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Influence of restorative material types on 3D printed aligner accuracy using intraoral scanners

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Abstract

Objectives

This study evaluated the effects of restorative materials and intraoral scanners on the mesh data quality of dental models and the accuracy of 3D-printed clear aligners.

Materials and methods

Reference scan data were obtained with a tabletop scanner, while test data were collected using PrimeScan, Trios 3, and i600 scanners. Typodonts with metallic (gold) and non-metallic (zirconia) crowns were scanned. Data from each scanner were assessed for mesh quality and 3D accuracy. 3D printed aligners were subsequently printed based on each scanner's mesh data and evaluated.

Results

The i600 scanner had the highest mesh quality (0.81), followed by PrimeScan (0.76) and Trios 3 (0.74) scanners, whereas the restorative material had no significant effect on mesh quality ($p < 0.05$). Resin and zirconia crowns were generally measured larger than actual sizes, while gold crowns tended to be similarly measured or smaller. PrimeScan showed the highest accuracy for full-arch scans, while Trios 3 measured significantly smaller than the other two scanners $p < 0.05$). For gold crowns, i600 displayed the highest RMS value at 59 μm $p < 0.05$). Aligners printed from i600 scans showed the largest RMS value on the inner surface near gold crowns, averaging 94 μm.

Conclusions

Types of restorative material and scanner can significantly affect the accuracy of 3D printed aligners and mesh quality. Metallic restorations can decrease accuracy with triangulation-based scanners.

Clinical Relevance

Clinical application of intraoral scanners that are less influenced by restorative materials, particularly metallic restorations, may improve the predictability of 3D-printed aligner treatment and help optimize clinical outcomes.

Keywords: 3D printed aligner, intraoral scanner, metallic restorations, accuracy, mesh quality

1. Introduction

Clear aligner treatment has gained significant attention in the orthodontic market worldwide. The shift towards digital dentistry facilitated by widespread adoption of intraoral scanners and advancements in CAD/CAM systems has substantially contributed to the increase in prescription 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. [1-3] Digitizing patient oral information commonly involves tabletop scanners for plaster casts, offering reliable and stable results. [4] Intraoral scanners can directly capture and digitize intraoral data, eliminating intermediate steps. [5] However, the scanning accuracy can be affected by environmental factors such as lighting conditions, saliva, and presence of prostheses in the mouth. [6-8] Since the accuracy of a scanner directly affects quality of the final appliance, the quality of scan data becomes an essential factor.

Data generated by intraoral scanners can vary depending on the specific optical and 3D imaging technologies utilized, even when scanning the same object. Technically, scanned data consist of point clouds formed by capturing the positional information of an object. [9] Optical methods used by intraoral scanners for acquiring positional information include confocal laser scanning microscopy and triangulation. Positional data collected in the form of point clouds are processed through three-dimensional computations to reproduce the original shape of a scanned object. [10] The final three-dimensional shape is rendered as a mesh utilizing proprietary software and algorithms provided by each manufacturer. [11]

Through the above process, the shape of a scanned object and the structure of the mesh can be determined. Given that the mesh structure is fundamental in CAD, it can directly influence the quality of 3D printed aligners. Furthermore, since aligners are designed to achieve precise tooth movements in increments of less than 0.5 mm per step, any loss of accuracy in scan data could lead to treatment delays or a reduction in the overall quality of treatment. [12]

To fabricate clear aligners, individual teeth must be separated from the digitized dental model with their movements simulated step by step. Therefore, assessing mesh quality is an important factor when selecting an intraoral scanner as mesh quality indicates the reliability and efficiency of three-dimensional computational modeling. [13] However, studies on mesh quality of intraoral scan data are limited. Moreover, little consideration has been given to the impact of different types of restoration and prostheses on mesh quality.

Several factors, including scanner accuracy, mesh quality, environmental conditions (such as lighting conditions and saliva), and the presence of prostheses, become even more critical for 3D printed clear aligners. Because 3D printed aligners are fabricated without an intermediary dental model, mesh accuracy will multiple directly into aligner outcome. [14] Given inherent technical variability among intraoral scanners, [5, 10, 15-20] accurately reproducing clear aligners and ensuring their proper fit—particularly in the presence of various prostheses—is a crucial clinical consideration. [21] Therefore, understanding the impact of different materials in accordance with different intraoral scanning technologies on intraoral surface is essential for assessing the quality of clear aligners produced through a fully digital workflow.

Thus, this study aimed to examine whether the accuracy of dental mesh and 3D printed clear aligners could be influenced by the type of restorative materials (such as metallic and non-metallic prostheses) and the intraoral scanner used in treatment planning.

The null hypothesis was that there would be no significant differences in the quality of the dental mesh and the accuracy of the 3D printed clear aligners, regardless of the intraoral scanner's technical method or the type of restorative material used.

2. Materials and methods

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

In a dental typodont (Nissin Dental, Kyoto, Japan), artificial resin teeth were prepared at 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. Non-metallic zirconia widely preferred due to its excellent properties and metallic gold alloy were chosen. To contrast with unaltered resin teeth on the opposite side, right and left sides were split (Fig 1).

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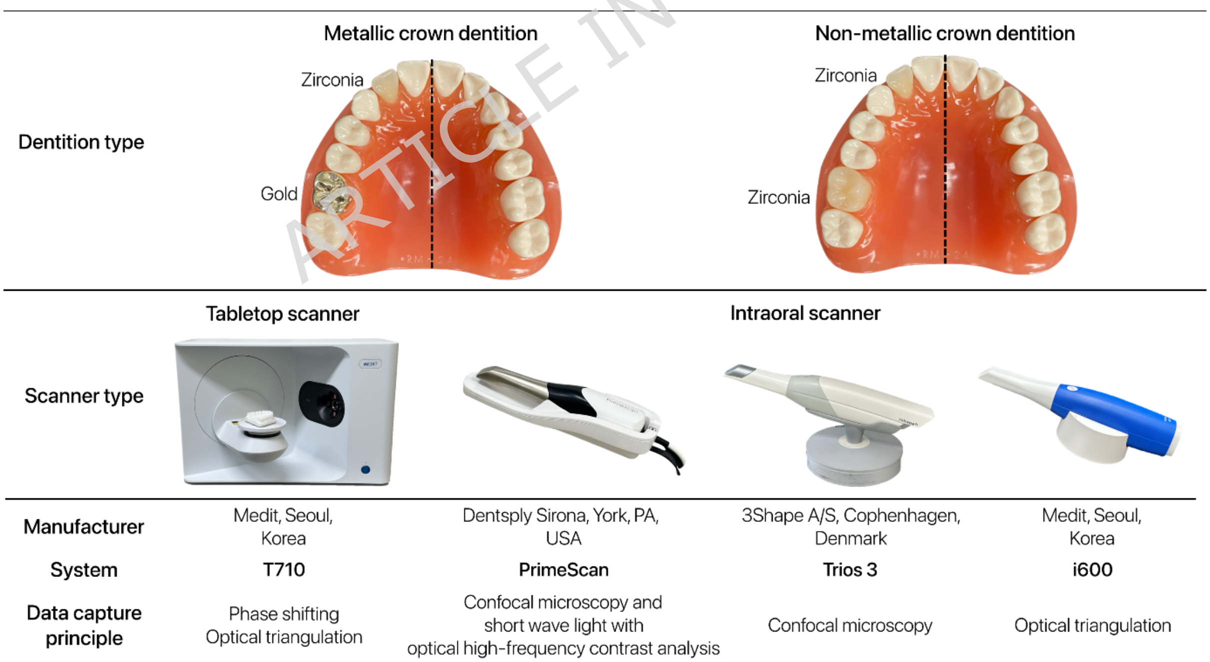

Fig 1. Characteristics of scanners and dentitions based on crown materials and positions

To evaluate the impact of different restorative substrates on intraoral scan workflows, gold and zirconia crowns were prepared with standardized surface treatment protocols. The gold crowns were fabricated utilizing a commercial low-gold dental casting alloy (<50% Au) and finalized by polishing with a rouge compound to achieve a high-luster surface finish.

The monolithic zirconia crowns were prepared using a combined glazing and polishing regimen. Following full sintering, coloring, and glazing according to the manufacturer's instructions, the outer surfaces were finalized by mechanical post-polishing using a diamond-impregnated polisher to control variable light reflectivity. All specimens were ultrasonically cleaned in a distilled water bath for 10 minutes prior to the intraoral scanning procedures.

The dentition model was digitalized from a tabletop scanner (Medit T710; Medit, Seoul, Korea). 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) using a casting process (Fig 2).

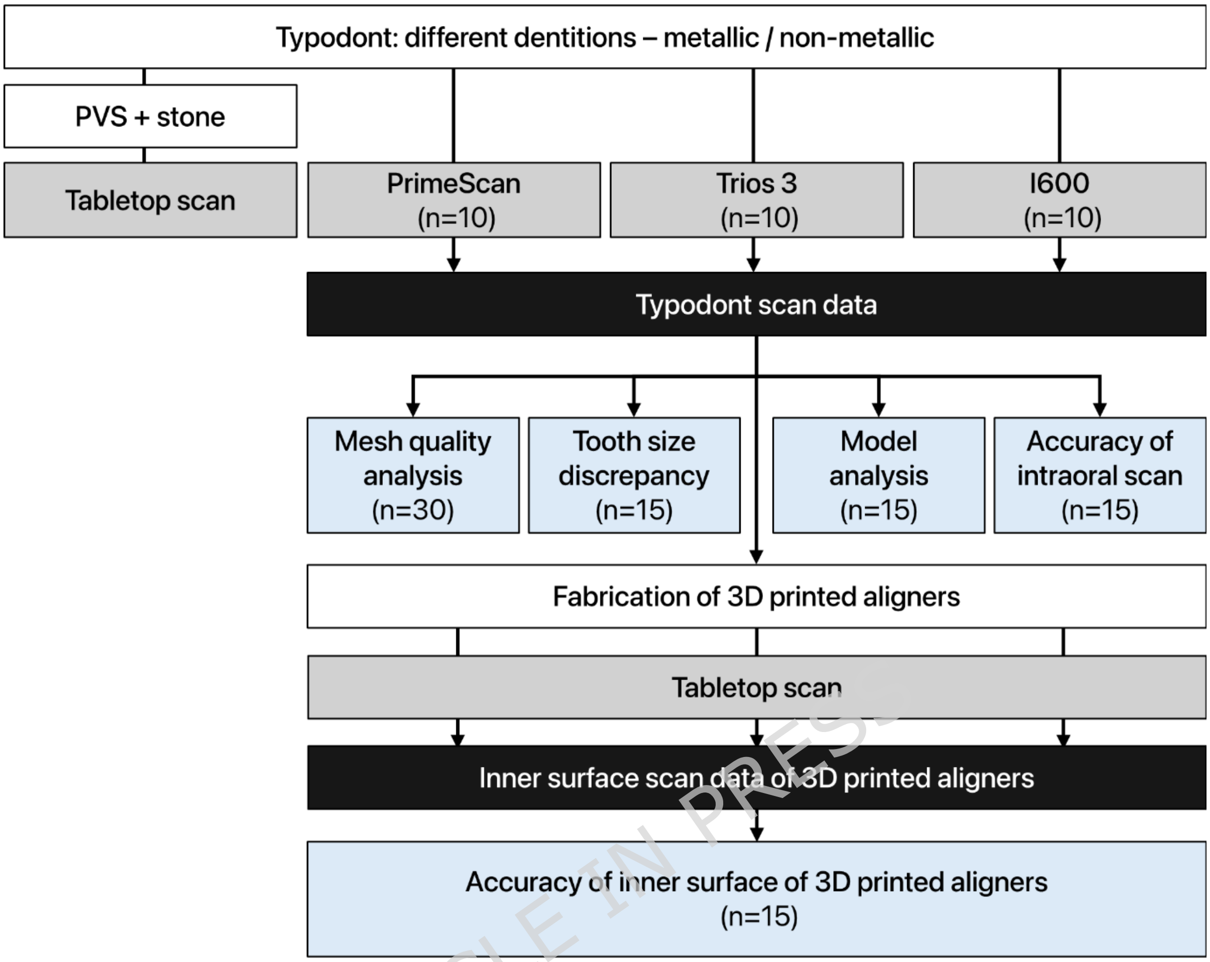

Fig 2. Schematic diagram of research process

2.2. Scanning process

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. Polyvinyl siloxane (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. Reference models were digitalized using a tabletop scanner (Medit T710; MEDIT, Seoul, Korea) (Fig 1).

Experimental scan data in this study were digitized from three intraoral scanners for two types of dentitions. The following three 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) (Fig 1). 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.

2.3. Mesh quality analysis

The Joe Liu metric was used to determine if there were differences in the quality of dental meshes generated based on the scanner and material of the prosthetics. The Joe-Liu mesh value ranges from 0 to 1, where a higher value indicating a higher quality of mesh elements. [22] To explore differences in mesh quality based on restorative 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.

2.4. Model analysis

To investigate impact of dental mesh differences, orthodontic measurements (five measurements taken per group) were performed using tooth model data. A comparative evaluation focused on differences due to material used for restorations was conducted for lateral incisors and first molars where alternative restorations were placed. To include a comparison with unaltered artificial resin teeth, similarly shaped contralateral teeth were also compared. Actual sizes of crowns and resin teeth were directly measured using a digital vernier caliper (instrumental resolution: ± 0.01 mm) in triplicate by a single calibrated operator to obtain a reference for tooth size. All other tooth measurements were performed with an automatic model analysis program (LaonSetUp beta version 200722; LAONPEOPLE, Seongnam, Korea) except for reference tooth size measurements [23].

Since clear aligners are applied to the full arch, fabricating 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) was evaluated. Using automatic model analysis software, all teeth were automatically separated into individual teeth.

2.5. Scan accuracy of intraoral scanners

3D dimensional differences were analyzed using a 3D inspection software (Geomagic Control X; 3D Systems, Rock Hill, SC, USA). All 3D analyses were compared using the best-fit superimposition method. Additionally, root-mean-square (RMS) values were calculated using 3D inspection software. The accuracy of 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 differences in trueness of scan data based on the material of conservative restorations, evaluation areas were set to include the area of the replaced single crown and areas of teeth surrounding the crown. Deviation range in color maps was expressed as ± 250 μm and the tolerance range was expressed as ± 50 μm.

2.6. 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, CA, USA) and orthodontic clear resin (TC-85 DAC, Graphy, Seoul, Korea) with a layer thickness of 100 μm. Excess resin was removed from printed aligners using a centrifuge (TeraHarz spinner, Graphy, Seoul, Korea) at 500 rpm for five minutes. Subsequently, 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). Post-cured aligners were then immersed in boiling water at 100 °C for one minute before being dried at 45 °C for five minutes. Five inner surface scan data per group were digitized using a tabletop scanner with scanning spray (EZ Scan, Alphadent, Goyang, Korea)

2.7. Accuracy of inner surface of clear aligners

Inner surface scan data of clear aligners were compared against STL data designed from reference scan data. Accuracy assessments were conducted for three areas: 1) the molar crown and surrounding teeth area, 2) the occlusal area, and 3) the proximal area between molar crown and surrounding teeth. 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 mesial and distal contacts of the molar crown. The occlusal area was defined as the region between proximal areas.

2.8. Statistical analysis

The sample sizes for this study were determined based on prior dental and orthodontic literature; specifically, n = 10 per group was used for mesh quality evaluation. [4, 8, 22], and n = 5 per group was applied to workflows including tooth size discrepancy, model analysis, intraoral scan accuracy, and clear aligner inner surface accuracy [24-26]. Before analyzing the data, the assumptions for the Kruskal-Wallis test were checked using the Shapiro-Wilk test for normality and Levene's test for homogeneity of variances ($P < 0.05$). Then, Kruskal-Wallis's test was used to assess statistical significance of difference in mean mesh quality, model analysis, scan data accuracy, and clear aligner inner surface accuracy by scanner and restoration material type, followed by a Mann-Whitney post hoc test. The significance level for post hoc tests was adjusted using the Bonferroni's method ($p < 0.05$). All statistical analyses were performed using SPSS 26.0 (SPSS Inc., Chicago, IL, USA) and Origin 2021 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Mesh quality analysis

The quality of the mesh for each material and scanner used in prosthetic restoration was compared and evaluated (Fig 3A). It was measured on a 0 to 1 scale, with a higher value representing a better quality. For gold crown and surrounding teeth, the mesh quality value was 0.808 ± 0.001 for i600, 0.757 ± 0.001 for PrimeScan, and 0.741 ± 0.004 for Trios 3 (Fig 3B). Similarly, for zirconia crown and surrounding teeth, the mesh quality value was 0.809 ± 0.001 for i600, 0.759 ± 0.001 for PrimeScan, and 0.741 ± 0.002 for Trios 3 (Fig 3C). Among the three scanners, i600 demonstrated the highest mesh quality, followed by PrimeScan and then Trios 3. The two materials used in prosthetic restorations resulted in no significant differences in mesh quality.

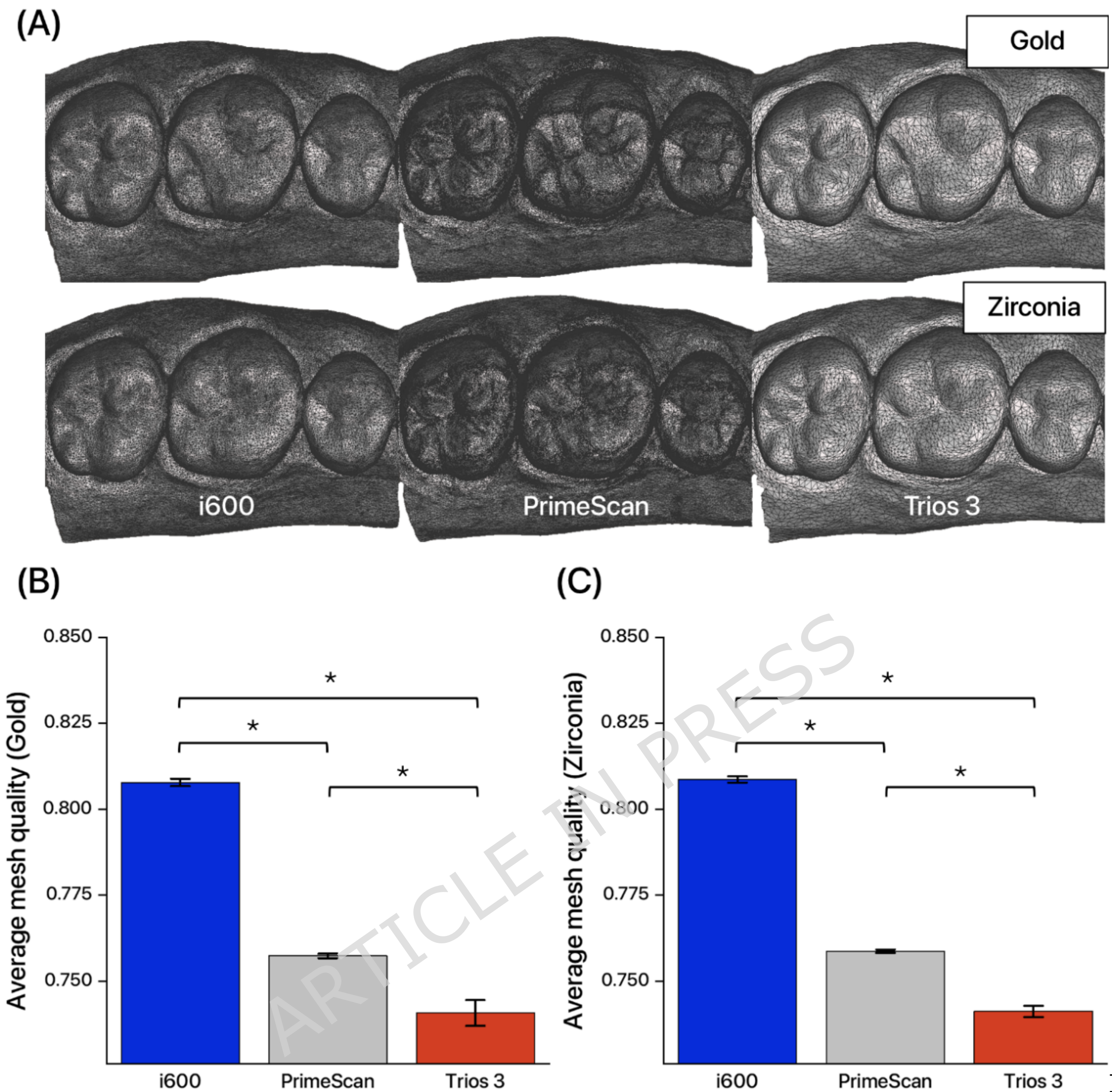

Fig 3. Average mesh quality differences in crown and surrounding teeth area with different scanners. (**A**) Meshed images using intraoral scanners, (**B**) Average mesh quality differences in gold dentitions, (**C**) Average mesh quality differences in zirconia dentitions. Asterisks indicate significant differences between scanners ($p < 0.05$)

3.2. Tooth size discrepancy

Tooth size differences were compared by subtracting manually measured values from automatically measured values. The evaluation focused on the lateral incisor and first molar, where existing typodont resin teeth were replaced with prosthetic restorations. Results are 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 ($p < 0.001$). However, measurements of resin teeth were not significantly different among scanners. 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 differences with the three scanners were significantly different from each other ($p < 0.05$). For all scanners and materials, automatic measurements were generally larger than manual measurements (Table 1).

For the first molar, measurements of gold teeth were similar to or smaller than manual measurements. Zirconia showed significantly larger measurements with PrimeScan at 0.15 ± 0.03 mm than with the other two scanners ($p < 0.05$). Resin teeth with Trios 3 were significantly smaller at 0.13 ± 0.05 mm than with the other two scanners ($p < 0.05$). Both resin teeth and zirconia tended to be measured larger in automatic measurements than in manual measurements (Table 1).

Table 1. Comparison of tooth size discrepancy between reference scans

Position	Materials	Scanner			***p***	Post-hoc
		PrimeScan [a] (mm)	**Trios 3** [b] (mm)	**i600** [c] (mm)		
Lateral incisor	Zirconia	0.21 ± 0.04[a]	0.00 ± 0.04[c]	0.06 ± 0.04[b]	0.000	a > c > b
	Resin (contralateral)	0.42 ± 0.14	0.41 ± 0.10	0.45 ± 0.08	0.699	NS
First molar	Gold	0.00 ± 0.06[a]	-0.07 ± 0.14[b]	-0.11 ± 0.06[b]	0.044	a > b, c
	Zirconia	0.15 ± 0.03[a]	0.10 ± 0.07[b]	0.04 ± 0.04[b]	0.002	a > b, c
	Resin (contralateral)	0.27 ± 0.03[a]	0.13 ± 0.05[b]	0.21 ± 0.06[a]	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 ($p < 0.05$). Values are presented as mean ± standard deviation. NS: not significant.

3.3. Comparison of model analysis

Statistical analysis of size differences among model analysis values revealed no significant differences attributable to the type of restorative material. 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 ($p < 0.05$). In terms of intercanine width (ICW) and intermolar width (IMW), both PrimeScan and i600 measured significantly larger values than Trios 3 ($p < 0.05$) (Table 2).

Table 2. 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	<0.001	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	<0.001	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 ($p < 0.05$). Values are presented as 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.

3.4. Accuracy of full arch scan

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

Trueness comparison between intraoral scanners against tabletop scanner reference revealed significant differences ($p < 0.05$). RMS values increased progressively in the following order: 44 ± 5 μm with PrimeScan < 65 ± 11 μm with i600 < 113 ± 39 μm with Trios 3 (Fig 4C).

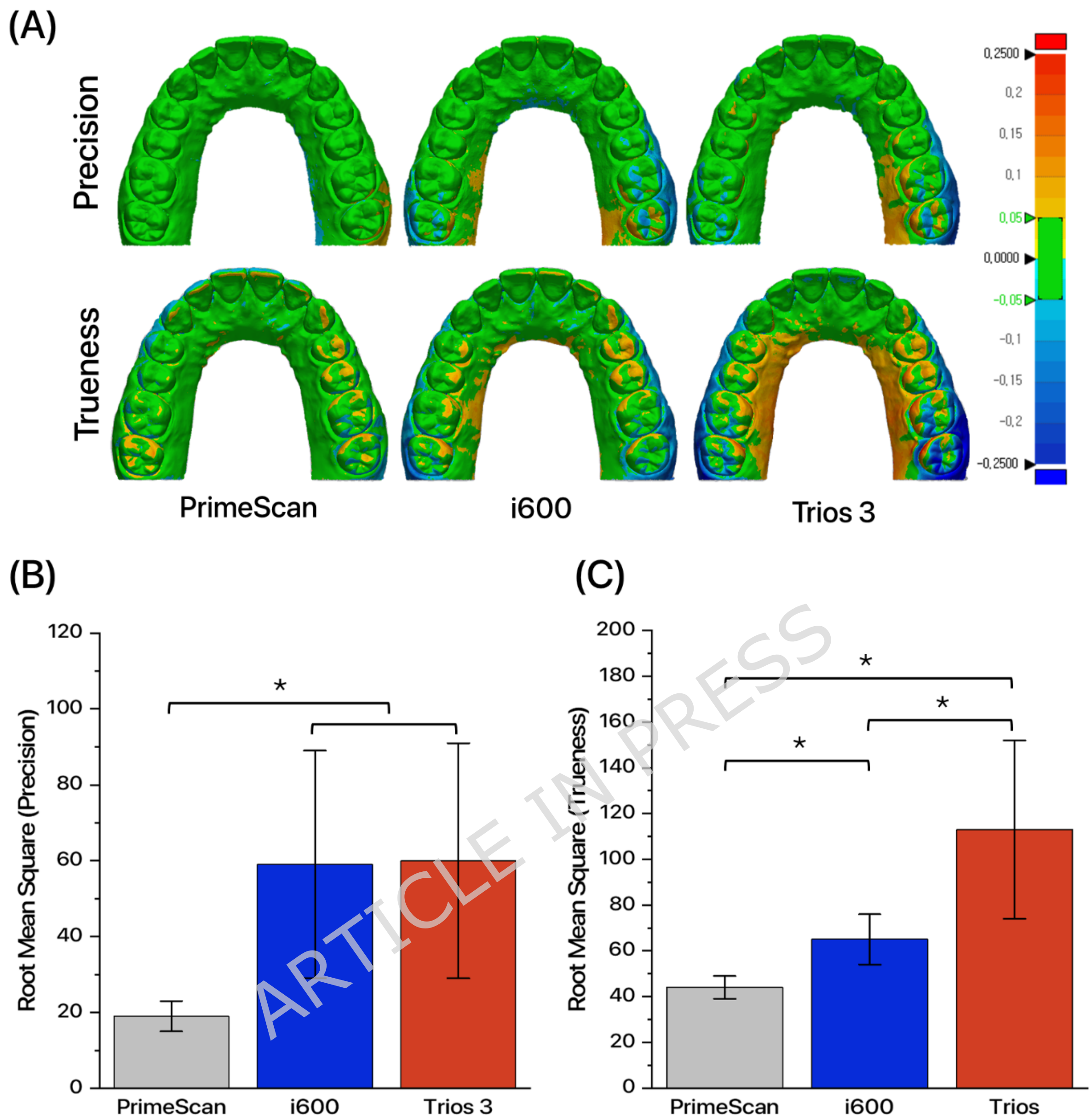

Fig 4. Precision and trueness of full-arch intra oral scanner data against tabletop scanner reference. (**A**) Root mean square (RMS) deviation in 3D comparison, (**B**) RMS values of precision, (**C**) RMS values of trueness. Asterisks indicate significant differences between scanners ($p < 0.05$)

3.5. Trueness of restorative crown and surrounding teeth

The evaluation of trueness in scan data showed no significant differences in RMS value among scanners for the lateral incisor zirconia crown and surrounding teeth. However, for the first molar zirconia crown, there were statistically significant differences, with Trios 3 (25 ± 0 μm) and i600 (24 ± 3 μm) showing larger RMS values than PrimeScan (20 ± 1 μm). For the surrounding teeth, Trios 3 (33 ± 4 μm) had a significantly larger RMS value 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 3)

Table 3. 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[a] (μm)	**Trios 3** [b] (μm)	**i600**[c] (μm)		
Anterior	Zirconia	23 ± 3	25 ± 3	23 ± 3	0.552	NS
	Resin (surrounding)	31 ± 2	31 ± 2	29 ± 2	0.093	NS
Posterior	Gold	31 ± 1	33 ± 3	59 ± 1	0.006	c > a, b
	Resin (surrounding)	31 ± 1	33 ± 3	29 ± 1	0.017	b > c
	Zirconia	20 ± 1	25 ± 0	24 ± 3	0.007	b, c > a
	Resin (surrounding)	30 ± 0	33 ± 4	29 ± 3	0.033	b > a

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 ($p < 0.05$). Values are presented as mean ± standard deviation. NS: not significant.

3.6. Comparison of clear aligner inner surface

3D printed aligners were digitized and analyzed area by area for RMS values calculated through 3D comparison (Fig 5). For gold crowns, a significant difference between groups was found as a result of 3D comparison of the molar crown and surrounding teeth areas, with i600 showing significantly larger area than Trios 3 ($p < 0.05$). Although occlusal area showed no significant differences among scanners, the proximal area with i600 was significantly larger than those with PrimeScan and Trios 3 ($p < 0.05$). On the other hand, for zirconia crowns, occlusal and proximal areas showed no significant differences between groups.

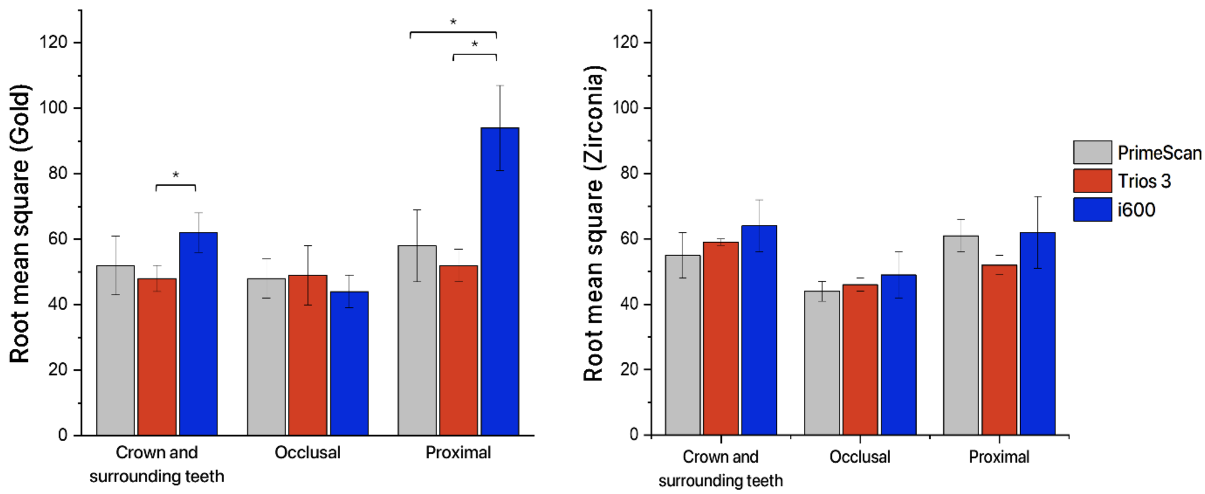

Fig 5. Comparison of root mean square (RMS) values for inner surface of clear aligners with restorative material as a factor. Asterisks indicate significant differences between scanners ($p < 0.05$)

4. Discussion

Digital orthodontics and clear aligner treatment have been facilitated by advances in technology, leading to easier and more cost-effective production of aligners using clear 3D printing resin. However, technological differences along with variations in patients' intraoral conditions can lead to unpredictable variations outcomes. Among factors influencing clear aligner quality, this study focused on the technical aspect of the initial digitization stage—specifically, intraoral 3D scanning in the presence of two different restorative materials.

The present study compared three intraoral scanners for their efficacies in measuring 3D scanning typodonts having 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 the 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 impact of restorative materials on scan data of adjacent teeth, prosthetic restorations were not placed consecutively. The arch was split to ensure that artificial teeth on the opposite side were not affected by restorations.

Full-arch digitization was performed using three intraoral scanners. Scanners used in this study were based on different data capture principles. The i600 scanner utilizes optical triangulation. Trios 3 employs confocal microscopy and 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 can enhance detailed textures and boundary information. [9] Due to differences in scanning methods, the form and quality of the final intraoral image data can vary. Therefore, experimental groups were designed based on data capture principles of scanners used in this study.

Meshes of a digitized dental model are essential for guiding tooth segmentation and planning tooth movement. [3, 27, 28] In addition to print accuracy, mesh quality is also a critical factor in 3D simulation and modeling as it affects computation time and optimization. Furthermore, it influences the occurrence of errors and computational stability. [8] Therefore, mesh quality is one of the critical factors to consider when selecting an intraoral scanner as it serves as an indicator of reliability and efficiency of three-dimensional computational modeling. Given the sensitivity of CAD program to the mesh quality, we analyzed mesh quality using the objective Joe Liu metric. The Joe-Liu metric can quantify the quality of triangulation on a surface, such as the geometry of teeth, by evaluating each individual triangle. [29] It provides a dimensionless normalized range from 0 to 1. A value near 1 has a higher mesh quality, representing an equilateral triangle, while values near 0 suggest lower quality, corresponding to an almost degenerate triangle. [8]

The mesh quality showed significant differences among scanners, although similar trends were observed for zirconia and gold crowns. Based on the findings, the null hypothesis—that there would be no significant differences in the quality of the dental mesh and the accuracy of the 3D printed clear aligners regardless of the intraoral scanner's technical method or the type of restorative material used—was partially rejected. This study successfully demonstrated that while there was no significant difference in mesh quality based on the type of restorative materials, scanner choice significantly influenced dental mesh quality. An interesting finding was that although the i600 scanner consistently provided the highest mesh quality, it showed a significant decrease in accuracy at connections between gold crowns and surrounding teeth, indicating that both the scanner technology and the presence of metallic restorations significantly affect scanning and aligner accuracy. This suggests that the influence of mesh quality is determined not during optical technology-based position data collection phase, but rather during the 3D image processing phase, specifically by triangulation algorithm and software used. [8] However, a limitation of this study is that while differences in mesh quality were observed by restorative material and scanner type, further research is needed to assess their impact on the accuracy of direct 3D printed aligners.

In orthodontic treatment planning, tooth-size accuracy is a significant determinant. [1, 23] Reliability of tooth size measurement not only influences the treatment plan, but also the final aligner fit. [21, 30] Comparing the influence of zirconia and gold, it could be observed that deviation from the actual size was due to difference in tooth material. Here, tabletop scanner digitized data served as external reference. [21] The fidelity of intra oral scanners varied notably for both zirconia and gold crowns. Zirconia crowns with Trios 3 scanner showed the highest fidelity with minimal deviations at both lateral incisor and first molar region. However, when replaced with gold restoration at the first molar region, Trios 3 and i600 scanners both caused underestimation compared to actual sizes. [31]

When comparing size discrepancies of lateral incisors, a zirconia crown relative to its contralateral incisor with a similar shape was analyzed to assess differences in materials. Measurements were taken from three different scanners, including a tabletop scanner. They were then compared with dimensions obtained using a digital caliper. Automated tooth size measurements consistently showed an overestimation of 0.2–0.4 mm. Clinically, these minor errors can accumulate across the full arch, potentially compromising clear aligner tracking and fit. Resin teeth typically measure larger than teeth made of gold or zirconia, reflecting material-dependent variations. Furthermore, proximal spaces were identified around resin lateral incisors. Since these spaces are difficult to distinguish using a scanner, errors in tooth size measurement may increase. [32]

Mesh quality differences also affected the efficiency of 3D model rendering calculations. However, findings of this study indicated that, when comparing fabricated aligners, the shape of the object played a more critical role in determining aligner quality than mesh quality differences. Further research is required to evaluate the impact of mesh quality on final dental appliances, particularly when intraoral scanners are used.

Clear aligners are a full-arch coverage appliance. Therefore, a 3D surface assay of full-arch scan data accuracy is better for comparing digitization efficacy for clear aligners with different scanners. [33] In a 3D comparison of full arch scans, RMS values for trueness and precision showed that digitization through Primescan was most similar to a tabletop scanner, but different significantly from both Trios 3 and i600. As a result, we found that Primescan could reliably provide accurate scan information for the full arch area, consistent with previous research findings. [4]

This research also confirmed that the type of restorative material affected scan accuracy. High reflectance materials such as gold present challenges in scanning accuracy, particularly with scanners using triangulation. [34] With the i600 scanner, zirconia with a relatively low surface reflectance showed an RMS value of 24 μm, whereas gold showed an RMS value of 59 μm, which was approximately twice as large. This discrepancy underscores the need for further development of 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, exhibit lower scanning accuracy when using triangulation-based methods to collect shape information. [10, 17, 35] This finding was consistent with our results. We investigated why the accuracy of triangulation was affected by surface reflectance. In the case of optical triangulation, scanning is generally effective in capturing object position information with objects having higher diffuse reflectance. [36] When more diffuse light reaches the sensor, the less the scan is affected by external noise and light, resulting in better resolution. [37] On the other hand, for metallic objects with high reflectance, the light undergoes specular reflection rather than diffuse reflection when it hits the object. [38-40] This makes it difficult to collect accurate positional information of the object during scanning. Such 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. [11, 20, 41, 42] However, scanning agents can increase scanning time, cause discomfort to patients, and lead to thickness errors. [43] Therefore, it is recommended to choose an intraoral scanner that is minimally affected by restorative materials.

Evaluation of inner surface accuracy of clear aligners showed that the i600 scanner and the Trios 3 scanner had significantly different RMS values. While there were no significant differences in the occlusal area across all groups, RMS values of the i600 scanner were significantly higher in the proximal area compared to those of the other two intraoral scanners. This indicated 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 may occur, compromising orthodontic anchorage and causing unintended tooth movement. This highlights the need for predictive and preventive strategies to minimize scan errors.

This study has several limitations, including its focus on a limited range of dental materials and scanners. Specifically, to strictly control variables, the restorative conditions were limited to single crowns utilizing zirconia and gold, which were selected based on their high clinical popularity and widespread preference in routine dental practice. Consequently, other common materials such as cobalt-chromium and complex prosthetic designs like bridges were excluded, which may limit the immediate generalization of these findings to more complex clinical cases. Due to an in vitro experimental design, environmental factors such as humidity and temperature during scanning could not be accounted for. A dental typodont was used to control variables and represent restorative materials. However, typodont teeth made from resin might produce different outcomes compared to human teeth, where natural variations in refraction and reflectance occur. Furthermore, this laboratory setup cannot fully replicate dynamic intraoral conditions, such as the presence of saliva, which alters surface reflectivity, and patient movement, which can introduce stitching tracking errors during full-arch scanning. Additionally, the presence and magnitude of malocclusion were not evaluated in this study. Therefore, further research focusing on diverse real-world clinical conditions is needed to refine best practices for achieving optimal outcomes of digital orthodontics.

5. Conclusions

This study highlights that intraoral scanner technology, and restorative materials can significantly influence the accuracy of dental mesh data and 3D printed clear aligners. Among scanners tested, the scanner utilizing confocal microscopy and high-frequency contrast analysis demonstrated superior full-arch scanning accuracy and trueness, making it more suitable for applications requiring precise digitization of complex dental structures. Notably, metallic restorative materials, particularly gold, introduced greater discrepancies in scan data compared to non-metallic materials, thereby compromising the internal surface accuracy of the fabricated clear aligners.

Clinically, while practitioners must consider practical factors such as equipment costs and system compatibility, selecting an intraoral scanner technology highly resistant to specular reflection is recommended to achieve stable full-arch digitization without relying on clinical scanning aids.

Data availability

Data supporting the findings of this study are available from the corresponding author upon request.

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Contributions

J.-H.Y.: Methodology, Software, Investigation, Formal analysis, Data curation, Visualization, Writing - original draft, and Writing - review & editing; U.M.: Methodology, Software, Supervision, and Writing - review & editing; J.L.: Methodology, Software, and Writing - review & editing; H.-S.Y.: Methodology, Supervision, and Writing - review & editing; K.-J.L.: Methodology, Supervision, and Writing - review & editing; J.-S.K.: Supervision and Writing - review & editing; S.-H.C.: Conceptualization, Methodology, Data curation, Supervision, Project administration, and Writing - review & editing; J.-Y.C.: Conceptualization, Methodology, Data curation, Supervision, Project administration, and Writing - review & editing.

Ethics declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Dentition type

Metallic crown dentition

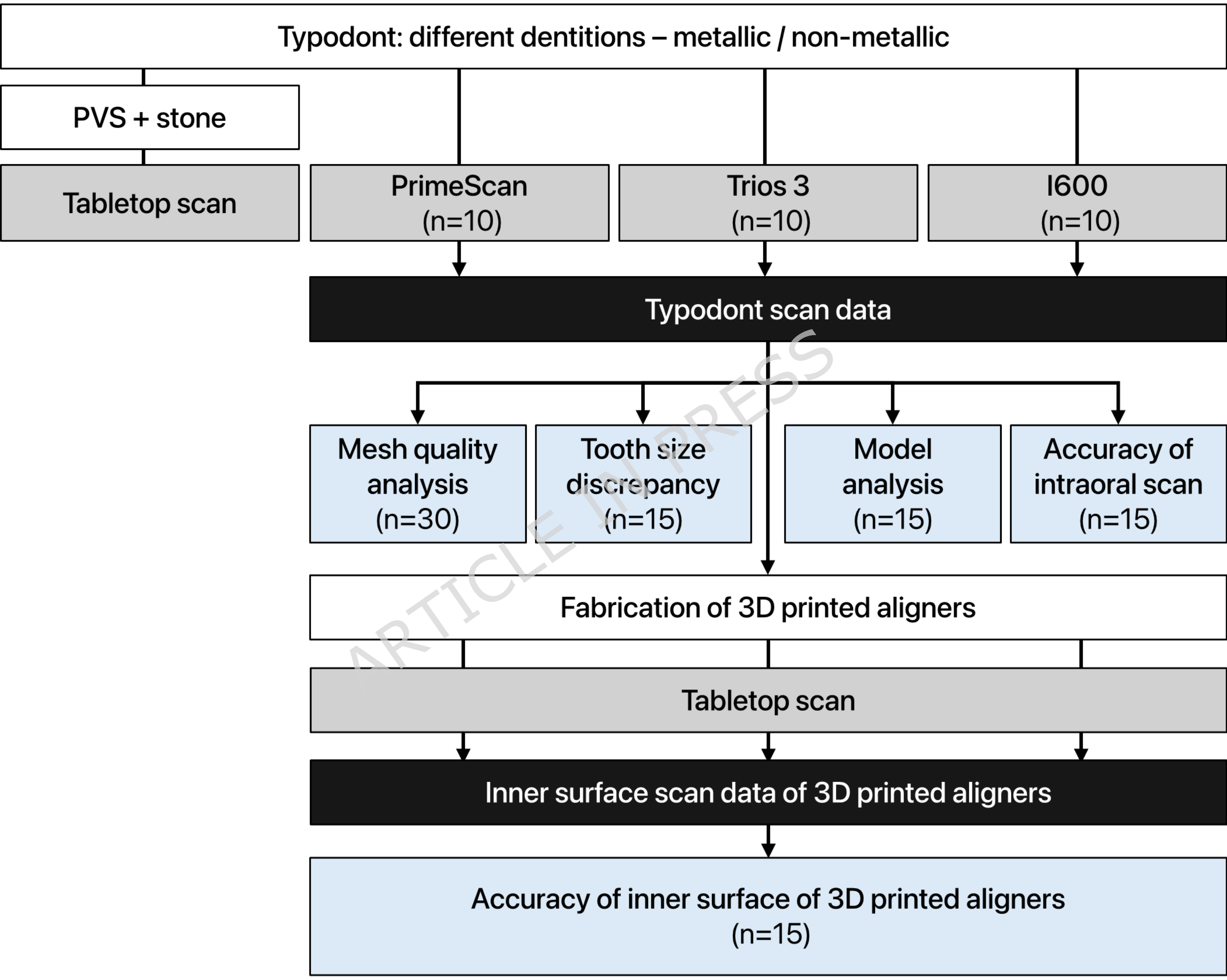
Non-metallic crown dentition

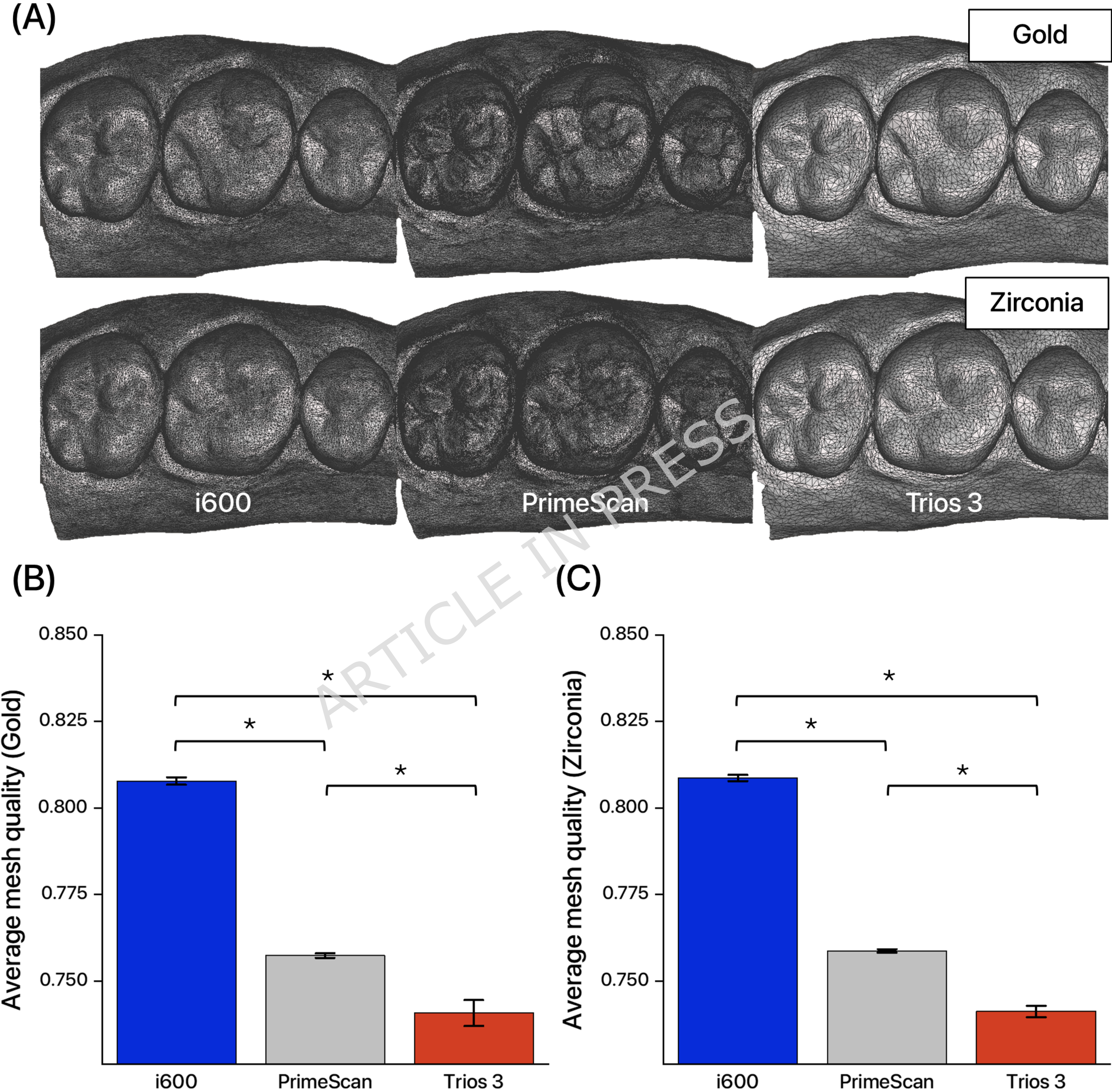
Scanner type

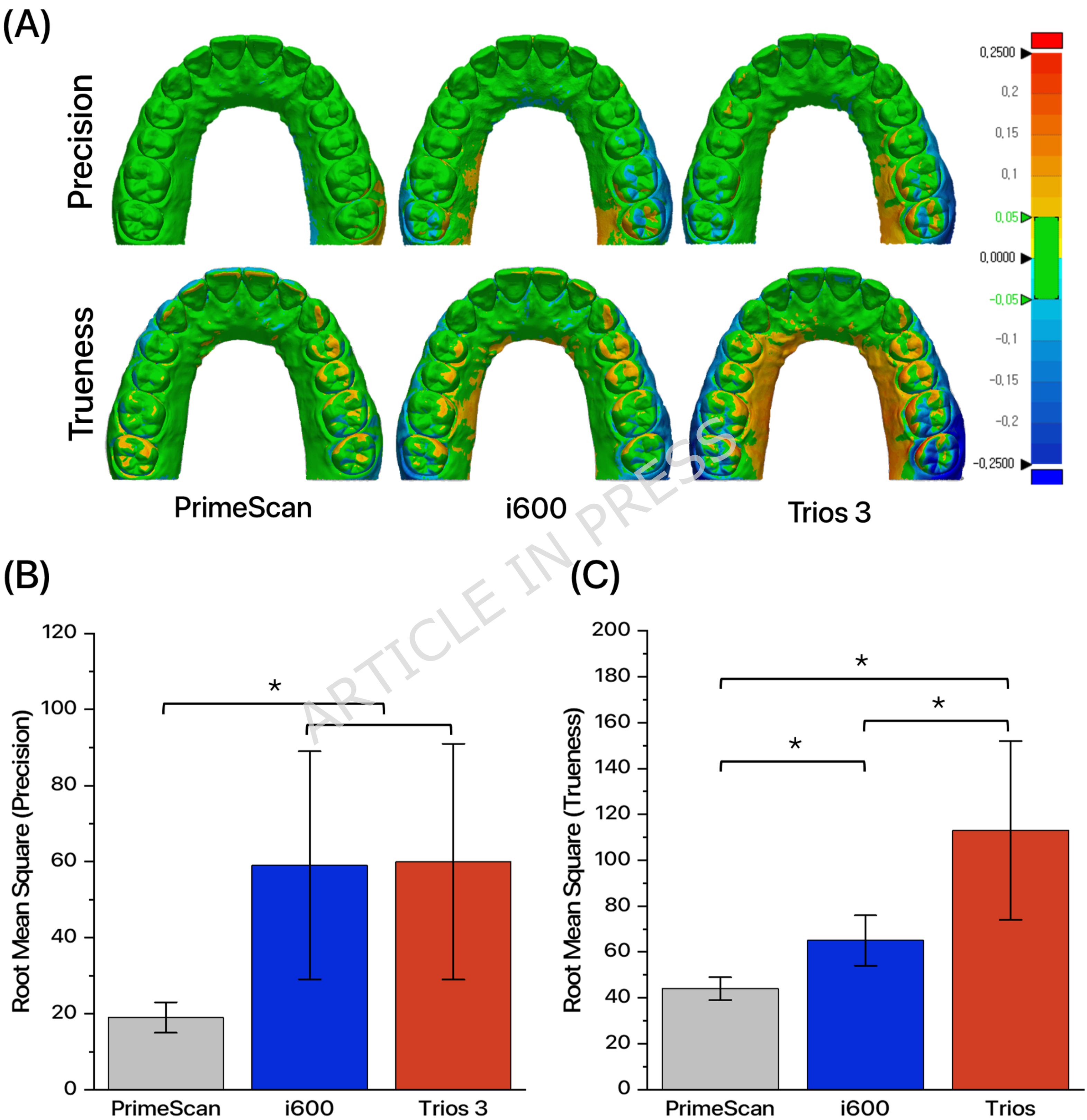
Tabletop scanner

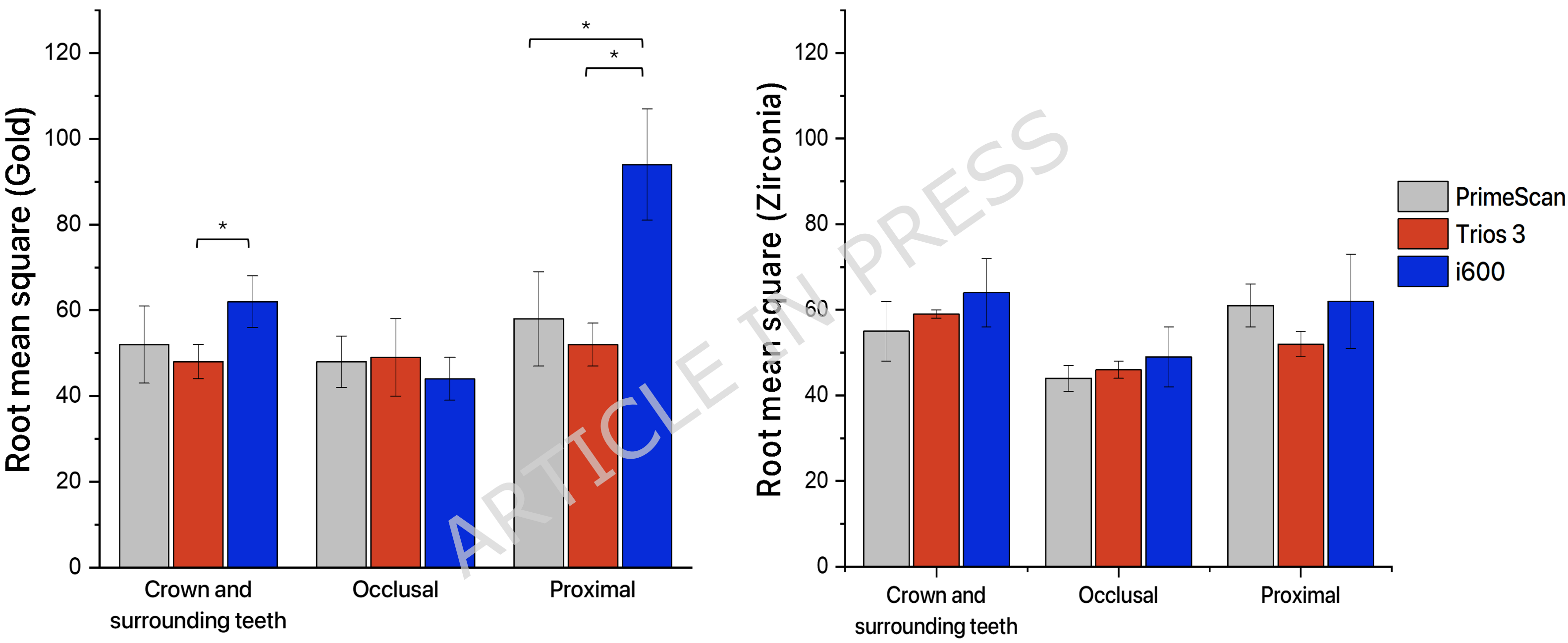
Intraoral scanner

	Tabletop scanner	Intraoral scanner		
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


Typodont: different dentitions – metallic / non-metallic
PVS + stone
Tabletop scan
PrimeScan
(n=10)
Trios 3
(n=10)
I600
(n=10)
Typodont scan data
Mesh quality analysis
(n=30)
Tooth size discrepancy
(n=15)
Model analysis
(n=15)
Accuracy of intraoral scan
(n=15)
Fabrication of 3D printed aligners
Tabletop scan
Inner surface scan data of 3D printed aligners
Accuracy of inner surface of 3D printed aligners
(n=15)


(A)
Gold
Zirconia
i600
PrimeScan
Trios 3
(B)
Average mesh quality (Gold)
0.850
0.825
0.800
0.775
0.750
*
*
*
i600
PrimeScan
Trios 3
(C)
Average mesh quality (Zirconia)
0.850
0.825
0.800
0.775
0.750
*
*
*
i600
PrimeScan
Trios 3


(A)
Precision
Trueness
0,2500
0,2
0,15
0,1
0,05
0,0000
-0,05
-0,1
-0,15
-0,2
-0,2500
PrimeScan
i600
Trios 3
(B)
Root Mean Square (Precision)
0
20
40
60
80
100
120
*
PrimeScan
i600
Trios 3
(C)
Root Mean Square (Trueness)
0
20
40
60
80
100
120
140
160
180
200
*
*
*
PrimeScan
i600
Trios



Root mean square (Gold)
120
100
80
60
40
20
0
*
*
*
Crown and surrounding teeth
Occlusal
Proximal
Root mean square (Zirconia)
PrimeScan
Trios 3
i600

Table 1. Comparison of tooth size discrepancy between reference scans

Position	Materials	Scanner			*p*	Post-hoc
		PrimeScan[a] (mm)	Trios 3[b] (mm)	i600[c] (mm)		
Lateral incisor	Zirconia	0.21 ± 0.04[a]	0.00 ± 0.04[c]	0.06 ± 0.04[b]	0.000	a > c > b
	Resin (contralateral)	0.42 ± 0.14	0.41 ± 0.10	0.45 ± 0.08	0.699	NS
First molar	Gold	0.00 ± 0.06[a]	-0.07 ± 0.14[b]	-0.11 ± 0.06[b]	0.044	a > b, c
	Zirconia	0.15 ± 0.03[a]	0.10 ± 0.07[b]	0.04 ± 0.04[b]	0.002	a > b, c
	Resin (contralateral)	0.27 ± 0.03[a]	0.13 ± 0.05[b]	0.21 ± 0.06[a]	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 ($p < 0.05/3$).

Values are presented as mean ± standard deviation. NS: not significant.

Table 2. 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	<0.001	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	<0.001	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 ($p < 0.05/3$).

Values are presented as 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.

Table 3. Comparison of root mean square (RMS) values for the crown and surrounding teeth areas between reference and intraoral scan data

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

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 ($p < 0.05/3$).

Values are presented as mean ± standard deviation. NS: not significant.