Accuracy of 3D printed clear aligners according to restorative material types obtained by intraoral scanners

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ABSTRACT

Accuracy of 3D printed clear aligners according to restorative material types obtained by intraoral scanners

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(Directed by Professor Jung-Yul Cha, D.D.S., Ph.D.)

Orthodontic treatments using clear aligners are increasingly popular among adults due to their minimal impact on appearance and work life. The transformation of digital dentistry using intraoral scanners, facilitated by advancements in CAD/CAM technologies, has been pivotal in the widespread adoption of clear aligners. Recently, the direct 3D printed clear aligners using 3D printers has attracted attention from clinicians. Successful orthodontic treatment using clear aligner requires customized plans for sequential tooth movement and the precise fabrication of aligners to deliver proper orthodontic forces to target teeth.

The segmentation of teeth in treatment planning is crucial and is influenced by the quality of the mesh of the digital model. While intraoral scanners allow for immediate digitalization of the dentition of patients, their accuracy can vary depending on the restorative materials present in the mouth.

Therefore, this study aims to examine the effect of restorative material and intraoral scanners on the mesh data of teeth and the accuracy of 3D printed clear aligners. For comparative analysis, reference scan data were obtained using a tabletop scanner, and test data were collected using PrimeScan (Dentsply Sirona, York, PA, USA), Trios 3 (3Shape A/S, Copenhagen, Denmark), and i600 (Medit, Seoul, Korea) scanners from typodonts containing crown restoration made of metallic and non-metallic materials. The collected scan data from different scanners were evaluated for mesh quality and three-dimensional accuracy. Finally, 3D printed clear aligners based on different mesh information were assessed.

The results showed that mesh quality was superior in the following order: i600 (0.81), PrimeScan (0.76), and Trios 3 (0.74), regardless of the restorative material ($p <$ 0.05/3). Tooth size discrepancies showed that resin teeth and zirconia crowns were measured larger than their actual sizes, whereas gold crowns tended to be measured

similarly or smaller. In model analysis measurements, Trios 3 measured significantly smaller than the other intraoral scanners, while Primescan showed superior accuracy in full arch scan comparisons ($p < 0.05/3$). When scanning gold crowns, the i600 scanner had the largest RMS error value, averaging 59 µm ($p < 0.05/3$). In the accuracy comparison of the inner surface of printed clear aligners, the gold crown group scanned with the i600 showed the largest average RMS value in the proximal area, at 94 µm ($p < 0.05/3$).

In conclusion, the accuracy of clear aligners and mesh quality are affected by the type of restorative material and scanner used. Metallic restorative materials made it difficult to obtain accurate scans with triangulation technology, resulting in inaccurate clear aligners. Therefore, to improve treatment outcomes, clinicians should select scanners less affected by restorative materials or carefully consider the restorative materials in the patient's mouth during treatment.

Keywords: 3D dental mesh, intraoral scanner, restorative material, 3D printed aligner, mesh quality, scan accuracy

Accuracy of 3D Printed Clear Aligners Influenced by Intraoral Scanners and Restorative Materials

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I. INTRODUCTION

Recently, clear aligner treatment has gained significant attention in the orthodontic market worldwide. This treatment has negligible effect on appearance and social interactions during the orthodontic period, making it particularly advantageous for adults (Flores-Mir et al., 2018; Sharma et al., 2021).

The shift towards digital dentistry, facilitated by the widespread adoption of intraoral scanners and advancements in CAD/CAM systems, has significantly contributed to the proliferation of clear aligners. The ease of transmitting and storing digitized tooth model data has overcome geographical barriers, enhancing the convenience and efficiency of designing and manufacturing personalized orthodontic appliances (Im et al., 2022; Khanagar et al., 2021; Yoon et al., 2018). In recent years, breakthroughs in technology and materials have sparked the innovation of products that directly print clear aligners using a 3D printer, which are gaining attention. A previous study reported that the fit of 3D printed clear aligners was within the clinically acceptable range, as demonstrated through three-dimensional analysis (Park et al., 2023).

3D scanners in the dental field generally utilize two main technologies. The first is an optical technology that captures the location information of objects using light. Representative optical technologies for intraoral scanning include confocal laser scanning microscopy and optical triangulation. Confocal microscopy collects positional information of an object by selectively acquiring in-focus signals using a pinhole aperture, which eliminates out-of-focus signals. On the other hand, optical triangulation gathers positional information by measuring the distance between the projected light and the reflected light, which returns to the sensor after being reflected off the object's surface. The second technology converts this collected location data into a 3D image. This conversion involves reproducing the spatial information from a point cloud into its original form using techniques such as Delaunay triangulation (Cipriano et al., 2022; Pellitteri et al., 2022). The final three-dimensional shape is rendered in mesh form through each manufacturer's proprietary software and algorithms. Consequently, the shape and fineness of the mesh can vary based on the optical and 3D imaging technologies used in the scanner, even when scanning the same object (Figure 1)

Among the methods for digitizing patient oral information, using a tabletop scanner to digitize plaster casts is prevalent. This technique accurately and stably digitizes tooth model data (Mangano et al., 2019). However, it involves challenges such as the time-consuming use of alginate or silicone impression materials, which also require significant storage space and generate waste. Alternatively, using an intraoral scanner allows for the simultaneous acquisition and digitization of intraoral information, thereby eliminating any intermediate processes (Cho et al., 2023). However, the accuracy of intraoral scanners can be affected by the presence of different materials in the mouth. Previous research indicates that the accuracy of scan data can vary based on the intraoral prostheses present, such as crowns or inlays (Dutton et al., 2020; Emam et al., 2023; Lim et al., 2021; Revilla León et al., 2022)

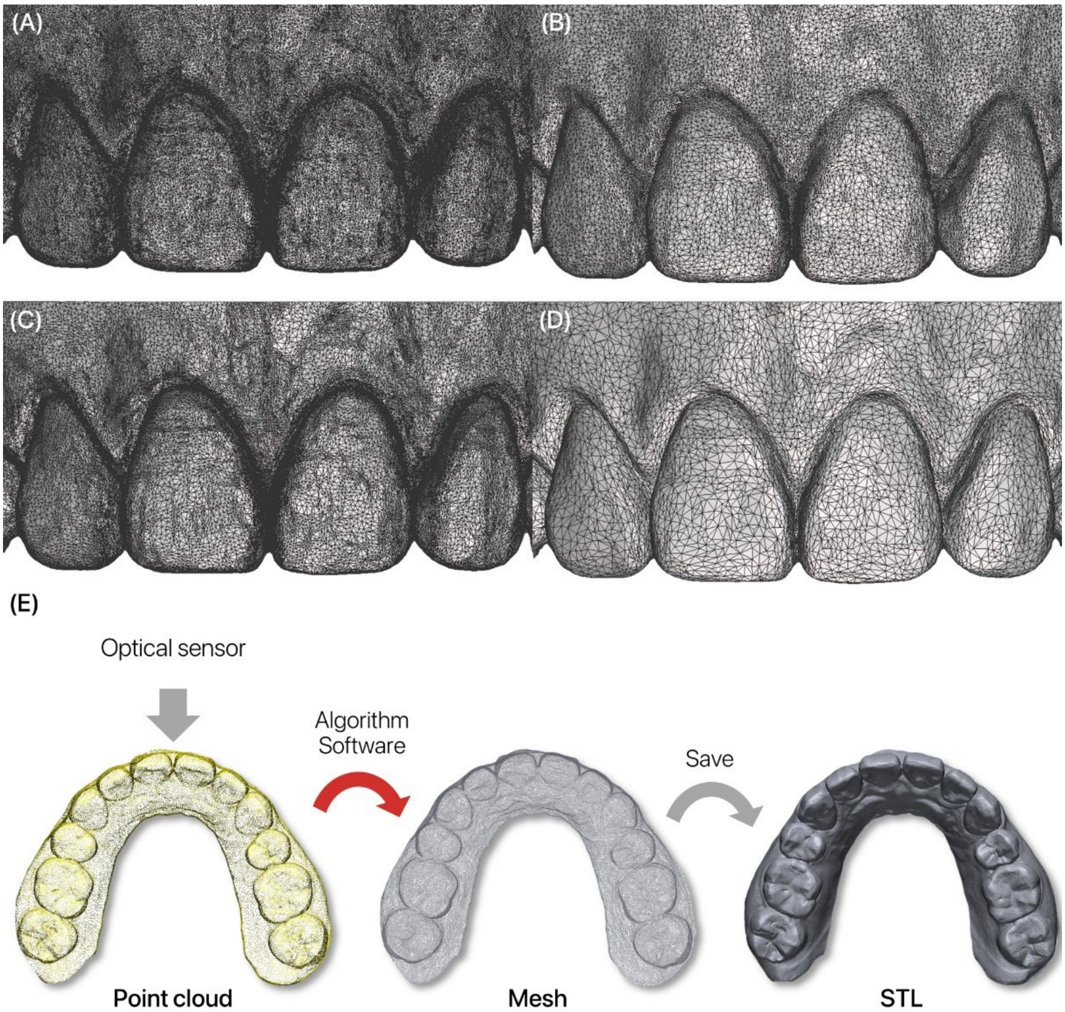


Figure 1. Dental mesh varies depending on applied technologies (A, B: optical triangulation; C, D: confocal digital image processing). (E) 3D imaging process of intraoral scanner based on optical technology.

Typically, it is recommended that intraoral scanners be used with consideration of the specific intraoral environment. Particularly, 3D printed clear aligners, which are fabricated without the process of manufacturing a physical dental model, may be more directly affected by the materials used in oral restorations. Given the inherent technical variability among intraoral scanners, accurately reproducing clear aligners and ensuring their proper fit—particularly in the presence of various prostheses—is a crucial clinical consideration (Park et al., 2023). Therefore, understanding the impact of different materials in accordance with different intraoral scanning technologies on the intraoral surface is essential for assessing the quality of clear aligners produced through a fully digital workflow.

Considering the above, this study aimed to investigate if the accuracy of collected dental mesh and 3D printed clear aligners is influenced by the type of restorative materials and intraoral scanner used in planning clear aligner treatments. The null hypotheses investigated were:

1. The quality of dental mesh is not influenced by the type of restorative materials, or the intraoral scanner used.
2. The scanning accuracy is not affected by the type of restorative materials or the intraoral scanner.
3. The accuracy of 3D printed clear aligners is not dependent on the type of restorative materials or the intraoral scanner used.

II. MATERIALS AND METHODS

1. Preparation of metallic and non-metallic crown dentition models

In a dental typodont (Nissin Dental, Kyoto, Japan), artificial resin teeth were prepared at the positions of the upper right lateral incisor and first molar respectively, as follows: the lateral incisor was replaced with a zirconia crown, and the first molar was replaced with both a gold crown and a zirconia crown. Considering clinical situations, metallic materials were excluded from the anterior region, and non-metallic zirconia, which is widely preferred due to its excellent properties, as well as metallic gold alloy, were chosen. To contrast with the unaltered resin teeth on the opposite side, the right and left sides were split (Figure 2).

The dentition model was digitalized from a tabletop scanner (Medit T710; Medit, Seoul, Korea), and the crown designs were created using dental CAD software (Exocad Dental; Exocad GmbH, Darmstadt, Germany). The zirconia crown for the upper right lateral incisor was manufactured using a milling machine (DWX-52D; Roland, Tokyo, Japan) with KATANA Zirconia STML material (Kuraray Noritake Dental, Tokyo, Japan). The first molar crowns were made in two types: gold and zirconia. The zirconia crown for the first molar was fabricated following the same process as for the anterior region. The gold alloy crown was produced by milling wax blocks (Super Green Wax; D-max, Daegu Korea) and then produced using a casting process (Figure 3).

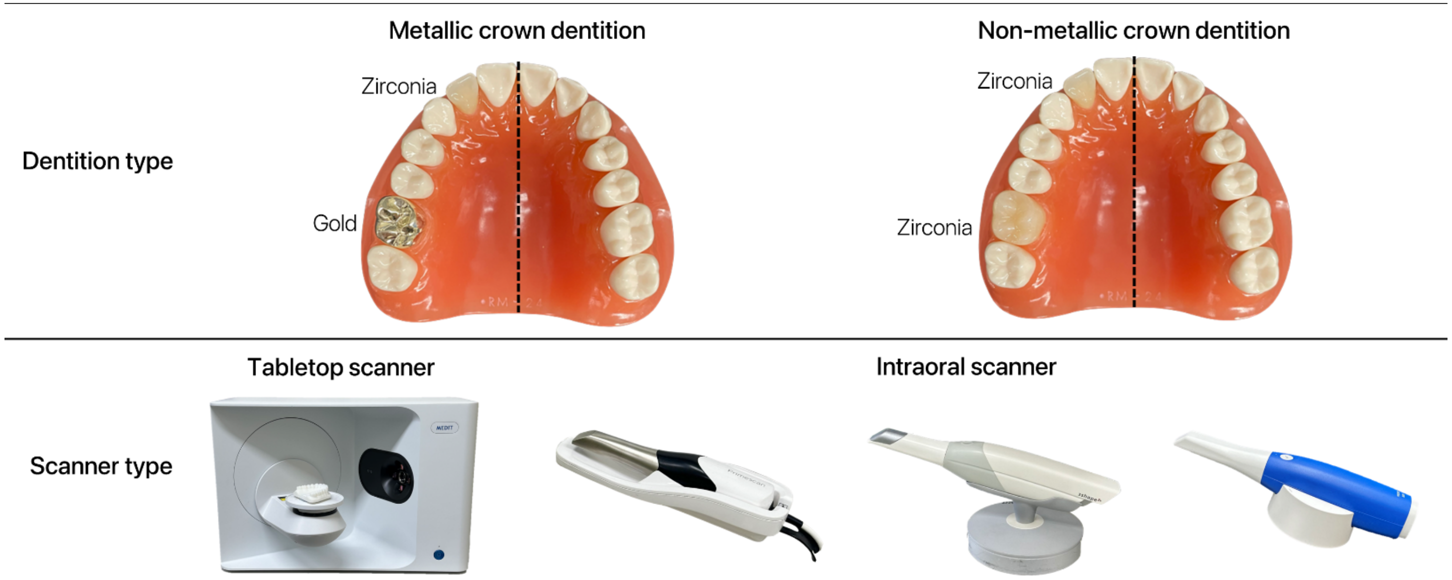
2. Scanning process

2.1 Reference scan

To create reference models, two types of artificial dentitions were impressed using polyvinyl siloxane impression material (I-SiL; Spident, Incheon, Korea) and a ready-made impression tray. The PVS impressions were then filled with high-strength dental stone (MG Crystal Rock; Maruishi Gypsum, Tokyo, Japan) to manufacture stone models according to the manufacturer's instructions. The reference models were digitalized using the tabletop scanner (Medit T710; MEDIT, Seoul, Korea) (Figure 2).

2.2 Intraoral scan

The experimental scan data in this study were digitized from three intraoral scanners for two types of dentitions. The intraoral scanners were selected to have different data capture technologies: Trios 3 (3Shape A/S, Copenhagen, Denmark), Medit i600 (Medit, Seoul, Korea), and Primescan (Dentsply Sirona, York, PA, USA) (Figure 2). All scanning processes were performed by a single operator in a controlled environment at room temperature of 23 (± 2) °C, following the manufacturer’s recommendations.



Manufacturer	Medit, Seoul, Korea	Dentsply Sirona, York, PA, USA	3Shape A/S, Cophenhagen, Denmark	Medit, Seoul, Korea
System	**T710**	**PrimeScan**	**Trios 3**	**i600**
Data capture principle	Phase shifting Optical triangulation	Confocal microscopy and short wave light with optical high-frequency contrast analysis	Confocal microscopy	Optical triangulation

Figure 2. Characteristics of scanners and dentitions based on crown materials and positions.

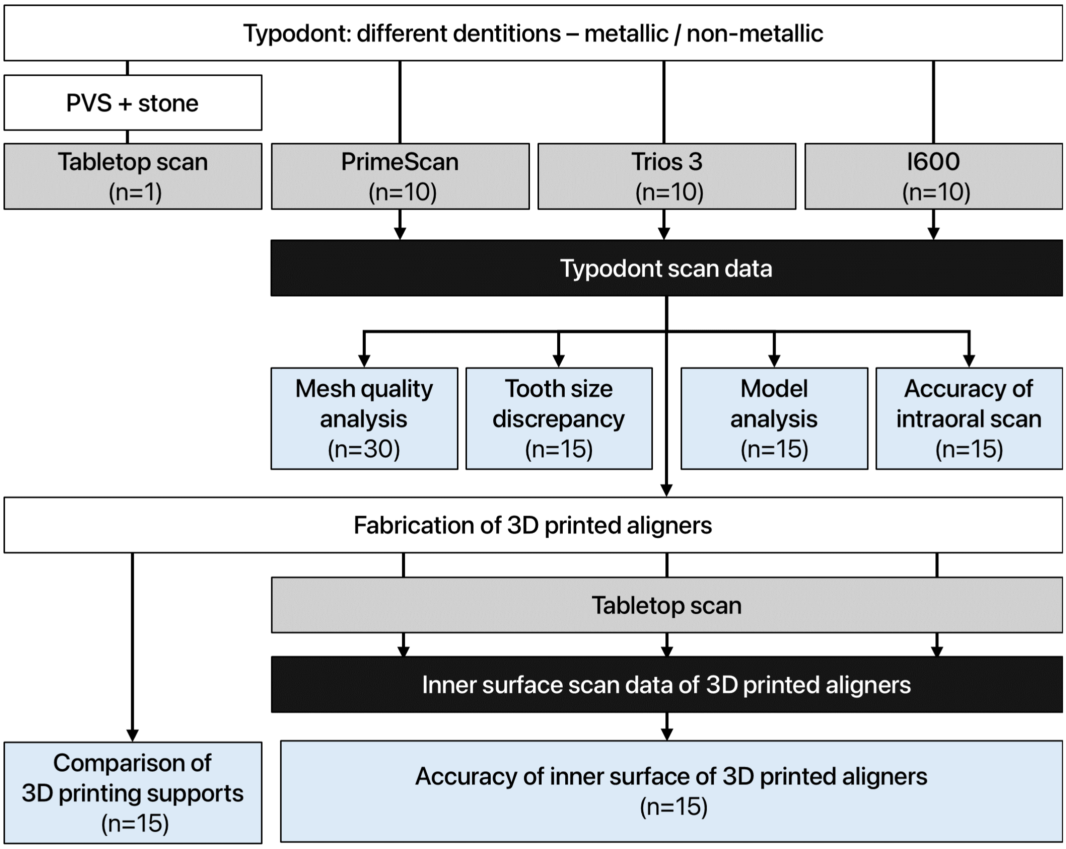


Figure 3. Schematic diagram of research process.

3. Mesh quality analysis

To determine if there were differences in the quality of the dental meshes generated, based on the scanner and material of the prosthetics, the Joe Liu metric was used to evaluate these differences. The Joe-Liu mesh value ranges from 0 to 1, where higher values indicate a higher quality of mesh elements (Revilla León et al., 2020). To explore the differences in mesh quality based on the material, digital scan data from ten specimens per scanner, including crowns and surrounding teeth in three tooth areas from the second premolar to the first molar, were evaluated. Mesh quality analysis was performed using the iso2mesh MATLAB package.

4. Model analysis

To investigate the impact of dental mesh differences, orthodontic measurements using tooth model data were performed, with five measurements taken per group. A comparative evaluation focused on the differences due to the material of the restorations was conducted for the lateral incisors and the first molars where alternative restorations were placed. To include a comparison with unaltered artificial resin teeth, similarly shaped contralateral teeth were also compared. The actual size of the crowns and resin teeth was directly measured using a digital vernier caliper to obtain a reference for tooth size. All other tooth measurements were performed by automatic model analysis program

(LaonSetUp beta version 200722; LAONPEOPLE, Seongnam, Korea), except for the reference tooth size measurements.

Clear aligners are applied to the full arch, fabricating the overall length and width are critical. Therefore, the sum of tooth sizes from the first molar to the contralateral first molar (12 teeth), inter-canine width (ICW), and inter-molar width (IMW) were evaluated. Using automatic model analysis software, all teeth were automatically separated into individual teeth. A successful tooth separation was defined as the boundary of the separated teeth being within ± 25% of the surrounding tooth boundary and the cervical margin. The success rate of tooth separation was then assessed.

5. Scan accuracy of intraoral scanners

3D dimensional differences were analyzed using a 3D inspection program (Geomagic Control X; 3D Systems, Rock Hill, USA). All 3D analyses were compared using the best-fit superimposition method. Additionally, root-mean-square (RMS) values were calculated using the software. The accuracy of the scan data was evaluated by assessing trueness and precision for five scan datasets per group.

To assess the accuracy of full arch scan data from each scanner, precision was verified by comparing full arch areas among data collected with the same scanner, and trueness was evaluated by comparing each intraoral scanner (IOS) scan data with the reference scan. To explore the differences in trueness of scan data based on the material of the conservative restorations, the evaluation areas were set to include the area of the replaced single crown and the areas of teeth surrounding to the crown. The deviation range in the color maps was expressed as ± 250 μm, and the tolerance range as ± 50 μm.

6. Fabrication of clear aligner

Clear aligners were fabricated for each group to evaluate the inner surfaces, based on differences in dental meshes. Each clear aligner was designed using aligner-specific software (Direct Aligner Designer, Graphy, Seoul, Korea). The design process adhered to the manufacturer's recommendations. The designed clear aligner shell was supported at a consistent angle and conditions before being extracted as STL files. These STL files were printed using a 3D printer with LED technology (NBEE, Uniz, San Diego, USA) and orthodontic clear resin (TC-85 DAC, Graphy, Seoul, Korea), with a layer thickness of 100 μm. Excess resin was removed from the printed aligners using a centrifuge (TeraHarz spinner, Graphy, Seoul, Korea) for five minutes. Subsequently, the aligners underwent post-curing for 20 minutes while supports remained intact under nitrogen conditions with ultraviolet light (385–405 nm) using a post-curing device (TeraHarz cure, Graphy, Seoul, Korea). The post-cured aligners were then immersed in boiling water at 100 °C for one minute before being dried, and five inner surface scan data per group were digitized using a tabletop scanner with scanning spray (EZ Scan, Alphadent, Goyang, Korea)

7. Accuracy of inner surface of clear aligners

Inner surface scan data of clear aligners were compared against the STL data designed from the reference scan data. The accuracy assessments were conducted three area, the molar crown and surrounding teeth area, occlusal area and proximal area between molar crown with surrounding teeth. The root-mean-square (RMS) values were calculated following best-fit superimposition and 3D comparison using Geomagic Control X software. The proximal area was defined as the 3 mm region near the mesial and distal contacts of the molar crown, and the occlusal area was defined as the region between the proximal areas.

8. Statistical analysis

To determine the statistical significance of mean mesh quality, model analysis, scan data accuracy, and clear aligner inner surface accuracy, the Kruskal-Wallis's test was used to assess statistical significance by scanner and restoration material type, followed by a Mann-Whitney post hoc test. The significance level for the post hoc tests was adjusted using the Bonferroni's method ($p < 0.05/3$). The statistical analyses were performed using the software SPSS 26.0 (SPSS Inc., Chicago, Illinois) and Origin 2021 (OriginLab Corporation, Massachusetts).

III. RESULTS

1. Mesh quality analysis

The quality of the mesh for each material and scanner used in the prosthetic restoration was compared and evaluated, measured on a 0 to 1 scale, where higher values represent better quality. For the gold crown and surrounding teeth, the mesh quality measurements were 0.757 ± 0.001 for PrimeScan, 0.741 ± 0.004 for Trios 3, and 0.808 ± 0.001 for i600. Similarly, for the zirconia crown and surrounding teeth, the values were 0.759 ± 0.001 for PrimeScan, 0.741 ± 0.002 for Trios 3, and 0.809 ± 0.001 for i600. Among the scanners, i600 demonstrated the highest mesh quality, followed by PrimeScan and then Trios 3 (Figure 4). No significant differences in mesh quality were observed between the two materials used in prosthetic restorations.

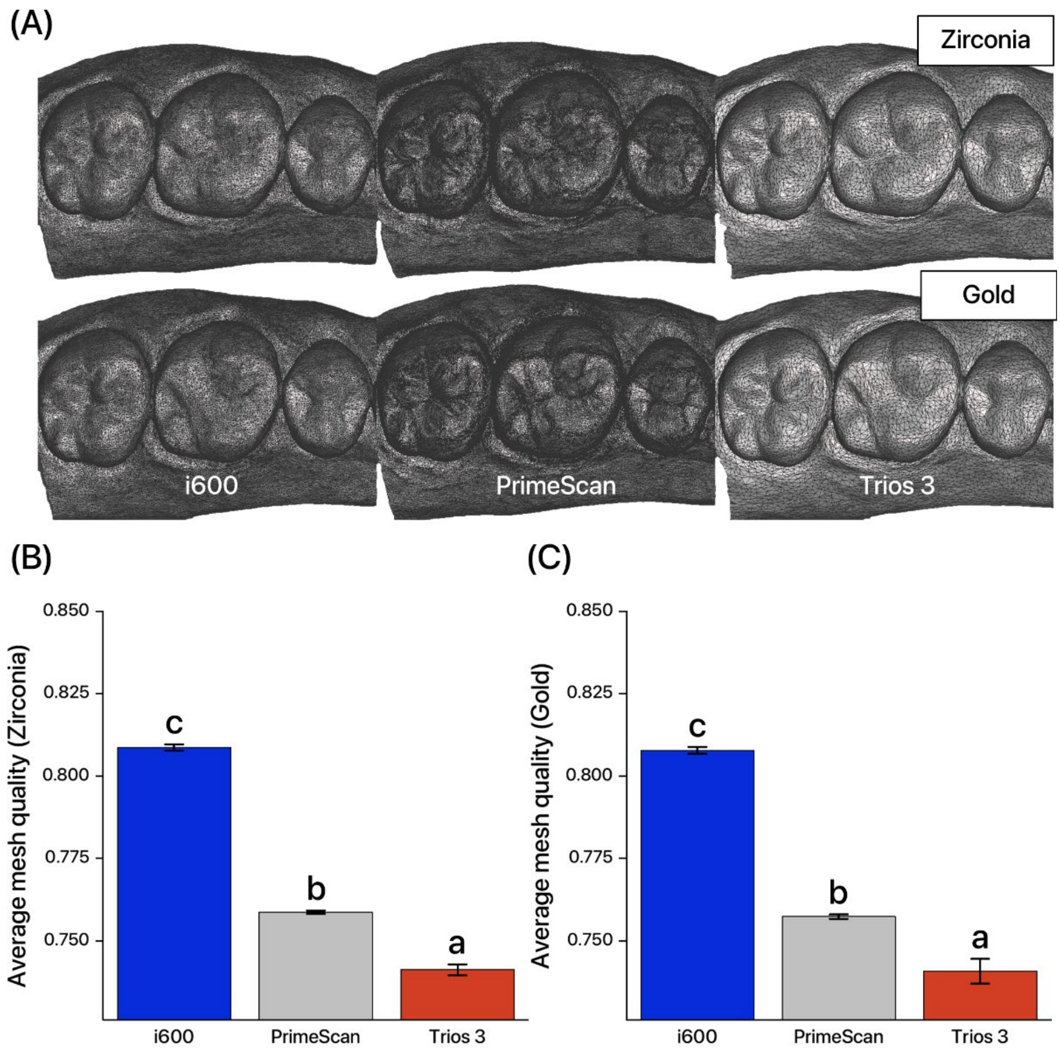


Figure 4. Average mesh quality differences in crown and surrounding teeth area with different scanners. (A) meshed images using intraoral scanners, (B) average mesh quality differences in zirconia dentitions, (C) average mesh quality differences in gold dentitions. dissimilar letters indicate significant differences from each group (p < 0.05/3).

2. Tooth size discrepancy

Tooth size differences are compared by subtracting the manually measured value from the automatically measured value. The evaluation focused on the lateral incisor and first molar, where existing typodont resin teeth were replaced with prosthetic restorations. The results were expressed in mm and mean ± standard deviation.

For the lateral incisor, measurements of resin teeth were significantly larger than those of zirconia across all scanners ($p < 0.001$). There were no significant differences observed among all scanners when measuring resin teeth. In the case of zirconia, the PrimeScan showed a difference of 0.21 ± 0.04 mm, the i600 scanner showed a difference of 0.06 ± 0.04 mm, while the Trios 3 showed the smallest difference at 0.00 ± 0.04 mm. These three scanners showed significant differences from each other ($p < 0.05/3$). For all scanners and materials, the automatic measurements were generally larger than the manual measurements (Figure 5).

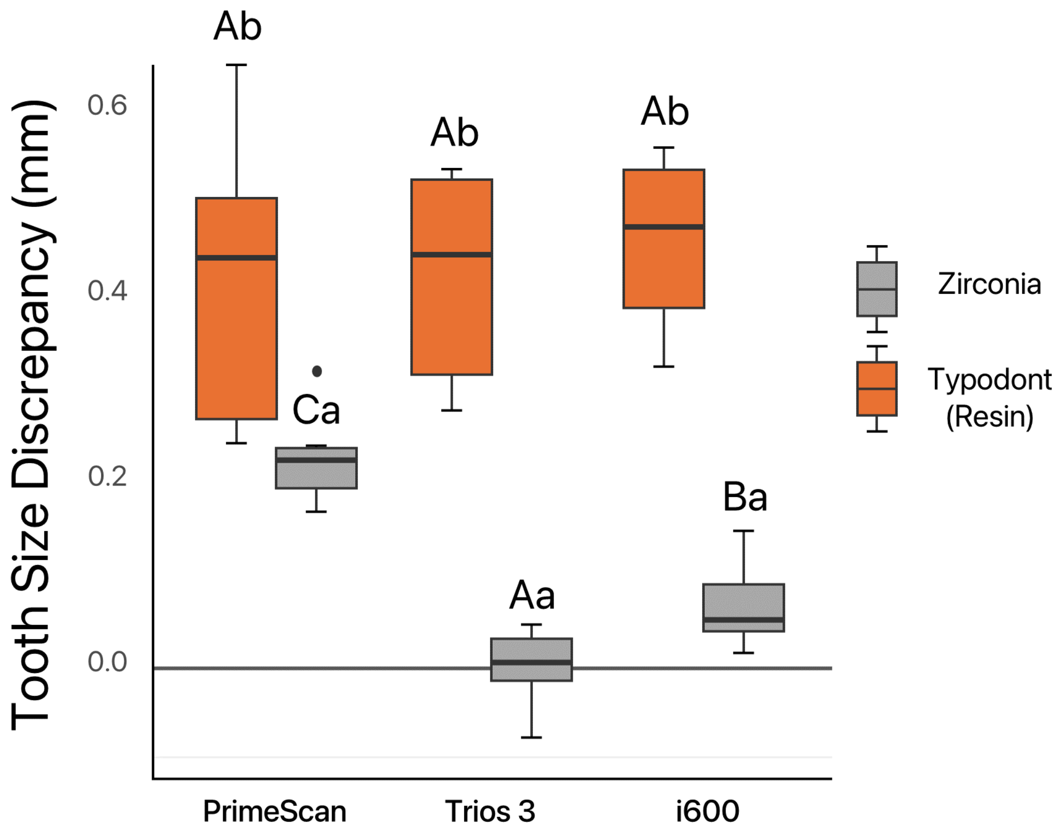


Figure 5. Tooth size discrepancy for lateral incisors using different scanners (PrimeScan, Trios 3, i600). Capital letters represent the differences between different scanners ($p < 0.05/3$), and lowercase letters represent the differences between different materials ($p < 0.05$).

For the first molar, measurements of resin teeth with Trios 3 were significantly smaller at 0.13 ± 0.05 mm compared to the other scanners ($p < 0.05/3$). In the case of zirconia, the PrimeScan showed significantly larger measurements at 0.15 ± 0.03 mm compared to other scanners ($p < 0.05/3$). Both resin teeth and zirconia tended to be measured larger in automatic measurements compared to manual measurements, while gold measurements were similar to or smaller than manual measurements (Figure 6).

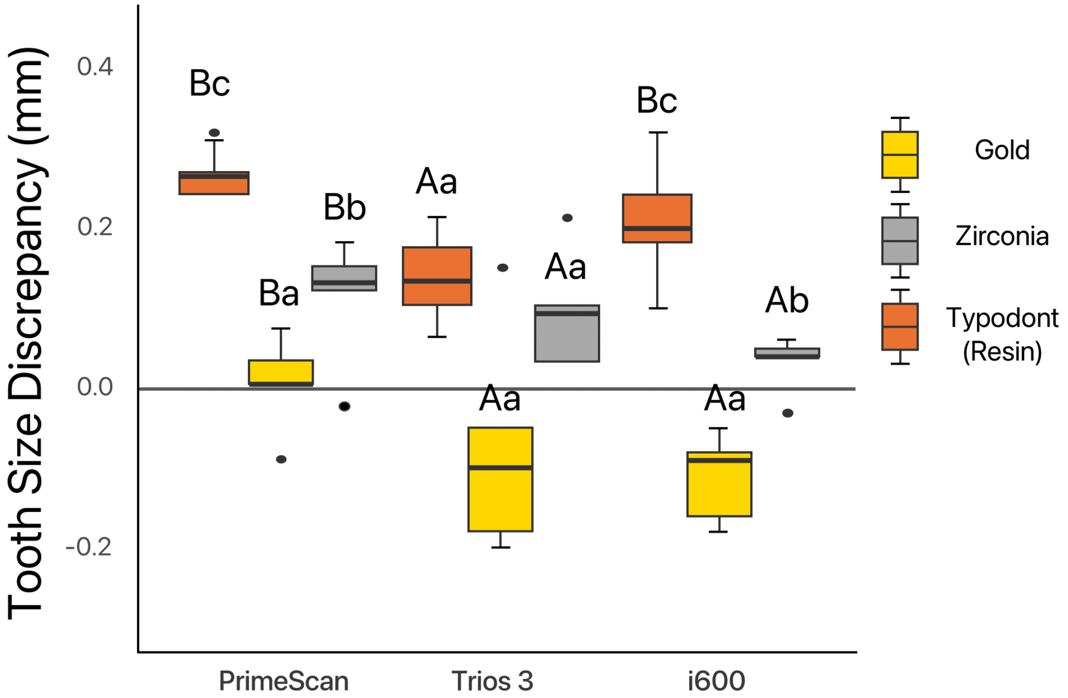


Figure 6. Tooth size discrepancy for first molars using different scanners (PrimeScan, Trios 3, i600). Capital letters represent the differences between different scanners, and lowercase letters represent the differences between different materials ($p < 0.05/3$).

3. Comparison of model analysis

Statistical analysis of the size differences among model analysis values revealed no significant differences attributable to the type of restorative materials. However, significant differences were observed among scanners across all categories. For 12 teeth, PrimeScan recorded the largest measurements, followed by i600 and Trios 3, showing significant size differences ($p < 0.05/3$). In terms of intercanine width (ICW) and intermolar width (IMW), both PrimeScan and i600 measured significantly larger than Trios 3 ($p < 0.05/3$) (Table 1).

Table 1. Comparison of model analysis variables for intraoral scan data

Variables	Scanner			p	Post-hoc
	PrimeScan[a] (mm)	**Trios 3**[b] (mm)	**i600**[c] (mm)		
12 Teeth	96.76 ± 0.06	95.28 ± 0.28	95.98 ± 0.24	0.000	a > c > b
ICW	34.96 ± 0.07	34.77 ± 0.15	34.99 ± 0.03	0.001	a, c > b
IMW	46.35 ± 0.10	45.22 ± 0.30	46.20 ± 0.22	0.000	a, c > b

Statistical analysis with kruskal-wallis test and post-hoc analysis with Mann-Whitney Test. The post hoc test significance level was adjusted by the Bonferroni's method ($p < 0.05/3$).
Value: mean ± standard deviation, NS: not significant.
12 teeth: sum of tooth sizes from first molar to contralateral first molar, ICW: inter canine width, IMW: inter molar width.

4. Accuracy of full arch scan

To evaluate the accuracy of each scanner, trueness and precision were assessed using full-arch scan data. Comparing data scanned with the same type of scanner, the mean (SD) RMS value for the tabletop scanner was significantly lower at 9 ± 7 μm compared to all other scanners ($p < 0.05/3$). Although there was no significant difference between Trios 3 (60 ± 31 μm) and i600 (59 ± 30 μm), both were significantly higher than PrimeScan, which recorded a mean RMS value of 19 ± 4 μm ($p < 0.05/3$) (Figure 7).

Comparing other intraoral scanners against reference scan data obtained from a tabletop scanner revealed significant differences among all scanners ($p < 0.05$). The RMS values increased progressively with PrimeScan at 44 ± 5 μm, i600 at 65 ± 11 μm, and Trios 3 at 113 ± 39 μm (Figure 7).

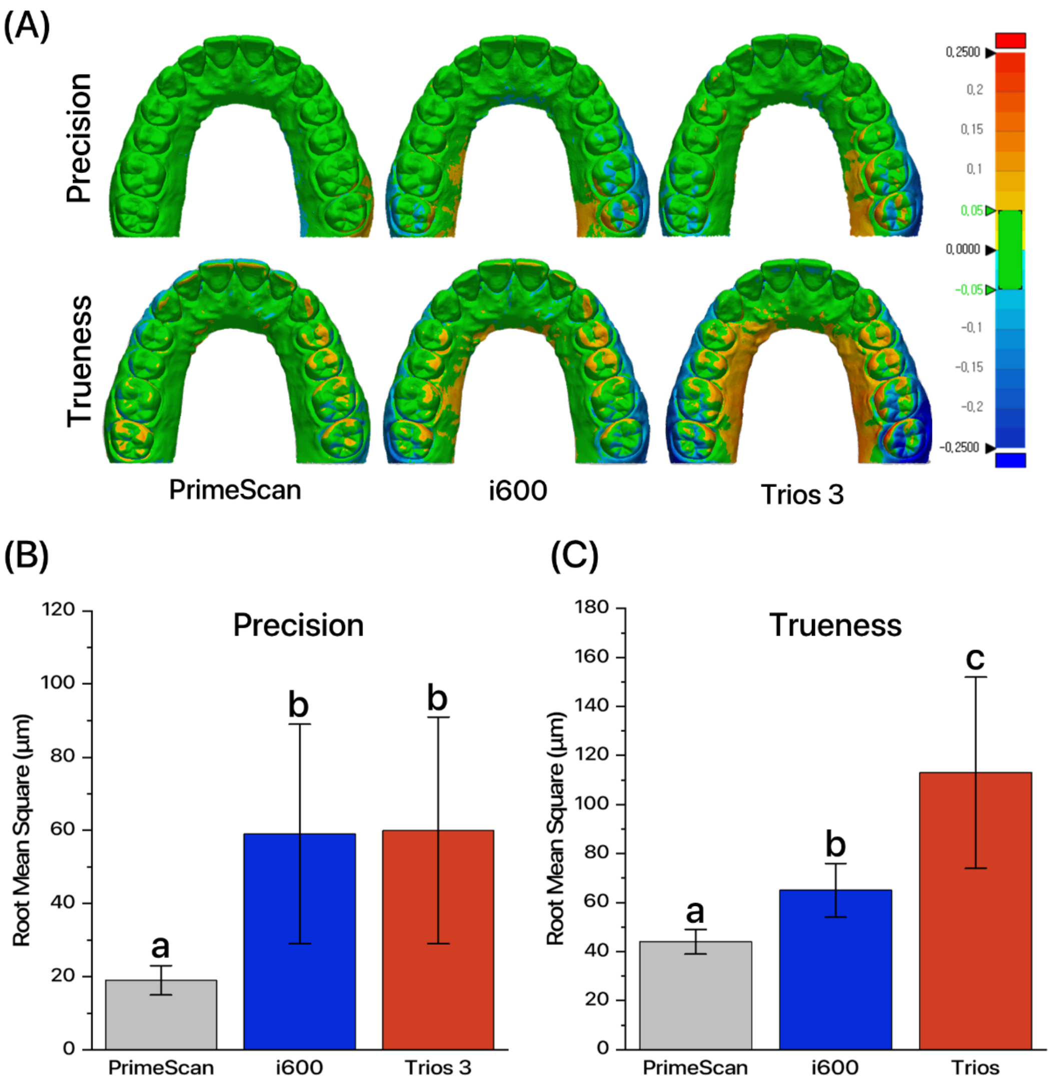


Figure 7. Precision and trueness of full-arch scan data (PrimeScan, Trios 3, i600). (A) deviation in 3D comparison, (B) RMS values of precision, (C) RMS values of trueness. Dissimilar letters indicate significant differences from each group ($p < 0.05/3$).

5. Trueness of restorative crown and surrounding teeth

The evaluation of trueness in scan data showed no significant differences among scanners for the lateral incisor zirconia crown and surrounding teeth. However, for the first molar zirconia crown, there were statistically significant differences: Trios 3 (25 ± 0 μm) and i600 (24 ± 3 μm) showed larger values compared to PrimeScan (20 ± 1 μm). For the surrounding teeth, Trios 3 (33 ± 4 μm) was significantly larger than PrimeScan (30 ± 0 μm). In the case of the first molar gold crown, the i600 scanner exhibited the highest RMS value at 59 ± 1 μm (Table 2) (Figure 8)

Table 2 Comparison of root mean square (RMS) values for the crown and surrounding teeth areas between reference and intraoral scan data

Position	Materials	Scanner			*p*	Post-hoc
		PrimeScan (μm)	**Trios 3** (μm)	**i600** (μm)		
Anterior	Zirconia	23 ± 3	25 ± 3	23 ± 3	0.552	NS
	Resin (Surrounding)	31 ± 2	31 ± 2	29 ± 2	0.093	NS
Posterior	Zirconia	20 ± 1	25 ± 0	24 ± 3	0.007	b, c > a
	Resin (Surrounding)	30 ± 0	33 ± 4	29 ± 3	0.033	b > a
	Gold	31 ± 1	33 ± 3	59 ± 1	0.006	c > a, b
	Resin (Surrounding)	31 ± 1	33 ± 3	29 ± 1	0.017	b > c

Statistical analysis with kruskal-wallis test and post-hoc analysis with Mann-Whitney Test. The post hoc test significance level was adjusted by the Bonferroni's method ($p < 0.05/3$).
Value: mean ± standard deviation, NS: not significant

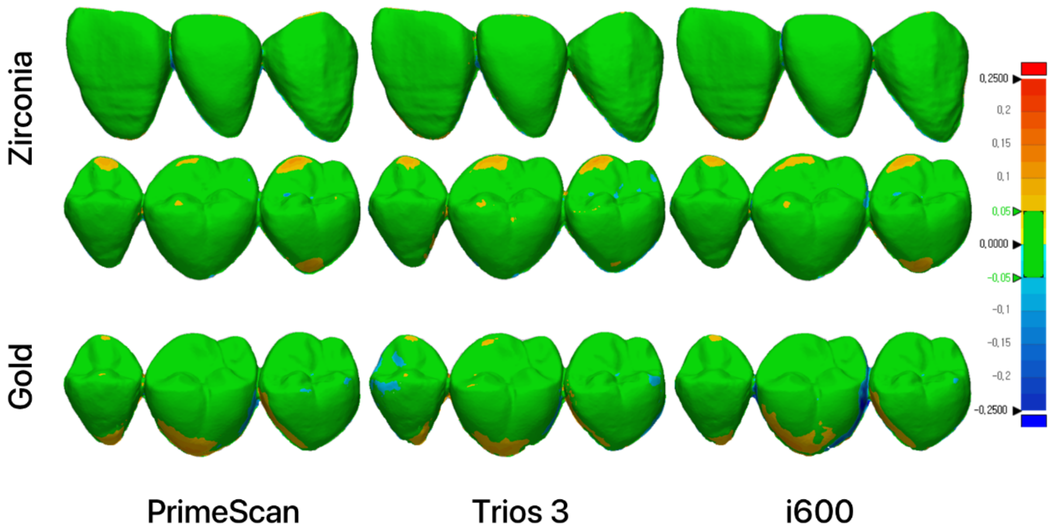


Figure 8. 3D Comparison of reference scan data with three intraoral scans (PrimeScan, Trios 3, i600): evaluation of prosthetic crowns (lateral incisors and first molars) and surrounding teeth

6. Assessment of clear aligner quality

6.1 Difference in CAD file setup of 3D printing supports

The study examined the influence of number of support arms generated on aligners designed based on mesh differences. Both the reference scanner and intraoral scanners showed no significant differences in the number of supports generated. Similarly, there were no significant differences in the number of support arms created in the island areas, and it was difficult to identify any specific patterns in the support arms created depending on the variable (Figure 9).

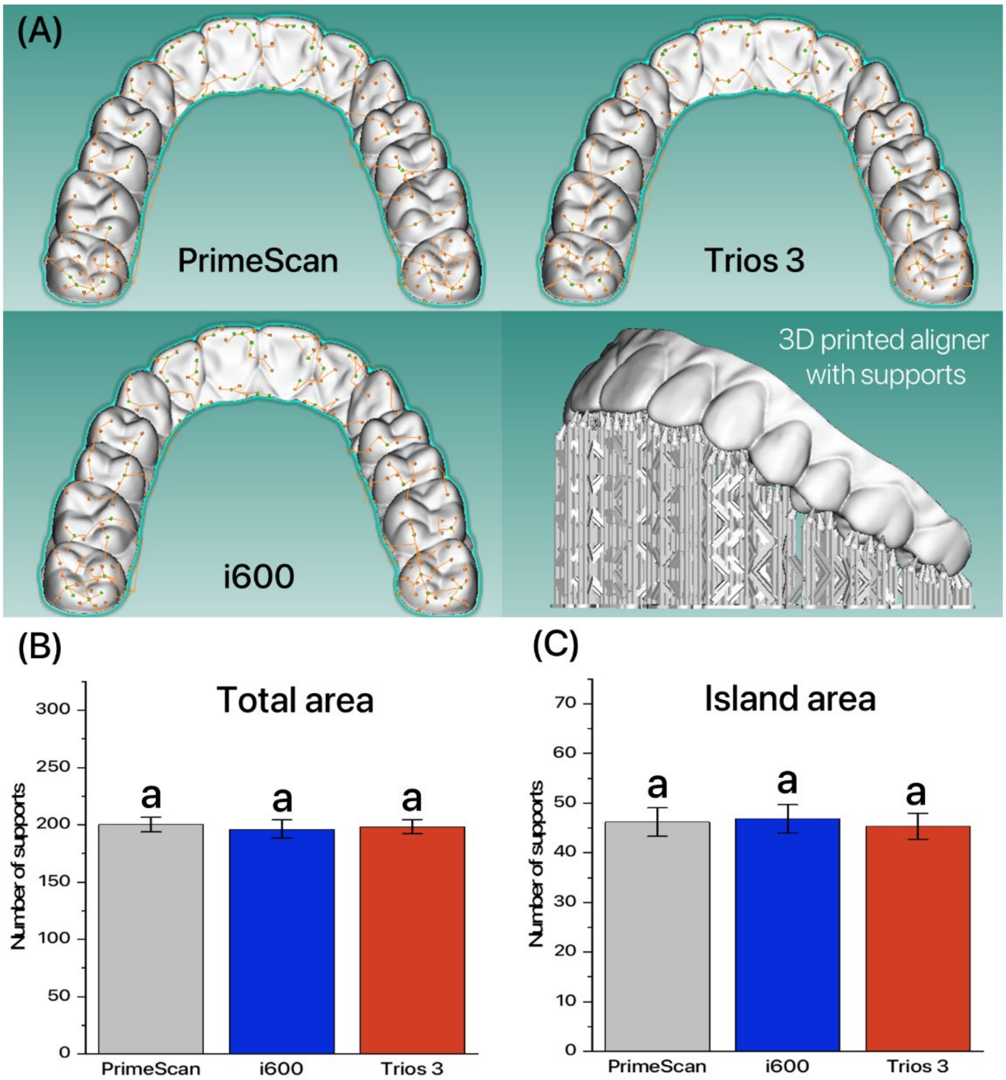
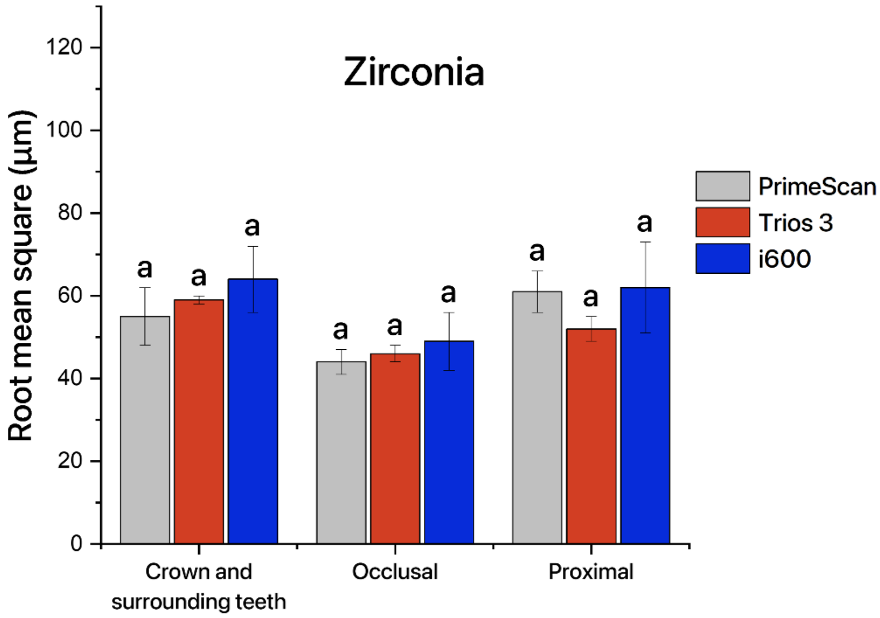


Figure 9. Comparison of 3D printing supports of clear aligners. (A) locations of supports for each group. orange points: locations of the created supports, green points: locations of the supports created in the island area. Comparison of number of supports created by group (B: total area, C: island area). same letters indicate no significant differences from each group.

6.2 Comparison of clear aligner inner surface

The 3D printed aligners were digitized and analyzed area by area for RMS values calculated through 3D comparison. In the gold group, a significant difference between groups was found as a result of the 3D comparison of the molar crown and surrounding teeth areas, with the i600 being significantly larger than the Trios 3 (Figure 11). No significant differences were found in the occlusal area, but in proximal area, i600 was significantly larger than PrimeScan and Trios 3 ($p < 0.05/3$). On the other hand, in the zirconia group, no significant differences between groups were found (Table 3).



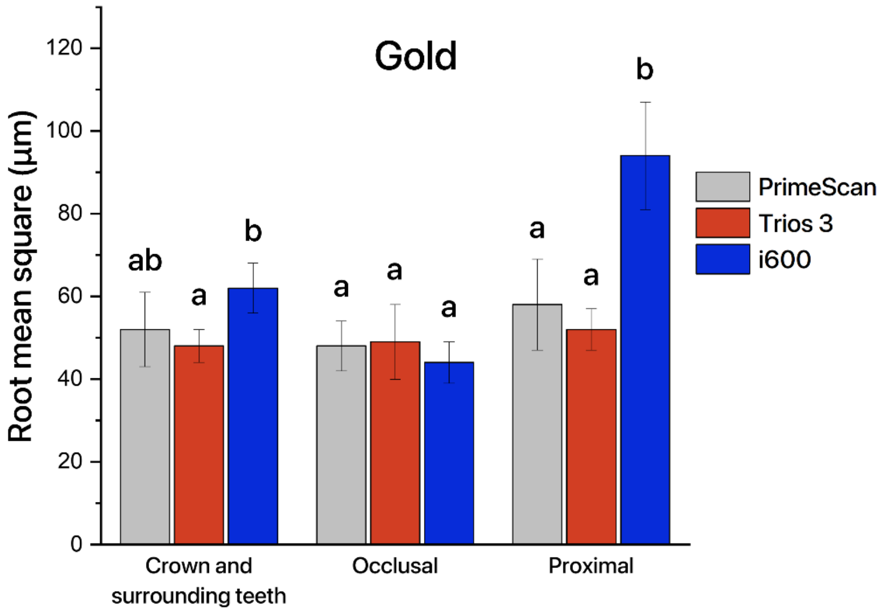


Figure 10. Comparison of root mean square (RMS) values for inner surface of clear aligners. Dissimilar letters indicate significant differences from each scanner ($p < 0.05/3$).

IV. DISCUSSION

Digital dentistry, including orthodontics, has firmly integrated into dental practices, with clear aligner therapy rapidly gaining popularity due to its benefits for both patients and clinicians. Advances in technology have facilitated the easier and more cost-effective production of aligners using clear 3D printing resin. The combination of intraoral scans, efficient CAD software, and 3D printing has nearly fully digitized the orthodontic treatment planning process. However, technological differences, along with variations in patients' intraoral conditions, can lead to unpredictable outcomes, including a lower quality of aligner fit that may impact overall treatment efficacy. While several factors can influence the quality of clear aligners, this study specifically investigates the effect of the initial step, i.e., intraoral 3D scanning, in the presence of two different restorative materials.

The present study compared three intraoral scanners for their efficacy on 3D scanning typodonts having of non-metallic (zirconia crown) and metallic (gold) restorations. While zirconia restorations were evaluated for both lateral incisor and first molar, the impact of gold was tested on first molar only. Considering clinical situations, zirconia was placed in the anterior region, while gold and zirconia were positioned in the posterior region. To minimize the impact of restorative materials on the scan data of adjacent teeth, the prosthetic restorations were not placed consecutively. The arch was split to ensure that the artificial teeth on the opposite side were not affected by the restorations.

Full-arch digitization was performed using three intraoral scanners. The scanners used in this study are based on different data capture principles. The i600 scanner utilizes optical triangulation, the Trios 3 employs confocal microscopy, and the PrimeScan uses a combination of confocal microscopy and short-wave light with optical high-frequency contrast analysis. Optical high-frequency contrast analysis is an image processing technique that enhances detailed textures and boundary information. Due to these differences in methods, the final intraoral image data's form and quality can vary. Therefore, we have differentiated the data capture principles of the scanners used in the study.

The meshes of the digitized dental model are essential in guiding tooth segmentation and planning tooth movement (Kim et al., 2020; Woo et al., 2023; Yoon et al., 2018). For the fabrication of clear aligners, individual teeth must be separated from the dental model and their precise movements simulated and modeled step by step. Therefore, to ensure accurate and stable three-dimensional computational modeling, an assessment of mesh quality can be performed. Thus, the scanners' mesh quality using the Joe Liu metric. The Joe-Liu metric quantifies the quality of triangulation on a surface, such as the geometry of teeth, by evaluating each individual triangle. It provides a dimensionless normalized range from 0 to 1 where near 1 value have higher mesh quality, representing an equilateral triangle, and values near 0 suggest lower quality, corresponding to an almost degenerate triangle (Revilla León et al., 2020). Mesh quality is a critical factor in 3D simulation and modeling, as it affects the accuracy of results, computation time, and optimization. Furthermore, it influences the occurrence of errors and computational stability (Revilla

León et al., 2020). Therefore, mesh quality can be considered one of the important factors to consider when selecting an intraoral scanner, as it serves as an indicator of the reliability and efficiency of three-dimensional computational modeling.

The mesh quality showed significant differences between all scanners, although similar trends were observed for both zirconia and gold groups. The study successfully demonstrated that while there is no significant difference in mesh quality based on the type of restorative materials, scanner choice significantly influences dental mesh quality. An interesting finding is that although the i600 scanner consistently provided the highest mesh quality, it showed a significant decrease in accuracy at the connections between the gold crown and surrounding teeth. This indicates that mesh quality is determined not during the optical technology-based position data collection phase, but during the 3D image processing phase, specifically by the triangulation algorithm and software utilized (Revilla León et al., 2020).

In orthodontic treatment planning tooth-size accuracy is a significant determinant (Im et al., 2022; Yu et al., 2023). Reliability in tooth size measurement not only influences the treatment plan but also the final aligner fit. Comparing the influence of zirconia and gold it could be observed that deviation from the actual size were observed due to difference in tooth material. Here, tabletop scanner digitized data served as external reference. The fidelity of the intra oral scanners varied notably for both zirconia and gold. For zirconia Trios 3 showed highest fidelity with minimal deviations at both lateral incisor and first molar region. However, when replaced with gold restoration at first molar region, Trios 3 and i600 both displayed underestimation from actual size (Shin et al., 2021).

When comparing the size discrepancies of lateral incisors, we analyzed the zirconia crown relative to its contralateral incisor with a similar shape to assess differences in materials. Measurements were taken from three different scanners, including a tabletop scanner, and compared with dimensions obtained using a digital caliper. We observed a significant error range and an average discrepancy exceeding 0.4 mm. Resin teeth typically measure larger than teeth made of gold or zirconia. However, proximal spaces were identified around the resin lateral incisors, and since these spaces are difficult to distinguish using the scanner, errors in tooth size measurement may increase (Son et al., 2022).

Clear aligners are a full-arch coverage appliance. Therefore, a 3D surface assay of full-arch scan data accuracy is a better comparison of the digitization efficacy for clear aligners through different scanners. In a 3D comparison of full arch scans, the RMS values for trueness and precision showed that digitization through Primescan was most similar to a tabletop scanner and differed significantly from both Trios 3 and i600. As a result, we found that the Primescan can reliably provide accurate scan information for the full arch area, which is consistent with previous research findings (Mangano et al., 2019).

This research also confirmed that the type of restorative material affects scan accuracy. High reflectance materials, such as gold, present challenges in scanning accuracy, particularly with scanners like the i600. With the i600, zirconia, which has relatively low surface reflectance, showed RMS values of 24 μm, whereas gold showed RMS values of 59 μm, which is approximately twice as large. This discrepancy underscores the need for further development in scanner technologies to effectively handle a broader range of dental materials.

It has been reported that prosthetics with high reflectivity, especially those that are shiny, are more significantly affected by scanning methods that use triangulation to collect shape information, a finding consistent with our results (Elter and Tak, 2023; Logozzo et al., 2014; Winkler and Gkantidis, 2020). We investigated why the accuracy of triangulation is affected by surface reflectance. In the case of optical triangulation, scanning is generally more effective with objects that have higher diffuse reflectance (Paulus et al., 2014). The more diffuse light that reaches the sensor, the less the scan is affected by external noise and light, resulting in better resolution. On the other hand, for metallic objects with high reflectance, the light undergoes specular reflection rather than diffuse reflection when it hits the object. This makes it difficult to collect accurate positional information of the object during scanning.

The negative impact on shiny intraoral prosthetics can be reduced by using a scanning-aid agent to control the reflectivity of the prosthetic, thereby enhancing the accuracy of intraoral scan data (Kim et al., 2018; Mangano et al., 2024; Oh et al., 2021; Waldecker et al., 2021). However, scanning agents can increase scanning time, cause discomfort to patients, and lead to thickness errors. Therefore, it is recommended to choose an intraoral scanner that is minimally affected by restorative materials.

The evaluation of the inner surface accuracy of clear aligners showed that the i600 scanner had significantly different RMS values compared to the Trios 3 scanner. While there were no significant differences in the occlusal area across all groups, the RMS values of the i600 scanner were significantly higher in the proximal area compared to the other two intraoral scanners. This indicates that issues caused by high reflectance were particularly pronounced in the proximal area. Defects in clear aligners at the proximal area can cause several problems. Premature contact can occur, leading to issues in securing orthodontic anchorage and causing unintended tooth movement. Inaccurate clear aligners can degrade the quality of orthodontic treatment, thus necessitating predictive and preventive strategies to mitigate scan errors.

The study's limitations include its focus on only a few types of dental materials and scanners. Future research should expand to include a wider range of materials and newer scanner models to provide more comprehensive guidelines for clinical practice. Additionally, the impact of environmental factors, such as humidity and temperature during scanning, warrants further investigation. Furthermore, we controlled for other variables and used a dental typodont to establish the restorative material. Typodont teeth are made from resin, which may cause differences in outcomes compared to human teeth (Bocklet et al., 2019). Therefore, future studies should investigate the impact of different restorative materials under conditions using human teeth.

V. CONCLUSION

We aimed to evaluate the effects of restorative materials and types of intraoral scanners on the accuracy of dental mesh and 3D printed clear aligners, leading to the rejection of all null hypotheses based on the following findings:

1. While no significant differences were observed in mesh quality based on the type of restoration, significant differences were noted among scanner systems; i600: 0.81, PrimeScan: 0.76, and Trios 3: 0.74, indicating significant disparities in dental mesh quality ($p < 0.05/3$).

2. In terms of scanning accuracy across the full arch area, there was a significant order of accuracy: PrimeScan > i600 > Trios 3 ($p < 0.05/3$). When evaluating the accuracy of crown and surrounding teeth scan data, the i600 scanner showed significantly larger discrepancies when scanning gold crowns compared to resin or zirconia ($p < 0.05/3$).

3. The inner surface accuracy of the clear aligners, based on the i600 scanner, showed that the RMS value in the proximal area of the gold crown was significantly higher than that of other scanners ($p < 0.05/3$).

In conclusion, we found that the accuracy of clear aligners and mesh quality are influenced by the type of restorative material and scanner used. Specifically, metallic restorative materials made it difficult to obtain accurate scan shapes with scanners using triangulation technology, resulting in inaccurate clear aligners. Therefore, to improve clear aligner treatment outcomes, clinicians should either select scanners that are less affected by restorative materials or carefully consider the restorative materials present in the patient's mouth when performing clear aligner treatments.

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ABSTRACT (Korean)

구강스캐너를 활용한 치과 수복재료에 따른 3D 프린팅 투명교정장치의 정확성

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유 재 훈

투명 교정 치료는 외모와 직업생활에 미치는 영향이 적어 성인과 직장인 사이에서 인기를 얻고 있다. 구강 스캐너의 보급으로 인한 디지털 덴트스트리로의 전환과 CAD/CAM의 발전은 투명 교정 치료가 널리 퍼질 수 있던 핵심 배경으로 작용하였다. 최근 3D 프린터로 투명 교정 장치를 직접 출력하는 장치가 주목받고 있으며, 성공적인 교정 치료를 위해서는 환자 개인에게 최적화된 단계별 치아 이동 설계와 교정력을 올바르게 전달하기 위한 정확한 장치 제작이 필요하다. 구강 내 스캐너를 활용하면 환자의 치열을 즉각적으로 디지털화가 가능하지만, 구강 내 수복 재료에 따라 스캔 정확도의 차이가 발생할 수 있다.

따라서 본 연구는 구강 내 스캐너를 이용하여, 보철 수복 물의 재료에 따라 구강 스캔 데이터와 3D 프린팅 투명교정장치 내면의 정확성에 미치는 영향을 확인해 보고자 한다. 비교 평가를 위해 참조 스캔데이터는 테이블 탑 스캐너를 이용했고, PrimeScan (Dentsply Sirona, York, PA, USA), i600 (Medit, Seoul, Korea), and Trios 3 (3Shape A/S, Copenhagen, Denmark) 구강 스캐너를 이용해 각각 골드 소재와 지르코니아 소재로 만들어진 보철물이 포함된 두 가지 유형의 타이포돈트 데이터를 수집하였다. 수집된 스캔 데이터에 대해 메시 품질에 대한 평가와 3차원적인 정확도를 평가하였고, 최종적으로 서로 다른 메시 정보 기반의 3D 프린팅 투명교정 장치 내면 정확성에 대해 평가하였다.

실험 결과, 메시 품질은 보철물 재료에 따른 차이는 없었고, i600은 0.81, PrimeScan은 0.76, Trios 3는 0.74 순서로 품질이 우수했다($p < 0.05/3$). 소재에 따라서 레진과 지르코니아는 실측값에 비해 크게 측정되는 경향이 있었고, 골드는 비슷하거나 더 작게 계측되는 경향을 보였다. 모델 분석 측정에서 Trios 3는 다른 구강 스캐너보다 훨씬 작은 측정값을 보였고($p < 0.05/3$), Primescan은 전체 악궁 스캔 비교에서 우수한 정확도를 보여주었다($p < 0.05/3$). 골드 크라운을 스캔한 i600 스캐너의 RMS 값은 평균 59μm로 다른 스캐너들에 비해 유의하게 높았고($p < 0.05/3$), 프린팅된 투명교정 장치의 내면 정확도 비교에서도 i600으로 스캔한 골드 크라운 군에서 치아 인접면 영역에서 평균 RMS 값이 94μm로 가장 높게 나타났다($p < 0.05/3$).

결론적으로 구강 스캐너를 활용한 3D 프린팅된 투명교정 장치의 정확성은 일반적으로 양호한 결과를 보였지만, 삼각측량 기술 기반의 구강 스캐너로 골드 크라운의 정확한 외형 정보를 수집하기 어려웠다. 구강 내 스캐너의 선택은 메시의 품질과 투명교정 장치의 정확성 모두에 큰 영향을 줄 수 있다. 따라서 투명교정 치료 결과를 향상하기 위해, 수복 재료의 영향을 적게 받는 스캐너를 선택하거나 환자의 구강 내 수복 재료에 대한 신중한 고려가 필요하다.

핵심되는 말: 3D 치과 메시, 구강 스캐너, 치과 수복 재료, 3D 프린팅 투명교정장치, 메시 품질, 스캔 정확도