16, then Dental Designer™. ($p<0.05$).

**Keywords:** CAD software; Internal clearance; Trueness; Reproducibility

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## I. INTRODUCTION

In 1973, Dr. Fancois Duret published an article titled “Optical impression,” (Ala Omar Ali, 2015) and in 1989, Computer-Aided-Design/Computer-Aided-Manufacturing (CAD/CAM) CEREC system was launched by Dr. Mormann, which marked the beginning of fabrication of dental prostheses using optical digital impressions (Ueda and Yamaguchi, 2017). Subsequently, many changes in treatment paradigms have taken place in clinical dentistry, along with rapid advances in digital dentistry (Baba, 2014).

For fabrication of dental restorations, the CAD/CAM process can be divided largely into three steps. The first step is acquiring data through three-dimensional (3D) dental scanners; the second step uses such data to design the prosthesis in CAD software; and the third step fabricates the prosthesis using CAM (Abdullah et al., 2018). As described, the first step in the CAD/CAM system starts with digitization of intraoral information using a dental 3D scanner. Methods used for this include directly scanning the tissues inside the oral cavity, as well as conventional methods of taking an impression and scanning the impression body or fabricating a plaster model first, and then scanning the model (Alghazzawi, 2016; Flügge et al., 2013). Based on where the scan is performed, dental CAD/CAM systems could be classified as an examine room system, a dental lab system, a fabrication center system; or as in-office system if the CAM equipment and work performed is inside the examination room, and an out-office system if CAM-related work is performed in a lab or fabrication center (Beuer et al., 2008).

Using CAD/CAM methods for fabrication of dental prostheses offers many advantages over the traditional methods (Gabor et al., 2017), but errors in each fabrication step may still occur and that the sum of such errors is the final error of the prostheses is similar to that of traditional methods (Bankoğlu Güngör et al., 2018; Reich et al., 2005). In the early years after CAD/CAM was introduced, dental 3D scanners had very low accuracy, and as a result, there were many experiments that investigated the accuracy of various types of scanners used in clinical settings. However, with recent advances in science and technology, accuracy of scanners has improved enough for application in clinical settings (Ahlholm et al., 2018; Bankoğlu Güngör et al., 2018; Nedelcu et al., 2018; Pesce et al., 2018).

Meanwhile, because of market-leading companies being cautious about their proprietary technology and their business reasons to make it difficult for other companies to enter the market, dental 3D scanners almost exclusively output closed files (JS Lee, 2004). Moreover, conversion between closed files and open files was not allowed, and when using data output from a particular scanner, the choice of CAD software and CAM system had to follow the recommendation of the scanner manufacturer due to the risk of data loss (Grant et al., 2016). However, as technical capabilities became more advance, many more companies introduced scanners, CAD software, and CAM systems, which naturally led to emphasis on interoperability between each step through using open files. Consequently, dental offices and labs gradually gained the ability to selectively purchase the equipment and software needed (Van Noort, 2012).

Among the files used in dental CAD/CAM systems, the standard tessellation language (STL) format is a prime example of an open-file format, and by using this format, data transfer without loss between scanners and CAD software from different companies is possible. Based on such interoperability, many dental offices of today are equipped with dental 3D scanners for taking optical impressions and the collected data are sent to dental labs to complete the CAD software work and CAM-based fabrication of prostheses.

Under such environments, dentists were able to experience fabrication of prostheses using various types of CAD software, but they were not fully aware of the detailed specifications of each CAD software or the differences between software. Moreover, testing of possible errors in each step of the CAD/CAM process is relatively lacking, as compared to testing of the accuracy of dental 3D scanners. In particular, experimental studies on validation of CAD software are almost non-existent. Accordingly, it is believed that studies are needed to test the possibility of CAD software design errors that deviate from the design intent when designing particular prostheses using CAD software.

Marginal fitness is one of the key factors that determine the success of fixed prostheses (Rekow, 1993). Adequate marginal fit (MF) is essential for assuring acceptable life-span of prosthesis (Abduo et al., 2010; Bankoğlu Güngör et al., 2018), whereas inadequate MF may cause complications, such as secondary caries in the abutment tooth, periodontal disease, and pulpitis, to have a negative effect on long-term prognosis (Grasso et al., 1985; Schwartz et al., 1970; Walton et al., 1986). To achieve good prosthetic fit, appropriate internal clearance (IC) between the abutment tooth and fixed prosthesis is important. If IC is too small, the prosthesis installation may be incomplete (Wilson, 1994; Wu and Wilson, 1994), whereas excessively large IC may lead to reduced retention of the prosthesis and fracture resistance in complete ceramic restoration (Tuntiprawon and Wilson, 1995b).

Various studies have been conducted on MF and IC when fabricating fixed prosthesis by CAD/CAM methods. It appears that most of these studies used dental 3D scanners as an independent variable and MF and IC as dependent variables, while the study results did not properly control errors that different CAD software and CAM systems may have against each other. Accordingly, the present study set the type of CAD software and the parameter for IC as independent variables and aimed to compare the accuracy of CAD software using Exocad 2017 (Exocad GmbH, Darmstadt, Germany), 3shape DentalDesigner 2017 premium (3shape A/S, Copenhagen, Denmark), and inLab16 (Dentsply Sirona, York, PA, USA).

Among precedent studies, Shimizu et al. designed a single crown with the same MF and IC parameters in CAD/CAM system, after which, a 3D analysis program was used to analyze the CAD-based prosthesis. The results showed that MF was larger and IC was smaller than the set parameters (Shimizu et al., 2017). Shim et al. compared MF and IC of prostheses by using two different version of CAD software for a single CAD/CAM system and setting the IC parameter to 40 μm or 80 μm. The results showed that better fitness was seen in actual prostheses when the higher version was used with parameter set to 80 μm (Shim et al., 2015). According to a systematic review by Boitelle et al. on fitness of prostheses fabricated by CAD/CAM method, the IC parameter of prostheses set in the CAD software plays an essential role in achieving accurate fit, where accuracy of fit was associated with the intrinsic properties of CAD/CAM systems (Boitelle et al., 2014). Wettstein et al. reported that the differences in fitness between prostheses fabricated using different CAD/CAM systems are directly associated with the IC parameter set in the CAD software (Wettstein et al., 2008). Meanwhile, Jung reported that when the replica technique was used to investigate the IC of crowns fabricated by CAD/CAM method with IC set to 20 μm, the results were found to be ≥ 40 μm (JH Jung, 2016).

Accordingly, the present study aimed to determine differences in the accuracy of CAD software using three types of CAD software and three different IC values when designing three-unit zirconia fixed prostheses. For this, MF and IC of CAD prosthesis were measured and the conformity of internal 3D shape of the CAD prostheses fabricated under the same conditions was analyzed using a 3D analysis program. The null hypotheses were established as follows: 1) There will be no differences in MF and IC errors in CAD prostheses fabricated using different CAD software and IC parameter; and 2) There will be no differences in the conformity of internal shape of CAD prostheses fabricated under the same conditions.

# II. MATERIALS AND METHODS

## 1. Experimental group allocation

The present study used the type of CAD software and the IC parameter of #24–26 zirconia fixed partial denture (FPD) as independent variables in designing a total of nine experimental groups (Table 1). The general flowchart of the experiment was as shown in Figure 1.

**Table 1.** Experimental group allocation and abbreviations of each group`s name

| | Exocad | Dental Designer | inLab16 |
|---|---|---|---|
| 40 μm | EXO-40 | DD-40 | IN-40 |
| 80 μm | EXO-80 | DD-80 | IN-80 |
| 120 μm | EXO-120 | DD-120 | IN-120 |

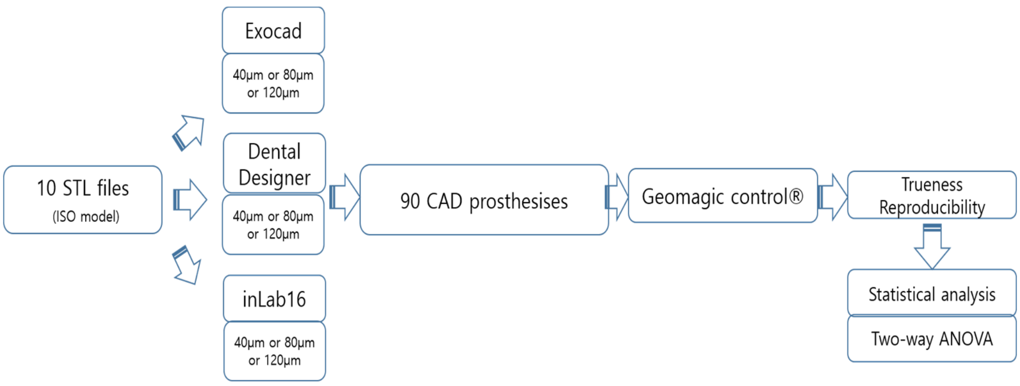
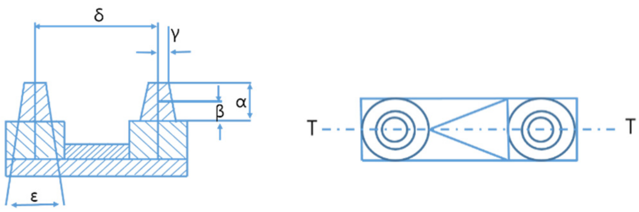


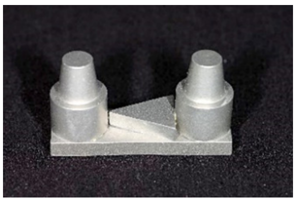

**Figure 1.** Flow chart of the present study

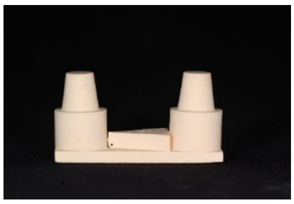
## 2. The abutment model for designing of CAD prosthesis

For the abutment model used in designing the CAD prostheses, the study used a model fabricated using stainless steel and scaled down by 70% from the model explained in ISO 12836:2015 (Fig. 2).




1)





2) 3)

**Figure 2**. The abutment model used for designing of CAD prosthesis in the present study

1) Schematic design of 70% reduced ISO 12836 model (SH OH, 2015) : α. (7.00±0.35)mm, β. (3.50±0.35) mm, γ. (1.80±0.10) mm, δ. 21.00±0.70) mm, ε. (16±1)°, T–T. Transversal line of examination for internal clearance. 2) Stainless steel model of 70% reduced ISO 12836 model. 3) Type IV stone model of 70% reduced ISO 12836 model for scanning.

To simulate the CAD/CAM process involved in fabrication of the prostheses using the model scanner, impressions of the abutment model described above were taken using polyvinyl siloxane (Empress II, 3M ESPE, USA) and putty (Exafine putty type, GC America Inc., USA) impression materials. Subsequently, type-4 four high-strength dental stone (Fuji Rock, GC Co, Tokyo, Japan) was vacuum mixed with water according to the mixture ratio given by the manufacturer, and the mixture was injected into the impression bodies to fabricate the stone models (Fig. 2).

### 3. The dental model scanner and scanning procedure

The Freedom HD (DOF Inc., Seoul, Korea) scanner uses a white LED light source to irradiate structured light with a particular pattern on top of the target object and acquires 3D shape information by a triangulation method based on the modified pattern on the surface of the target object recognized by the camera. According to the manufacturer, the scanner has an error range of approximately 10 μm of repeat scan precision. The formats and related extensions of the output files included stereolithography (STL), geometric object files (OBJ), and object file format (OFF).

By continuously scanning (ten times) the stone models fabricated by the method described above, the final triangularly-meshed digital shape information consisting of an average of 362,338 faces was obtained as ten STL files.

## 4. The dental CAD software programs

The present study used three different types of CAD software: Exocad® 2017, 3shape Dental Designer™ 2017 premium, and inLab16®. They are commercial products available worldwide. The general features of each software product are as shown below (Table 2).

Table 2. Product information for the three types of dental CAD software

| | Exocad | Dental designer | inLab16 |
|---|---|---|---|
| Company | Exocad GmbH | 3shape A/S | Dentsply Sirona |
| CAD/CAM system | Open system | Closed system | Closed system |
| Export file format | STL | DCM / STL | DXD / STL |
| Option for range decision of marginal no-IC* zone | Present | Present | Absent |
| Option for milling bur size & offset | Presence | Presence | Restricted[‡] |
| Additional properties | link with 3D printer | Optional link with 3D printer | Mandatory selection of milling system before FPD design |

*IC: internal clearance

[‡]Restricted: Unable to set the parameter for the drill offset but just click for "consideration for configure of the drill"

For all three types of CAD software, a round bur with a diameter of 1 mm was used for CNC milling. For Exocad and Dental Designer, the drill offset was set to 1.2 mm, whereas for inLab16, the settings were set to "consideration for milling bur shape" and to use "5-axis CNC milling other than Dentsply Sirona."

## 5. The design of a fixed partial denture (FPD)

The FPD was designed by the following method using each of the aforementioned CAD software applications. The design was based on a 3-unit FPD (#24–#26) assuming the anatomical shape when the #25 tooth is missing. No IC was given to the terminal margins of #24 and #26 abutments and this area was a part of the shoulder margin. In Exocad and Dental Designer, the area without IC could be set to 1 mm from the terminal margin, but inLab16 did not have such an option and processed this automatically. Subsequently, the IC for a part of the shoulder margin, axial wall and occlusal surface area was set to 40 μm, 80 μm, or 120 μm (Table 1).

The IC of the FPD acts as cement space, which must allow for the thickness of the cement, roughness of the teeth and prosthesis, inaccuracy of the die, and deformation of the wax pattern when fabricating the FPD according to existing methods (Anadioti et al., 2015). In the present study, the range of IC was set to 40 μm, 80 μm, and 120 μm in consideration of easy installation of the FPD and with reference to previous study results reporting that crown fracture strength may decrease if the clearance in the axial wall area exceeds 122 μm (Tuntiprawon and Wilson, 1995a; Wilson, 1994; Wu and Wilson, 1994). May et al. reported that uniformity of IC is important for complete ceramic crowns due to their brittleness (May et al., 1998).

## 6. Analysis of the CAD prosthesis

### 2.6.1 The measurement of marginal fit and internal clearance for 22 positions

Based on the triple scan protocol, the experiment was performed using the following method to properly position the abutment model file and CAD prosthesis file using the best-fit algorithm and global registration functions in the 3D analysis program Geomagic Control ®(3D Systems, Rock Hill, SC, USA) (Holst et al., 2011). From each CAD software, the CAD prosthesis properly positioned on the abutment model was output as a single STL file, while the CAD prosthesis for CAM work was output as a separate STL file. Moreover, only the best-fit algorithm and global registration functions were used to properly position the abutment model file and CAD prosthesis file on a single abutment model CAD prosthesis STL file, after which no manual correction was performed (Fig. 3).

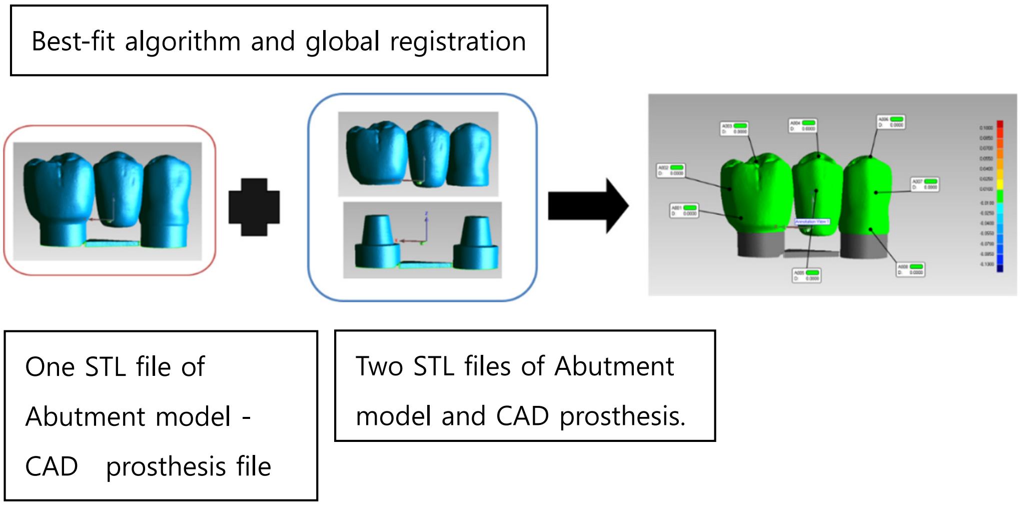
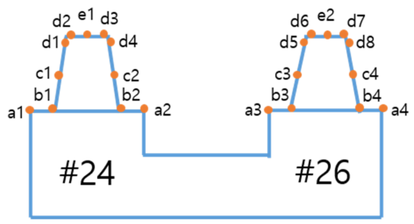
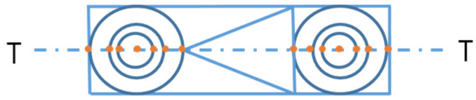



**Figure 3.** Positioning procedure with best-fit algorithm and global registration of Geomagic control®.

Subsequently, the MF and IC values from all 22 points (a1, b1, c1, d1, d2, e1, d3, d4, c2, b2, a2, a3, b3, c3, d5, d6, e2, d7, d8, c4, b4, and a4) of the abutment model were derived. In designating these points, “a” represented the terminal margin area; “b” represented the margin-axial line angle area; “c” represented the axial wall area; “d” represented the axial-occlusal surface line angle area; and “e” represented the occlusal surface area (Fig. 4).




A)




B)

**Figure 4.** Reference points for measurement of marginal fit and internal clearance. A) a1, a2, a3, and a4: terminal margin, b1, b2, b3, and b4: margin-axial line angle, c1, c2, c3 and c4: axial wall, d11, d2, d3, d4, d5, d6, d7, and d8: axial-occlusal surface line angle, e1 and e2: occlusal surface B) Reference points on transversal line of examination.

The IC value was set to “0” for approximately 1 mm medial to the terminal margin of the shoulder margin in all samples; thus, the measured value in the four “a” points was used as the resulting error value. In the four “c” points and the two “e” points representing axial wall and occlusal surface areas, the differences between the parameter and measured IC values were derived as the resulting error values for each points. In the four “b” point and eight “d” points representing the margin-axial line angle and axial-occlusal surface line angle areas, the measured IC value was used as the resulting value.

### 2.6.2 The three-dimensional comparison between the intaglio surfaces of the CAD prosthesis for same condition

The 3D shapes of the inner surfaces of the CAD prostheses designed using the same CAD software and IC value were compared to derive the root mean square error (RMSE) value. Among 10 samples fabricated using the same software and IC value, one CAD prosthesis was designated as the reference and the other nine samples were compared to the reference to derive the RMSE value (Fig 5). To designate one CAD prosthesis to be the reference, the sample with the smallest error values in the previous MF and IC measurements was selected.

## 7. Statistical Analysis

The statistical program used was PASW Statistics 18 (SPSS Inc., Chicago, IL, USA) and two-way analysis of variance (ANOVA) was performed with the type of CAD software and IC parameter as independent variables. The significance level was set to $\alpha<0.05$. Moreover, Bonferroni's test was used as the post hoc test for multiple comparisons.

In the present study, mesial and distal aspects were divided relative to each abutment to distinguish points a1, b1, c1, d1, d2, a3, b3, c3, d5, and d6 to represent the mesial aspect, and a2, b2, c2, d3, d4, a4, b4, c4, d7, and d8 to represent the distal aspect for statistical processing. Points e1 and e2, representing the occlusal surface, were distinguished by #24 and #26 abutments for statistical processing.

# III. RESULTS

## 1. Trueness of CAD software

Geomagic Control® was used to measure IC of each point in the abutment model (Fig. 4) and the results of statistical analysis by two-way ANOVA are discussed in the following sections.

### 3.1.1 The error value of fit at mesial margin

Statistical analysis of error value of MF at points a1 and a3 in the mesial margin of the abutment showed that MF varied depending on the CAD software and the IC parameter used (Table 3, $p < .00$). In the post hoc analysis, the results showed differences between all CAD software; while there were no differences between the IC parameter of 40 μm and 80 μm, the IC parameter of 120 μm showed significant differences as compared to the others.

Among the groups using Exocad, EXO-40 and EXO-80 equally showed a mean error value of 1.7 μm, while EXO-120 showed a relatively larger mean error value of 21.7 μm. Among the groups using Dental Designer, DD-40, DD-80, and DD-120 showed error values close to zero, which represented smaller error values than the other groups. Among the groups using inLab16 software, IN-40, IN-80, and IN-120 showed a mean error value of -4.5 μm, -5 μm, and -6.2 μm, respectively (Table 3, Fig. 5).

**Table 3.** Mean, standard deviation (error value), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in error value at mesial margin

| | Error value at mesial margin | | |
|---|---|---|---|
| | Exocad: Mean (SD) | Dental designer: Mean (SD) | inLab16: Mean (SD) |
| IC parameter | | | |
| 40µm | 1.7 (1.2) | 0 (0) | -4.5 (4.3) |
| 80µm | 1.7 (1.3) | 0 (0) | -5.0 (4.0) |
| 120µm | 21.7 (0.8) | 0 (0) | -6.2 (5.9) |

| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
|---|---|---|---|---|---|---|
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40µm-80µm(SE) | 40µm-120µm(SE) | 80µm-120µm(SE) |
| | .000 (.539) | .000 (.532) | .000 (.537) | 1.000 (.537) | .000 (.535) | .000 (.537) |

| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
|---|---|---|---|---|---|---|
| | F | P | F | P | F | P |
| | 332.962 | 0 | 88.53 | 0 | 110.52 | 0 |

SD: Standard deviation, SE: Standard error

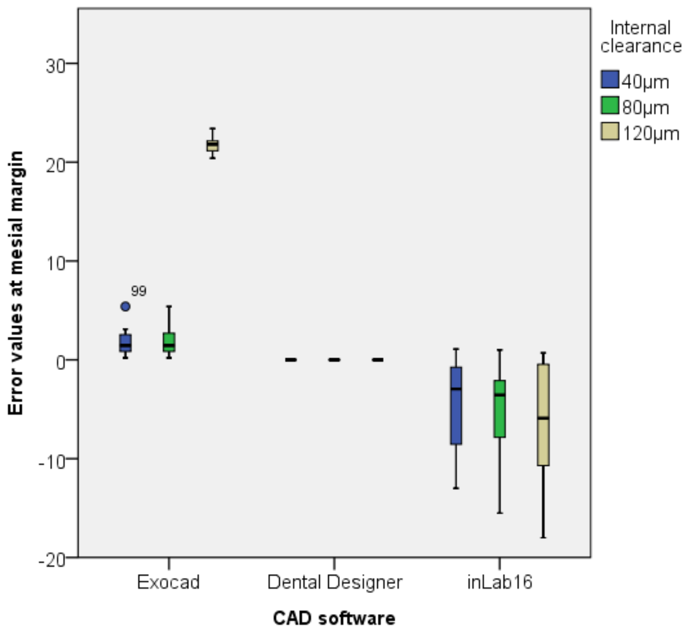



**Figure 5.** The error value of mesial marginal fit

### 3.1.2 The error value of fit at distal margin

Statistical analysis of the error value of MF at points a2 and a4 in the distal margin of the abutment showed that MF varied depending on the CAD software and IC parameter used (Table 4, $p < .00$). In the post hoc analysis, the results showed differences between all CAD software, and while there were no differences between IC parameter of 40 μm and 80 μm, the IC parameter of 120 μm showed significant differences as compared to the other two.

Among the groups using Exocad, EXO-40 and EXO-80 showed a mean error value of 1.4 μm and 1.2 μm, respectively, while EXO-120 showed a relatively larger mean error value of 21.9 μm. Among the groups using Dental Designer, DD-40, DD-80, and DD-120 showed error values close to zero, which represented smaller error values than the other groups. Among the groups using inLab16 software, IN-40, IN-80, and IN-120 showed a mean error value of -6.7 μm, -6.8 μm, and -6.6 μm, respectively (Table 4, Fig. 6).

**Table 4.** Mean, standard deviation (error value), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in error value at distal margin

| | Error value at distal margin | | | | | |
|---|---|---|---|---|---|---|
| | Exocad: Mean (SD) | | Dental designer: Mean (SD) | | inLab16: Mean (SD) | |
| IC parameter | | | | | | |
| 40μm | 1.4 (1.2) | | 0 (0.0) | | -6.7 (4.0) | |
| 80μm | 1.2 (1.2) | | 0 (0.1) | | -6.8 (3.1) | |
| 120μm | 21.9 (9.9) | | 0 (0.2) | | -6.6 (3.4) | |
| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40μm-80μm(SE) | 40μm-120μm(SE) | 80μm-120μm(SE) |
| | .000 (.402) | .000 (.406) | .000 (.409) | 1.000 (.406) | .000 (.406) | .000 (.406) |
| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
| | F | P | F | P | F | P |
| | 672.85 | 0 | 194.526 | 0 | 193.693 | 0 |

SD: Standard deviation, SE: Standard error

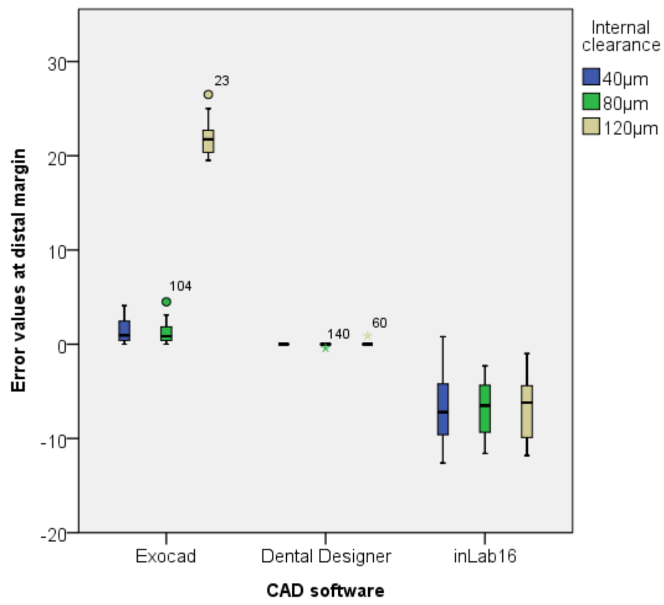



**Figure 6.** The error value of distal marginal fit

### 3.1.3 The internal clearance at mesial margin-axial line angle

Statistical analysis of IC measured at points b1 and b3 in the mesial margin-axial line angle area of the abutment showed that IC varied depending on the CAD software and IC parameter used (Table 5, $p < .00$). Post hoc analysis results confirmed differences among all CAD software and IC parameters used.

The results showed that the IC values measured in the mesial margin-axial line angle area increased as the IC parameter increased, while the groups using Exocad and Dental Designer showed mean values that were remarkably close to the IC parameter values. On the other hand, IN-40, IN-80, and IN-120 (groups using inLab16) showed mean value of 42 μm, 64 μm, and 88.8 μm, respectively, indicating that they were calculated as other values according to the IC parameter (Table 5, Fig. 7).

**Table 5.** Mean, standard deviation (internal clearance), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in IC value at mesial margin-axial line angle

| | IC at mesial margin-axial line angle | | | | | |
|---|---|---|---|---|---|---|
| | Exocad: Mean (SD) | | Dental designer: Mean (SD) | | inLab16: Mean (SD) | |
| IC parameter | | | | | | |
| 40µm | 41.0 (3.3) | | 41.5 (1.6) | | 42.0 (7.5) | |
| 80µm | 79.0 (6.1) | | 84.2 (3.7) | | 64.0 (5.5) | |
| 120µm | 119.0 (2.6) | | 125.9 (5.9) | | 88.8 (5.2) | |
| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40µm-80µm(SE) | 40µm-120µm(SE) | 80µm-120µm(SE) |
| | .000 (.901) | .000 (.913) | .000 (.909) | .000 (.905) | .000 (.905) | .000 (.913) |
| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
| | F | P | F | P | F | P |
| | 236.777 | 0 | 2963.546 | 0 | 81.472 | 0 |

SD: Standard deviation, SE: Standard error

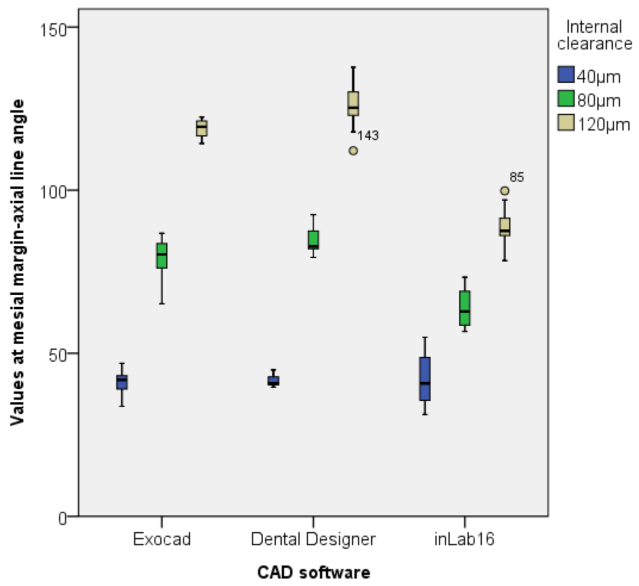



Figure 7. The internal clearance value at mesial margin-axial line angle

### 3.1.4 The internal clearance at distal margin-axial line angle

Statistical analysis of IC measured at points b2 and b4 in the distal margin-axial line angle area showed that IC varied depending on the CAD software and IC parameter used (Table 6, $p < .00$). In the post hoc analysis, the results showed no difference between Exocad and Dental Designer. However, inLab16 showed differences as compared to the other two. And there were differences among all IC parameters used.

The results showed that the IC values measured in the distal margin-axial line angle area increased as the IC parameter increased, while the groups using Exocad and Dental Designer showed mean values that were very close to the IC parameter values.

On the other hand, IN-40, IN-80, and IN-120 (groups using inLab16) showed mean IC value of 46 µm, 65.4 µm, and 91.6 µm, respectively, indicating that they were calculated as other values according to the IC parameter (Table 6, Fig. 8).

**Table 6.** Mean, standard deviation (internal clearance), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in IC value at distal margin-axial line angle

| | IC at distal margin-axial line angle | | |
|---|---|---|---|
| | Exocad: Mean (SD) | Dental Designer: Mean (SD) | inLab16: Mean (SD) |
| IC parameter | | | |
| 40µm | 39.1 (4.6) | 40.3 (0.9) | 46.0 (10.2) |
| 80µm | 78.0 (7.2) | 80.5 (1.1) | 65.4 (7.8) |
| 120µm | 119.8 (2.7) | 120.8 (5.0) | 91.6 (6.7) |

| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
|---|---|---|---|---|---|---|
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40µm-80µm(SE) | 40µm-120µm(SE) | 80µm-120µm(SE) |
| | 1 (1.11) | .000 (1.1) | .000 (1.114) | .000 (1.1) | .000 (1.1) | .000 (1.119) |

| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
|---|---|---|---|---|---|---|
| | F | P | F | P | F | P |
| | 80 | 0 | 1960.156 | 0 | 56.762 | 0 |

SD: Standard deviation, SE: Standard error

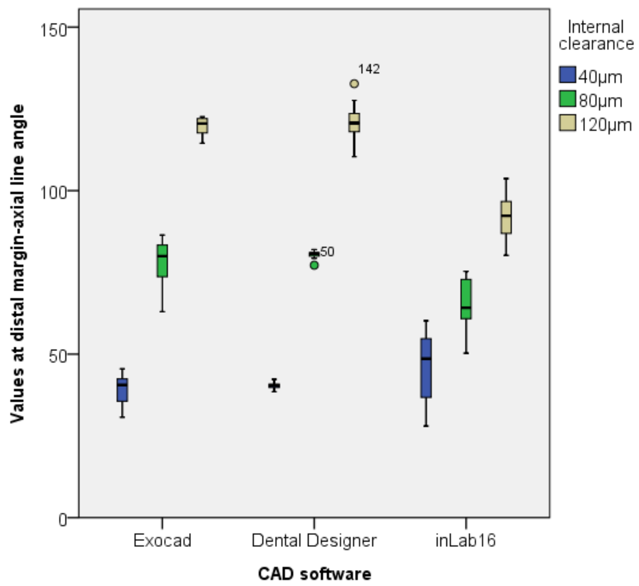


Figure 8. The internal clearance value at distal margin-axial line angle

### 3.1.5 The error value of internal clearance at mesial axial wall

The statistical analysis of error value of IC at points c1 and c3 in the mesial axial wall area showed that the error value varied depending on the CAD software and IC parameter used and that there was an interaction between the two factors (Table 7, $p < .00$). In the post hoc analysis, the results showed differences between all CAD software, and while there was no significant difference in error value between IC parameter of 40 μm and 80 μm, 80 μm and 120 μm, but significant difference between IC parameter of 40 μm and 120 μm.

The groups using Exocad and Dental Designer showed a mean error value of ≤ 2 μm, whereas IN-40, IN-80, and IN-120 (groups using inLab16) showed a mean error value of -16.1 μm, -16.6 μm, and -16.2 μm, respectively (Table 7, Fig. 9).

**Table 7.** Mean, standard deviation (error value), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in error value at mesial axial wall

| | Error value at mesial axial wall | | | | | |
|---|---|---|---|---|---|---|
| | Exocad: Mean (SD) | | Dental designer: Mean (SD) | | inLab16: Mean (SD) | |
| IC parameter | | | | | | |
| 40µm | 2.0 (0.1) | | 0.1 (0.6) | | -16.1 (1.7) | |
| 80µm | 2.0 (0.1) | | 0.1 (0.5) | | -16.6 (1.3) | |
| 120µm | 0.0 (0.1) | | 0.2 (0.8) | | -16.2 (1.5) | |
| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40µm-80µm(SE) | 40µm-120µm(SE) | 80µm-120µm(SE) |
| | .000 (.176) | .000 (.175) | .000 (.176) | .421 (.176) | .000 (.173) | .067 (.176) |
| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
| | F | P | F | P | F | P |
| | 6351.806 | 0 | 7.974 | 0 | 11.281 | 0 |

SD: Standard deviation, SE: Standard error

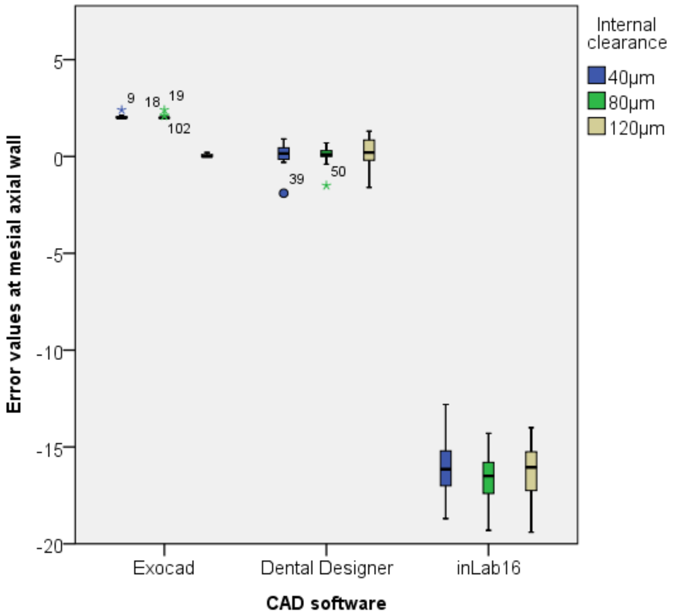



**Figure 9.** The error value of internal clearance at mesial axial wall

### 3.1.6 The error value of internal clearance at distal axial wall

Statistical analysis of the error value of IC at points c2 and c4 in the distal axial wall area showed that there were differences in error values depending on the CAD software and IC parameter used and that there was an interaction between the two factors (Table 8, $p < .00$). In the post hoc analysis, the results showed differences between all CAD software, and while there were no differences in error values between IC parameter of 40 μm and 80 μm, the IC parameter of 120 μm showed significant differences in error value as compared to the other two.

The groups using Exocad and Dental Designer showed a mean error value of ≤ 2 μm, whereas IN-40, IN-80, and IN-120 (groups using inLab16) showed a mean error value of 7.9 μm, 7.9 μm, and 7.7 μm, respectively (Table 8, Fig. 10).

**Table 8.** Mean, standard deviation (error value), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in error value at distal axial wall

| | | | | | | |
|---|---|---|---|---|---|---|
| | Error value at distal axial wall | | | | | |
| | Exocad: Mean (SD) | | Dental designer: Mean (SD) | | inLab16: Mean (SD) | |
| IC parameter | | | | | | |
| 40μm | 2.0 (0.1) | | 0.1 (0.2) | | 7.9 (1.3) | |
| 80μm | 2.0 (0.1) | | 0.1 (0.3) | | 7.9 (1.9) | |
| 120μm | 0.1 (0.1) | | 0.0 (0.4) | | 7.7 (1.3) | |
| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40μm-80μm(SE) | 40μm-120μm(SE) | 80μm-120μm(SE) |
| | .000 (.172) | .000 (.17) | .000 (.172) | 1 (.172) | .000 (.171) | .000 (.171) |
| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
| | F | P | F | P | F | P |
| | 1181.61 | 0 | 13.086 | 0 | 8.724 | 0 |

SD: Standard deviation, SE: Standard error

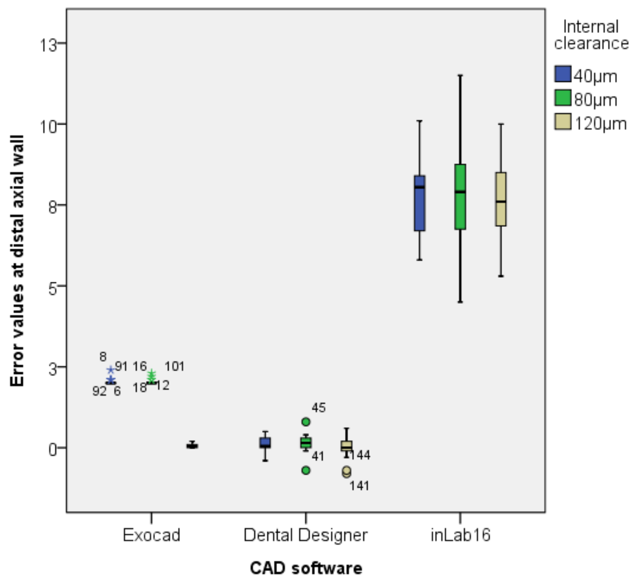



Figure 10. The error value of internal clearance at distal axial wall

### 3.1.7 The internal clearance at mesial axial-occlusal line angle

Statistical analysis of the IC measured at points d1, d2, d5, and d6 in the mesial axial-occlusal line angle area showed that the IC varied depending on the CAD software and IC parameter used and that there was an interaction between the two factors (Table 9, $p < .00$). In the post hoc analysis, Exocad and inLab16 did not show differences against each other, whereas Dental designer showed differences against the other two CAD software products.

The results showed that IC value was significantly larger when designed with Dental designer than the other two CAD software products (Table 9, Fig. 11).

**Table 9.** Mean, standard deviation (internal clearance), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in IC value at mesial axial-occlusal line angle

| | IC at mesial axial-occlusal line angle | | | | | |
|---|---|---|---|---|---|---|
| | Exocad: Mean (SD) | | Dental designer: Mean (SD) | | inLab16: Mean (SD) | |
| IC parameter | | | | | | |
| 40µm | 84.3 (3.2) | | 130.1 (12.1) | | 82.5 (29.5) | |
| 80µm | 97.0 (4.0) | | 165.1 (7.2) | | 98.2 (10.5) | |
| 120µm | 124.9 (1.6) | | 195.2 (9.4) | | 131.3 (10.0) | |
| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40µm-80µm(SE) | 40µm-120µm(SE) | 80µm-120µm(SE) |
| | .000 (2.188) | .434 (2.23) | .000 (2.257) | .000 (2.236) | .000 (2.217) | .000 (2.217) |
| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
| | F | P | F | P | F | P |
| | 494.781 | 0 | 272.319 | 0 | 7.184 | 0 |

SD: Standard deviation, SE: Standard error

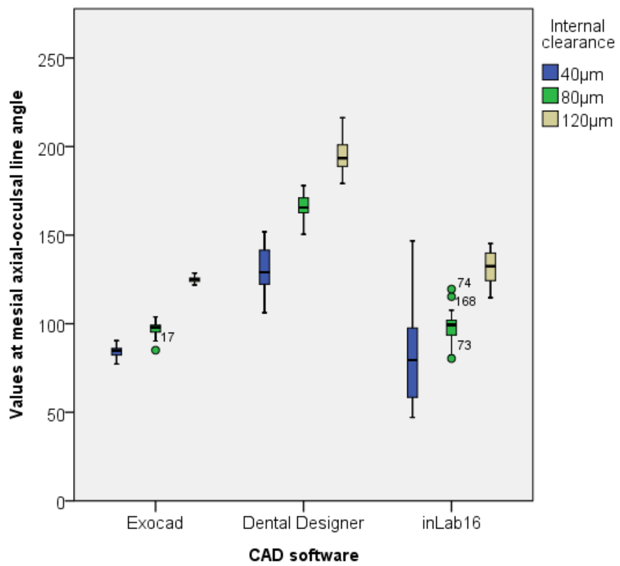



Figure 11. The internal clearance value at mesial axial-occlusal line angle

### 3.1.8 The internal clearance at distal axial-occlusal line angle

Statistical analysis of the IC measured at points d3, d4, d7, and d8 in the distal axial-occlusal line angle area showed that IC varied depending on the CAD software and IC parameter used and that there was an interaction between the two factors (Table 10, $p < .00$). In the post hoc analysis, the results showed differences between all CAD products.

The results also showed that IC value was significantly larger when designed with Dental Designer than the other two CAD products (Table 10, Fig. 12).

**Table 10.** Mean, standard deviation (internal clearance), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in IC value at distal axial-occlusal line angle

| | IC at distal axial-occlusal line angle | | | | | |
|---|---|---|---|---|---|---|
| | Exocad: Mean (SD) | | Dental designer: Mean (SD) | | inLab16: Mean (SD) | |
| IC parameter | | | | | | |
| 40µm | 81.7 (3.4) | | 127.1 (6.4) | | 83.0 (10.8) | |
| 80µm | 96.6 (3.2) | | 159.4 (13.7) | | 108.8 (7.7) | |
| 120µm | 124.4 (1.1) | | 189.2 (9.5) | | 144.4 (5.3) | |
| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40µm-80µm(SE) | 40µm-120µm(SE) | 80µm-120µm(SE) |
| | .000 (1.461) | .000 (1.476) | .000 (1.507) | .000 (1.482) | .000 (1.501) | .000 (1.46) |
| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
| | F | P | F | P | F | P |
| | 851.351 | 0 | 681.752 | 0 | 11.127 | 0 |

SD: Standard deviation, SE: Standard error

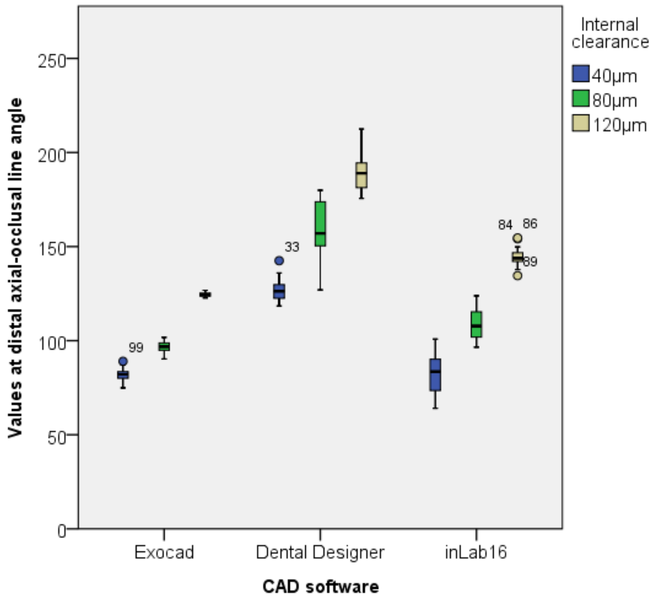



Figure 12. The internal clearance value at distal axial-occlusal surface line angle

### 3.1.9 The internal clearance at occlusal surface of #24

Statistical analysis of the error value of IC at the occlusal surface of #24 abutment showed that there were differences according to the type of CAD software used ($p < .00$), but no differences according to the IC parameter used ($p = .110$), while also showing an interaction between the two factors (Table 11, $p = .001$). In the post hoc analysis, the results showed differences between all CAD software, while no differences between all IC parameters used.

The groups using Exocad and Dental Designer showed a mean error value of ≤ 2 µm, whereas IN-40, IN-80, and IN-120 (groups using inLab16) showed a mean error value of 3 µm, 3.1 µm, and 3.4 µm, respectively (Table 11, Fig. 13).

**Table 11.** Mean, standard deviation (error value), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in error value at #24 occlusal surface

| | Error value at #24 occlusal surface | | | | | |
|---|---|---|---|---|---|---|
| | Exocad: Mean (SD) | | Dental designer: Mean (SD) | | inLab16: Mean (SD) | |
| IC parameter | | | | | | |
| 40µm | 2.0 (0.1) | | -0.1 (0.1) | | 3.0 (2.1) | |
| 80µm | 2.0 (0.1) | | 0.0 (0.1) | | 3.1 (1.3) | |
| 120µm | 0.1 (0.1) | | 0.1 (0.6) | | 3.4 (1.8) | |
| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40µm-80µm(SE) | 40µm-120µm(SE) | 80µm-120µm(SE) |
| | .000 (.176) | .000 (.175) | .000 (.176) | 1 (.176) | .232 (.173) | .191 (.176) |
| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
| | F | P | F | P | F | P |
| | 66.438 | 0 | 2.27 | 0.11 | 5.021 | 0 |

SD: Standard deviation, SE: Standard error

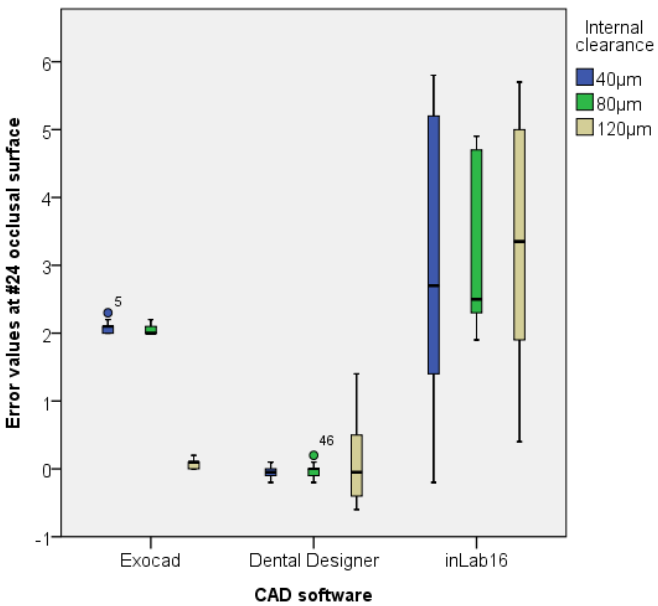



Figure 13. The error value of internal clearance at #24 occlusal surface.

### 3.1.10 The internal clearance at occlusal surface of #26

Statistical analysis of error value of IC at the occlusal surface of #26 abutment showed that that error values varied depending on the CAD software and IC parameter used and that there was an interaction between the two factors (Table 12, $p < .00$). In the post hoc analysis, the results showed differences between all CAD software, and while there were no differences in error values between IC parameter of 40 μm and 80 μm, the IC parameter of 120 μm showed significant differences as compared to the other two (Table 12, Fig. 14).

**Table 12.** Mean, standard deviation (error value), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in error value at #26 occlusal surface

| | Error value at #26 occlusal surface | | | | | |
|---|---|---|---|---|---|---|
| | Exocad: Mean (SD) | | Dental designer: Mean (SD) | | inLab16: Mean (SD) | |
| IC parameter | | | | | | |
| 40μm | 2.0 (0.1) | | 0.1 (0.3) | | -4.9 (1.2) | |
| 80μm | 2.0 (0.1) | | 0.1 (0.2) | | -5.4 (1.2) | |
| 120μm | 0.1 (0.1) | | -0.1 (0.4) | | -5.3 (1.2) | |
| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40μm-80μm(SE) | 40μm-120μm(SE) | 80μm-120μm(SE) |
| | .000 (.126) | .000 (.129) | .000 (.13) | .453 (.129) | .000 (.127) | .000 (.129) |
| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
| | F | P | F | P | F | P |
| | 1428.662 | 0 | 24.658 | 0 | 16.53 | 0 |

SD: Standard deviation, SE: Standard error

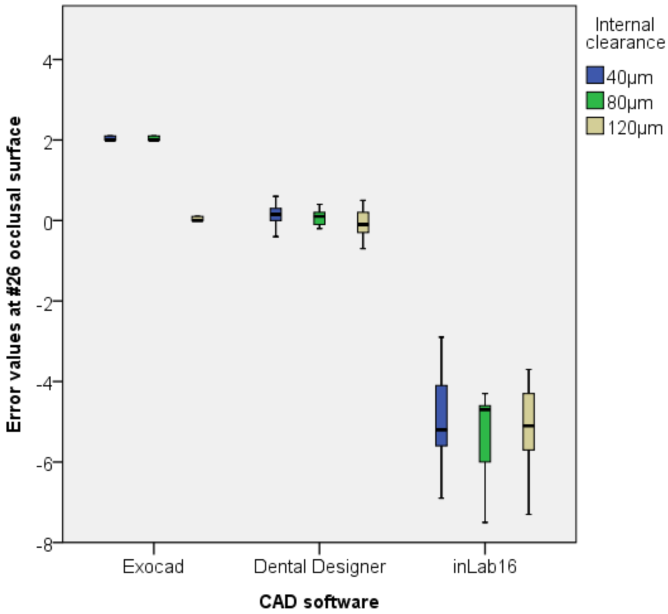



Figure 14. The error value of internal clearance at #26 occlusal surface.

## 2. Reproducibility of CAD software

The results of statistical analysis by two-way ANOVA on RMSE values obtained by comparing the 3D shapes of CAD prostheses designed with the same CAD software and IC parameter using Geomagic Control® were as follows:

### 3.2.1 The root mean square error (RMSE) between CAD prosthesis of same condition

The results showed that there were differences in error values depending on the CAD software and IC parameter used and that there was an interaction between the two factors (Table 13, p < .00). In the post hoc analysis, the results showed differences between all CAD software and IC parameters.

The results also showed that RMSE value was statistically significantly higher when designed with Dental Designer than the other two CAD software (Table 13, Fig. 15).

**Table 13.** Mean, standard deviation (RMSE), two-way ANOVA (CAD software, IC parameter, and interactions) with Bonferroni post hoc in RMSE value

| | RMSE value | | | | | |
|---|---|---|---|---|---|---|
| | Exocad: Mean (SD) | | Dental designer: Mean (SD) | | inLab16: Mean (SD) | |
| IC parameter | | | | | | |
| 40μm | 85.4 (3.9) | | 270.5 (19.6) | | 183.0 (6.1) | |
| 80μm | 115.2 (3.0) | | 292.9 (11.4) | | 194.0 (2.4) | |
| 120μm | 127.1 (0.1) | | 319.1 (13.0) | | 171.5 (5.3) | |
| Whole sample by CAD software and IC parameter | CAD software | | | IC parameter | | |
| | EXO-DD (SE) | EXO-IN (SE) | DD-IN (SE) | 40μm-80μm(SE) | 40μm-120μm(SE) | 80μm-120μm(SE) |
| | .000 (2.564) | .000 (2.514) | .000 (2.564) | .000 (2.562) | .000 (2.538) | .003 (2.538) |
| Main effects and interactions | CAD software | | IC parameter | | CAD software *IC parameter | |
| | F | P | F | P | F | P |
| | 2620.827 | 0 | 59.478 | 0 | 31.353 | 0 |

SD: Standard deviation, SE: Standard error

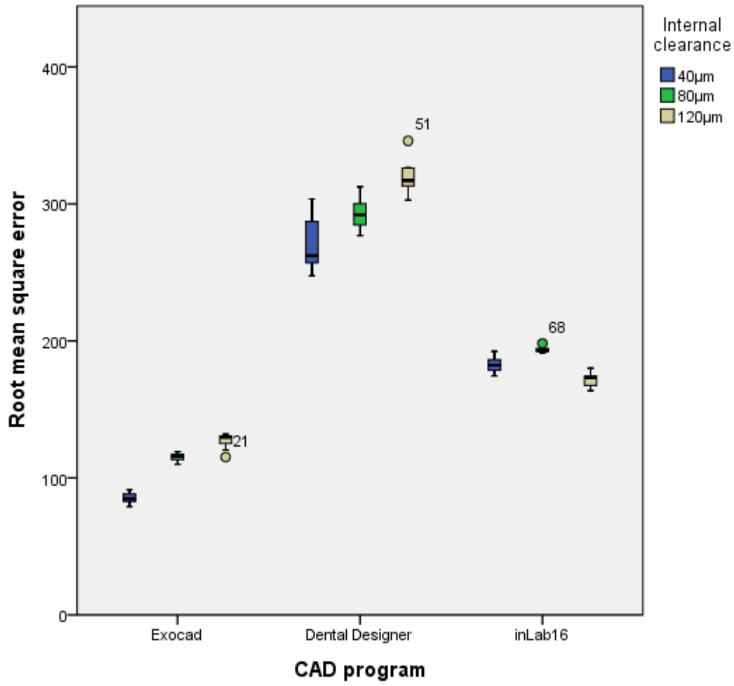



Figure 15. The RMSE value between CAD prosthesis of same condition

# IV. DISCUSSION

Based on the findings in the study, the null hypotheses that there will be no differences in MF and IC errors in CAD prostheses fabricated using different CAD software and IC parameters and that there will be no differences in the conformity of the internal shape of CAD prostheses fabricated under the same conditions were rejected.

Dental CAD software would inevitably be affected by the subjective ideas and computer skill levels of individual companies and their surrounding environment. Therefore, even when the same settings are used to design prostheses, the outcome may vary depending on the CAD software used. For example, inLab16 is based on a closed CAD/CAM system, whereas Exocad is based on an open CAD/CAM system, and companies using a closed system may need to produce their CAD software with the consideration of accuracy of their own scanners and CAM processes. Moreover, adjusting the prostheses using CAD would be relatively easier than improving the accuracy of scanners and CAM processes.

The experiments in the present study were designed considering that trueness, repeatability, and reproducibility are primarily used as the concepts that demonstrate the accuracy of dental 3D scanners. Accordingly, the present study analyzed CAD prostheses with the objective of determining the trueness and reproducibility of CAD software according to types of CAD software and IC parameters. The trueness of

CAD software was assumed to represent the degree of agreement between the IC parameter arbitrarily set by the operator when designing the fixed prosthesis and the actual IC value of the CAD prosthesis measured when the CAD software was implemented. Meanwhile, the reproducibility of CAD software was assumed to represent the degree of agreement between the 3D shapes of the inner surface of the CAD prosthesis obtained by implementing the design in CAD software under the same conditions with continuous scans of an abutment model by a single model scanner.

Under such assumptions, it was necessary in the present study to properly position the CAD prosthesis and abutment model files in the 3D analysis program to determine the trueness according to types of CAD software and IC parameters. However, when the CAD prosthesis is designed by the CAD software and the design is output for the CAM process, the CAD prosthesis file output has the XYZ coordinate axes transformed. Therefore, if the abutment model and CAD prosthesis files are simply imported into the 3D analysis program, the abutment model and CAD prosthesis could not be properly positioned. Algorithms for transformation of XYZ coordinate axes are different from one company to the next and are usually confidential; thus, a special method had to be devised to carry out the experiments in the present study. Among existing studies that used 3D analysis programs to measure the fitness or IC values of CAD prostheses, it was difficult to find any study that provided detailed explanation of the experimental methods other than some basic information, such as using a best-fit algorithm supplied by the analysis program.

Moreover, it appeared that previous experiments used a best-fit algorithm and subsequently performed correction work but doing so may have a non-objective effect on the results. On the other hand, using the method in the present study could ensure an accurate position of the abutment model and CAD prosthesis without additional correction in the 3D analysis program (Fig. 3); what makes this possible is the fact that by using a single abutment model CAD prosthesis file as the reference, the outer appearance of the CAD prosthesis designed based on the anatomical shape and outer appearance of the abutment model could be used as reference area that is wide enough to accurately position these.

The reasons that a model that was scaled down by 70% from ISO12836 model was used in the present study were two-fold. First, it would be easy to perform additional experiments since the specification of the model is accurately known. Secondly, comparisons with results of existing studies on IC and fitness would be easier since the size of the abutment model used in the experiments would be similar (Shimizu et al., 2017; Wu and Wilson, 1994). Moreover, the present study also considered the fact that in previous experiments that investigated the fitness of the inner surfaces of zirconia prostheses fabricated by the CAD/CAM method, the lab technician manually applied an "adaptation process" in an arbitrary manner to the inner surface (Abduo et al., 2010), but when the convergence angle of the abutment axial wall was ≥ 12°, previous experiments showed no significant differences in MF from before and after the manual adaptation process (Beuer et al., 2009). Furthermore, the present study used a model that assumed an abutment for a dental bridge, and as a result, fitness was measured at many more points than when using a single crown model. If a follow-up experiment to the present study is conducted to determine the fitness of actual fabricated prostheses, then it would be possible to install the prostheses in the same direction in all samples since the mesial-distal and labial-lingual directions of the abutment model and prostheses have been restricted.

The primary reason for analyzing the IC values measured in the CAD prosthesis separately for mesial and distal aspects of the abutment was that when using inLab16, there were significant differences in the estimated marginal mean between the mesial and distal margins of a and c points for all IC parameters, and similarly, there were differences in the estimated marginal mean from e points in abutment #24 and #26 (Fig. 16). In relation to this, if future studies fabricate actual prostheses and measure the IC value at each point, then it would be possible to determine whether differences between mesial and distal position found in CAD prostheses are reflected in actual prostheses.

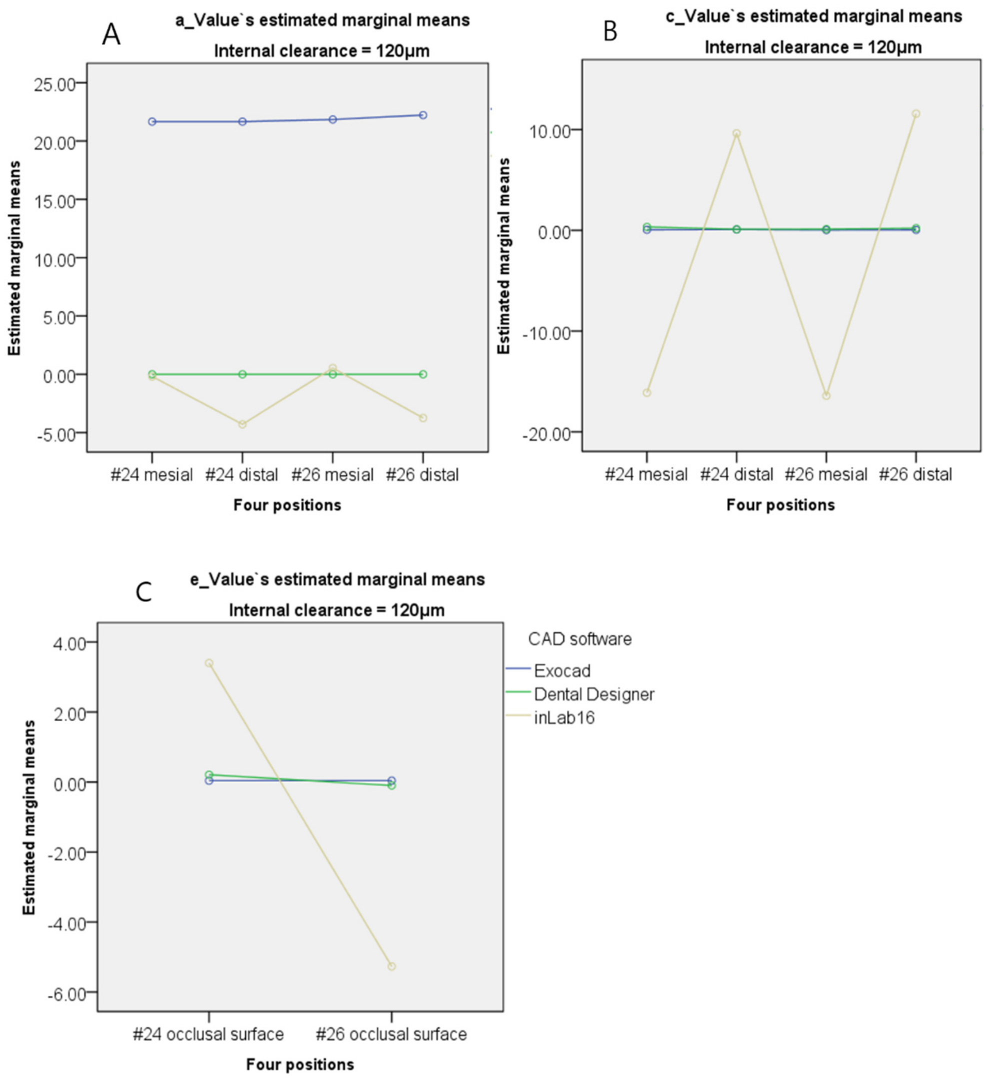



Figure 16. The estimated marginal means of error values of a, c, and e positions. A) The estimated marginal means of the error value at mesial and distal margins. B) The estimated marginal means of the error value at mesial and distal axial walls. C) The estimated marginal means of the error value at occlusal surfaces of #24 and #26

In the post hoc analysis of the margins, setting the IC parameter to 120 μm showed differences as compared to other IC parameters for both the mesial and distal margins; this may be attributed to EXO-120 showing a mean MF error value of 21.7 μm, which was significantly larger than that of EXO-40 and EXO-80. When designing CAD prostheses using Exocad, IC could generally be set up to 100 μm, but to set the IC value any higher, the “Additional spacing” option must be selected. Therefore, it may be necessary to determine whether a system error had occurred in relation to this.

The ability to automatically recognize and set the margins in ISO12836 mode, which is a model with relatively accurate margins used in the present study, was poorer in Dental Designer than the other two CAD products. Despite this fact, Dental Designer showed the lowest MF error value in the CAD prostheses. When inLab16 was used, points in both mesial and distal margins showed negative MF error value, which indicated that the system may have designed the margins to be longer; it is suspected that this may have been intentional on the part of the CAD software manufacturer. Considering that clinical tolerance for MF error in FPD is approximately 120 μm, the errors found in the CAD software were within an acceptable range in all groups.

For the margin-axial line angle and axial-occlusal line angle areas, the study did not compare the IC parameters to measured IC values for calculation of error values. The reason for this was that the IC value may change by CAD software according to the size and shape of the milling bur in areas where the shape may change (Dahl et al., 2017). With respect to possible changes in IC values in areas where the shape changes, Exocad and Dental Designer have the option to set the shape, size and correction value for the bur used in CNC milling and inLab16 has the option to set the shape and diameter of the bur and milling system that are expected to be used prior to CAD prosthesis design and selecting "consideration of milling bur shape."

With respect to IC values in the axial wall area, CAD prostheses designed using inLab16 showed the highest IC error values, and, as described in the Results section, the points in the mesial margin-axial wall area showed negative error values, whereas points in the distal margin-axial wall area showed positive error values. The cause of this, as identified by 3D analysis program, was that CAD prostheses was designed to be distally slanted when viewed horizontal cross-section of the abutment model (Fig. 17).

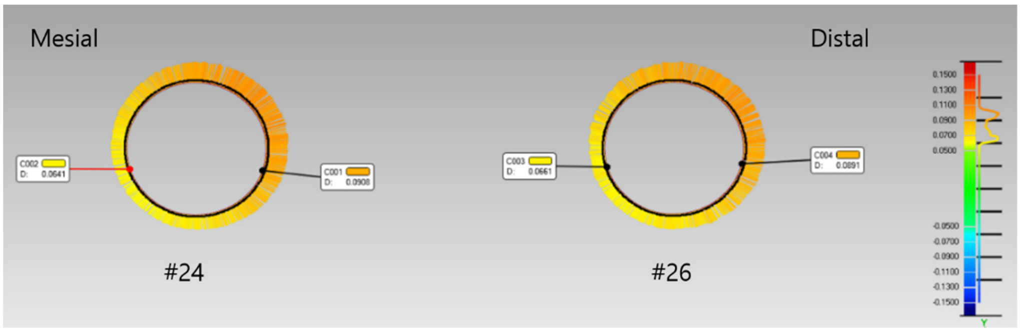



Figure 17. The relative position of the abutment model and a CAD prosthesis designed by inLab16 on horizontal cross section view in the Geomagic control®.

The present study used models with the abutment having an axial wall angle of 16° and two abutments having a parallel axis. Moreover, the CAD software automatically recognized the axes of the abutment model relatively accurately, while there were no areas marked as undercut. Therefore, it is believed that there were no design errors caused by the operator during the “insert axes setting” process that may have affected the experimental results when designing the FPD using inLab16,.

With respect to the IC values in the axial-occlusal line angle area, the groups using Dental Designer showed IC values that were higher than those of the groups using the other CAD software. Moreover, when the IC values were viewed on a color difference map, the results showed that the amount and range of relief given, in addition to the IC parameter of the CAD prosthesis in the area near the axial-occlusal line angle, were different for each CAD software. Exocad, inLab16, and Dental Designer showed the narrowest, intermediate, and widest range of relief, respectively (Fig 18).

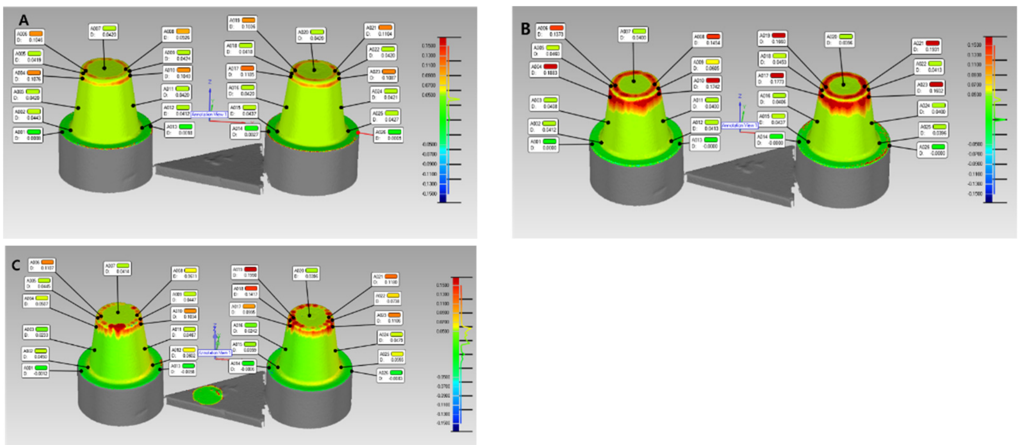



Figure 18. The color difference map of internal clearance between abutment model and CAD prosthesis. A) No.1 model-CAD prosthesis of EXO-40, B) No. 1 model-CAD prosthesis of DD-40, C) No. 1 model-CAD prosthesis of IN-40.

With respect to IC error values in the occlusal surface area, EXO-120 showed the lowest error value among the nine groups. Excluding EXO-120, the groups using Dental Designer showed smaller IC error values in the occlusal surface area than the other CAD software. EXO-40 and EXO-80 showed IC values that were 2 μm larger, on average, than the parameter value, the same for the occlusal surface of both #24 and #26 abutment models. On the other hand, inLab16 showed IC values that were approximately 3 μm larger, on average, in the #24 occlusal surface and approximately 5 μm smaller, on average, in the #26 occlusal surface, while error values showed relatively large deviations with the same group.

To verify the reproducibility of CAD software, RMSE values should have been derived for 45 possible combinations for two CAD prostheses out of 10 CAD prostheses per each group. However, the present study faced some limitations that did not allow this. In the present study, a single CAD prosthesis was designated as the reference in each group and the remaining nine CAD prostheses were compared to the reference. The method for designating the reference CAD prosthesis was as follows. The measured IC values from the experiment on the trueness of CAD software were used to select the reference sample. In the areas where the error values from the a, c, and e points were derived, the absolute values of the corresponding values were ranked in ascending order, and in the areas where the error values from the b and d points were derived, and the absolute values of the differences between the mean value of 10 CAD prostheses with the same group and corresponding sample value were ranked in ascending order. The sample with the lowest sum rank for a, b, c, d, and e points was designated as the reference. The samples designated as the reference CAD prosthesis in each group were as follows: eighth sample in EXO-40, eighth sample in EXO-80, seventh sample in EXO-120, sixth sample in DD-40, second sample in DD-80, fourth sample in DD-120, first sample in IN-40, first sample in IN-80, and eighth sample in IN-120.

Units used to express differences based on comparisons of different 3D shapes include RMSE and mean absolute deviation (MAE). While the MAE gives the same weight to all errors, the RMSE penalizes variance as it gives errors with larger absolute values more weight than errors with smaller absolute values and it always have a bigger value than MAE (Chai and Draxler, 2014). The appropriate unit is used according to the nature of the experiment, and in the present study, RMSE was used by referencing similar previous studies in dentistry. It was reported that RMSE ≤ 10 μm represents excellent fit, whereas RMSE ≥ 50 μm represents poor fit (Peters et al., 1999). The mean RMSE values shown by the nine groups in the present study, EXO-40, EXO-80, EXO-120, DD-40, DD-80, DD-120, IN-40, IN-80, and IN-120 were 85 μm, 115 μm, 127 μm, 270 μm, 292 μm, 319 μm, 183 μm, 194 μm, and 171 μm, respectively, which were relatively high. The primary reason for this may have been the difference between the internal shapes in the axial-occlusal line angle area. The range of additional IC values applied in this area varied between CAD software; this area was identified as an area where difference in the internal shape usually occurred (Fig. 19). Dental Designer had the widest area where additional IC was applied near the axial-occlusal line angle area and showed differences between internal shapes. Consequently, the largest RMSE and the lowest reproducibility were shown. It is believed that, as future work, excluding the area where additional IC is applied near the axial-occlusal line angle area and investigating the RMSE values in the remaining areas may be meaningful.

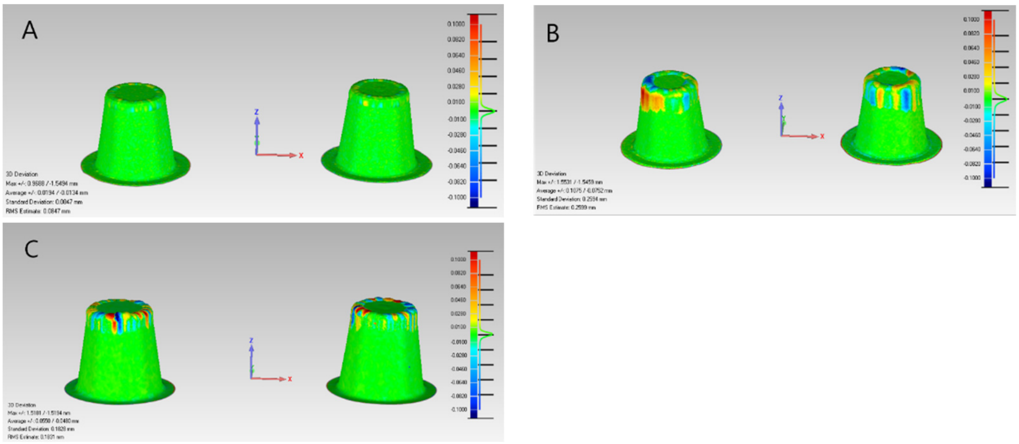



Figure 19. The color difference map of RMSE between CAD prosthesis of same condition. A) reference CAD prosthesis of No. 8 and test CAD prosthesis of No. 1 in EXO-40, B) reference CAD prosthesis of No. 1 and test CAD prosthesis of No. 2 in DD-40, C) reference CAD prosthesis of No. 6 and test CAD prosthesis of No. 1 in IN-40.

The significance of the present study is that it confirms the fact that errors may occur in CAD software when using the CAD/CAM method to fabricate a 3-unit FPD, which is a common treatment option in clinical practice. However, the present study was limited to investigating just the IC error of CAD prostheses and reproducibility of the internal shape when fabricating 3-unit FPDs. Therefore, it is believed that additional experiments should be conducted in the future to determine how much of the errors in CAD prostheses found in the present study are reflected in prostheses that are actually fabricated and to investigate error values separately for the 3D scan, CAD, and CAM stages.

Moreover, dental CAD software provides libraries for fabrication of various types of prostheses; thus, it is believed that it is also necessary to identify errors that may occur when various clinical situations are assumed.

# V. CONCLUSIONS

Within the limitations of the present study, the following conclusions were derived:

1. There were differences in the accuracy of CAD software according to the type of CAD software and the IC parameter used.

2. The trueness of CAD software, as confirmed by IC error values in margin, axial wall, and occlusal surface areas of CAD prostheses, was highest in Dental Designer, followed in order by Exocad and inLab16.

   CAD prostheses designed using inLab16 showed greater differences in IC error values between the mesial and distal margins of the abutment than those designed using the other two CAD software applications.

3. The reproducibility of the CAD prosthesis, as confirmed by RMSE values based on comparison of the internal shapes of the CAD prosthesis, was highest in Exocad, followed in order by inLab16 and Dental Designer.

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## 국문요약

# 고정성 보철물 디자인에 대한 치과용 캐드 소프트웨어의 정확도 비교 연구

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**이 용 상**

치과 보철물 제작에 있어서 CAD/CAM 방법은 전통적인 방법에 비해 많은 장점이 있으나, 각 단계 마다 오차가 있고, 이런 오차들의 합이 최종 보철물의 오차인 점은 전통적인 방법과 유사하다. 하지만, CAD/CAM 방법의 각 단계에서 발생 가능한 오차에 대한 검증은 상대적으로 부족하다. 특히, CAD 소프트웨어에 대한 검증적 실험 연구는 거의 찾아볼 수 없다.

이에, 본 연구에서는 CAD 소프트웨어로 고정성 보철물을 디자인하는 단계에서 CAD 소프트웨어의 정확도를 참도와 반복재현성으로 나누어 검증하고자 하였다. 참도는 술자가 정하는 내면간극 설정 값과 CAD

소프트웨어에서 구현되는 CAD prosthesis 의 내면간극 값의 일치도로 정하였고, 반복재현성은 CAD 소프트웨어 상 동일하게 디자인된 CAD prosthesis 내면 간 3 차원적 형상 일치도로 정하였다. 3 종류의 CAD 소프트웨어와 3 가지 내면간극 설정 값에 따른 9 가지 실험군에서 3 차원 분석 프로그램을 이용하여 CAD prosthesis 내면간극 오차 값과 CAD prosthesis 내면의 3 차원적 형상 일치도를 계산하였다.

이원 분산 분석(two-way ANOVA)으로 통계분석을 시행하였고, 참도 및 반복재현성에서 CAD 소프트웨어의 종류와 내면간극 설정 값에 따른 유의한 차이가 있는 것으로 나타났다($p<0.05$). Exocad 의 경우 내면간극 값을 120 μm 로 설정할 때, 근심과 원심 마진에서 평균 22 μm 의 비교적 큰 오차 값을 나타냈고, 축벽과 교합면에서는 2μm 이하의 내면간극 오차 값을 나타냈으며, 내면간극을 40μm 또는 80μm 로 설정할 때는 근심과 원심측 마진, 축벽, 그리고 교합면에서 2 μm 이하의 내면간극 오차 값을 나타냈다. Dental designer 는 모든 내면간극 설정 값에서 근심과 원심측 마진, 축벽, 그리고 교합면에서 평균 1 μm 이하의 오차를 나타냈다. inLab16 은 내면간극을 40 μm, 80 μm, 그리고 120 μm 로 설정하였을 때, 근심측 마진 오차는 평균 -5μm 로 나타났고, 원심측 마진 오차는 평균 약 -6.7μm 로 나타났고, 근심측 축벽 오차는 평균 -16.5 μm, 원심측 축벽에서는 평균 7.8 μm 의 오차를 나타냈고, #24 교합면에서는 평균 3.2

μm 의 오차를 나타냈고, #26 교합면에서는 평균 -5.2 μm 의 오차를 나타냈다.

각 군에서 RMSE 값은 CAD 소프트웨어의 종류와 내면간극 값에 따라 유의한 차이를 보였다(P<0.00). 내면간극 설정 값이 40 μm, 80 μm, 그리고 120 μm 일 때 Exocad 의 CAD prosthesis 간의 RMSE 값은 평균 85 μm, 115 μm , 그리고 127 μm 였고, Dental designer 는 평균 270 μm, 292 μm, 그리고 319 μm 였으며, inLab16 은 평균 183 μm, 194 μm , 그리고 171 μm 의 RMSE 값을 나타냈다.

본 연구의 실험 한계에 안에서 다음의 결론을 얻을 수 있었다. 1. 치과용 CAD 소프트웨어 종류 및 내면간격 설정 값에 따라 CAD 소프트웨어의 accuracy는 차이가 있다.

2. CAD prosthesis의 마진부위, 축벽부위, 그리고 교합면 부위에서의 내면간극 오차 값으로 확인한 CAD software의 trueness는 Dental Designer가 가장 높았고, Exocad, inLab16 순이었다.

inLab16으로 디자인한 CAD prosthesis는 내면간극 오차 값에서 지대치의 근심과 원심 사이에 차이가 다른 2가지 CAD 소프트웨어의 경우보다 큰 것으로 나타났다.

3. CAD prosthesis 의 내면 형상 비교를 통한 RMSE 값으로 확인한 CAD software 의 reproducibility 는 Exocad 가 가장 높았고, inLab16, Dental designer 순이었다.

핵심되는 말 : CAD software; Accuracy; Internal clearance; Trueness; reproducibility