Ph.D. Thesis

Accuracy and Influencing Factors of Dental Models Obtained by Digital Scanning and 3D Printing

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List of Abbreviations

- **CAD/CAM**: Computer-aided design/computer-aided manufacturing
- **IOS**: Intraoral scanner
- **SLA**: Stereolithography
- **DLP**: Digital light processing
- **FDM:** Fused deposition modeling
- **PolyJet:** Photopolymer jetting
- **FFF:** Fused filament fabrication
- **RMS**: Root mean square
- **FOV**: Field of view
- **3D**: Three-dimensional
- **STL**: Standard tessellation language
- **CT:** Computed tomography
- **ISO:** International organization for standardization
- **HWB:** Hollow interior with perforated base
- **HB:** Hollow interior without base
- **S:** All solid
- **SWB:** Internal support structure with perforated base

Introduction

In the dental field, digitalization has emerged as the most significant trend. It refers to using digital technologies and devices to improve and streamline various aspects of dental practice.[1] In this era of digital dentistry, computer-aided design and manufacturing technology has become vital tool to achieve full-process digital dentistry. It is widely used in such fields as dental restoration,[1-3] orthodontics,[4] and implants.[1, 5] Dentists use intraoral or desktop scanners to obtain data of patients' teeth structure, design it on software for specific treatment purposes, and then use milling or 3D printing technology to fabricate various dental products such as restorations, orthodontic devices, or implant guides. Such a digital workflow has gained widespread acceptance and is now commonly employed in dental practice.[6]

Dental models are replicas of a patient's teeth and surrounding oral structures that play a crucial role in dental diagnosis and treatment. Due to the appearance of digital technologies such as digital scanning and 3D printing, there has also been a revolution in the way dental models are obtained. Dentists can obtain a virtual dental model using an intraoral or desktop scanner to scan the patient's mouth or plaster dental model and produce a physical dental model using milling or 3D printing technology. It is noted that whether for virtual or 3D- printed dental models, sufficient accuracy is always the most basic requirement. Accuracy is also one of the most important indicators of dental model quality. The international organization for standardization (ISO) standard 5725-1:1994[7] defines accuracy as trueness and precision. Trueness represents the difference between measured and true values, while precision refers to the consistency between multiple measurements obtained with the same test protocol for the same measuring object.

Recent studies have found that some factors will considerably affect the accuracy of the digital models created with an IOS, including the environment around the scanner (ambient light, water, saliva, and blood),[8-12] operators' experience,[13-15] scanning sequence,[16, 17] the translucency of the scanning object,[18] restoration materials used for the surrounding teeth,[19] and the depth of the finish line of the abutment teeth.[20] Factors that may affect the accuracy of 3D-printed casts have also been evaluated with different characteristics of printers,[21, 22] printing materials,[23] printing layer thicknesses,[24-26] printing orientation,[25, 27-29] as well as different post-processing methods, immersion solutions, and polymerizing time.[30, 31] However, several factors may affect the dental models' accuracy within the scanning and manufacturing process that has yet to be fully investigated, including liquid, scan span, and internal design.

1. Liquid

Liquid exists in the oral cavity in various forms, including saliva, blood, and gingival crevicular fluid. The high humidity of the oral environment is also a consideration. Some procedures involve extra liquids, such as rinsing the mouth, gargling, medicine application, and anesthesia. Currently, most IOSs are based on optical principles. Light traveling through different media, such as liquid and air, will be refracted, which naturally makes it easy to be questioned whether the accuracy of IOSs would be affected. Although the liquid is an inevitable factor in the oral environment, the direct data to clarify how much, liquid could affect the accuracy of intraoral scanners is still scarce. Although manufacturers recommend using compressed air from a three-way syringe to remove saliva on tooth surfaces before intraoral scanning, evidence regarding related procedures is still lacking.

2. Scan span

The scan head of an IOS is often designed to be small for smooth movement and scanning inside the mouth. However, the small design also limits the scan head's FOV. Therefore, IOSs usually use a stitching algorithm to align and stitch small local images to form a 3D image of the teeth or dentition.[32, 33] However, as the scan span increases, the stitching process also increases, raising concerns about whether the scanning accuracy of the IOS is affected. Some researchers have argued that the stitching process will generate errors that could decrease scanning accuracy.[32, 33] Some scholars attempted to avoid errors caused by the stitching process by adding customized attachments to scanning objects.[34] On the other hand, there is no FOV limitation for desktop scanners; thus, stitching during the imaging process may be minimal. However, little in the way of direct data is available for different scan spans to reveal the changing accuracy with the change in scan span for IOSs and desktop scanners. In addition, the exact accuracy of the different scanners for the same dentition at different scan spans has not been evaluated.

3. Internal design

Information on the effect of the internal design on the accuracy of dental models made through various 3D printing techniques is sparse. When considering fabricating dental models with 3D printing, the main concerns come from accuracy, printing speed, and cost.[31] For 3D printing dental models, the internal design has been reported to correlated significantly with printing time and material consumption.[35] A hollow internal design, for example, is more material- and time-efficient than a solid internal design. Therefore, investigations on how best to reduce material consumption, thereby reducing the cost of 3D printing, by changing the internal design while maintaining accuracy are needed. In addition, further research is also needed to determine the optimal internal design that would maximize printing accuracy.

Digitization brings not only innovation but also great uncertainty. The subsequent treatment steps go well when dental models obtained by digital scanning and 3D printing own sufficient accuracy.[36-39] Therefore, it is necessary to conduct experiments for the establishment of evidenced-based standards which enable dental technologists and dentists to differentiate between the various principles and capabilities of digital devices (intra-/extraoral scanners, 3D printers, and so on) and to integrate them into the digital workflow for the appropriate clinical cases. Thus, this study aimed to further investigate the accuracy of dental models obtained by digital scanning and 3D printing by assessing specific influencing factors including liquid, scan spans, and internal design.

Experiment 1 - Influence of liquid on the tooth surface on the accuracy of intraoral scanners: an in vitro study

Purpose

Previous research on the accuracy of intraoral scanners has mentioned or speculated that saliva, blood, gingival crevicular fluid, and the high-humidity environment in the mouth may affect the accuracy of scanning results.[8, 40-43] Some intraoral scanner manufacturers have recommended using compressed air for drying before undertaking intraoral scanning, thereby reducing scanning errors. To date, however, these claims are only speculations or inferences, and there is no direct evidence to confirm how liquid affects scanning results or if using a three-way syringe for drying is effective. To our knowledge, this is the first study to examine the effect of liquid attached to the tooth surface on the accuracy of the intraoral scanner.

This experiment aimed to explore the effect of liquid on the accuracy of intraoral scanners, in terms of both trueness and precision,[7, 44-46] via in vitro experiments and the effectiveness of the air-dry methods. The null hypotheses were (1) that no significant difference would be found in the accuracy of digital scans obtained under three conditions (dry, wet, and blow-dry tooth surfaces) and (2) that no significant difference would be found in the accuracy of digital scans obtained using two kinds of intraoral scanners under different conditions and (3) that no significant difference would be found in the accuracy of digital scans obtained under condition of using two kinds of liquids to create liquid-attached scanning object.

Materials and methods

A scanning platform was created to simulate the state of liquid on the tooth surface (Figure 1). It comprised two acrylic boxes of different sizes (60 × 119 × 106 mm and 60 × 110 × 159 mm). The smaller hexagonal box, with a 4-mm diameter hole on the bottom, was affixed to one of the upper corners of the large cuboid-shaped box. A mandibular jaw model (Prosthetic Restoration Jaw Model D16-500A(GSF)-GF, NISSIN, Japan) with three standard abutment tooth models (Tooth Position:31,34,36; Abutment Tooth Model A55A-310, A55A-340, A55A-362, NISSIN, Japan) replaced was used as the scanning object. The model was attached at the center of the bottom of the small box using utility wax (GC Corp., Tokyo, Japan).

The scanning platform was placed in a separate room without windows to control ambient light, temperature, and humidity. The temperature in the room was 25 ±2°C, the humidity was 55 ±5%, and the illuminance around the platform was 500 ±20 lux measured by a digital lux meter (HP-881D, HoldPeak, Zhuhai, China).

1. Scanning procedures

Both intraoral scanners were calibrated following the guidelines of the respective manufacturers. The mandibular model was scanned to obtain the reference scan using a high-accuracy industrial computed tomography device (Zeiss Metrotom 800, Zeiss, Gottingen, Germany; the manufacturer's specifications were accurate to within 8 μm). The scan data obtained were exported in STL format.

The mandibular jaw model was then scanned by using two intraoral scanners: Trios 3 (Software version: 19.2.5, 3Shape, Copenhagen, Denmark) and Primescan (Software version: 5.1.1.207230, Dentsply-Sirona, York, PA, USA). Two kinds of liquids were tested in this study: Ultra-pure water produced by a water purification system (PURELAB flex 3, ELGA LabWater, High Wycombe, UK) and artificial saliva (Saliveht Aerosol, Teijin Limited, Tokyo, Japan). Both intraoral scanners and liquids were combined in pairs to form four combinations: Trios 3 with ultra-pure water, Trios 3 with artificial saliva, Primescan with ultra-pure water, and Primescan with artificial saliva. After that, the following three-step scan was performed for each combination.

- Step 1: The dry-surface mandibular jaw model was scanned ten times with an intraoral scanner.
- Step 2: The hole of the small box was blocked with utility wax, and the liquid was slowly introduced from the corner of the small box until the mandibular jaw model was completely immersed and the liquid reached a predetermined height (4 cm from the bottom of the smaller box). The utility wax applied to seal the hole was then removed and the liquid was allowed to drain slowly from the small hole into the large box, leaving the model surface attached to the liquid in a repeatable pattern. The mandibular jaw model was then scanned again.
- Step 3: A three-way syringe (Air pressure: 3.3 ±0.1bar; Flow pressure; 4 x manometer) from a dental chair (Estetica E80, KaVo, Bielefeld, Germany) was used to continuously blow-dry the model from five selected teeth (Teeth position: 31,34,36,44,46) from 5 cm directly above the center of the incisal and fossa of the occlusal surface for 10 s. After drying, the mandibular

jaw model was scanned the third time. Steps 2 and 3 were performed continuously and this process was repeated ten times after completing Step 1. After all scans of one combination (n = 30) were completed, the mandibular jaw model was thoroughly dried with sterile paper towels and left to rest for 48 hours before the next combination was scanned.

According to the manufacturer's instructions, the two intraoral scanners adopted the same scanning strategy for scanning the mandibular jaw model: Starting from the occlusal surface of the second molar on the right side, follow the occlusal surface of other teeth and the incisal edges of the anterior teeth to the occlusal surface of the left second molar. Then, turning the scanning head to the lingual side, and following the lingual sides of all teeth to the right second molar. Finally, turning the scan head to the buccal side, and following the buccal sides of all teeth to the left second molar to finish the scan. All scanning operations were performed by an operator who is experienced with both scanners used in this study to avoid unnecessary errors. To prevent operator fatigue and to allow the scanner to be cooled, a ten-minute rest period was prescribed for every four times scans. Finally, 120 scans were obtained and exported in STL format. According to the scanning condition (dry, wet, blow-dry), the intraoral scanner used, and the liquid used, 120 virtual models were divided into 12 groups (10 scans in each group).

2. Scan processing and comparison

All reference and study scans were imported into dedicated software (Geomagic Control 2015; 3D Systems Inc., Rock Hill, SC, USA) for comparison and analysis. A common trimming plane was created based on the characteristics of the model surface and all scans were uniformly trimmed to create common borders and remove the superfluous portions. A comparable method had been previously established.[47]

For trueness comparison, each study scan (n = 120) from 12 groups was individually compared with the reference scan. Using the best-fit algorithm in Geomagic Control 2015, the reference scan and selected study scans were aligned. By using the software's 3D comparison function subsequently, the deviations between the two scans were shown quantitatively as the RMS value.[36, 37, 48] Additionally, a color map was used to observe the 3D differences between the two aligned scans visually. The software specified that the RMS value displays the RMS error of all points of comparison.[49] The smaller the value, the more precise the alignment. Hence, the trueness for each group was expressed as the mean of the RMS values obtained by comparing the within-group intraoral scan (n = 10) and the reference scan.

For precision comparison, all ten intraoral scans would go together with one another in each group to form 45 combinations. Then, 45 RMS values were obtained using the best-fit algorithm and 3D comparison for each combination. The mean of these 45 RMS values is the precision of one group. In this way, the precision of each group was obtained.

In addition, the virtual models obtained by two kinds of intraoral scanners under three conditions were best-fitted with the reference model, followed by a 3D comparison. A total of 120 color maps were obtained. These color maps were used for qualitative analysis to derive conclusions on deviation distribution/patterns. In the color maps, the areas that changed significantly from the dry condition and returned to their original state after blow-dry was considered to be the area susceptible to liquid.

3. Statistical analysis

The power analysis (G*Power v3.1.9.4, Heinrich-Heine-Universität, Düsseldorf, Germany) was used to determine the sample size. A pilot experiment was conducted five times, and ten times were calculated as the appropriate sample size per group (actual power = 95.7%; power = 95%; $\alpha = 0.05$).

All analyses were conducted using the Statistical Package for Social Science 25 (SPSS; IBM, Inc., Armonk, NY, USA), with the significance level set at $\alpha = 0.05$. The normality of deviations was evaluated using the Shapiro–Wilk test, and the homoscedasticity was assessed using the Levene test. The three-way ANOVA test (scanner, liquid, and condition) and the Tukey test were used to assess precision and trueness. The level of significance was set at 0.05.

Results

For trueness, Table 1 summarizes the mean and standard deviation of RMS value under different conditions according to different scanners and the type of liquid used. Trueness was influenced by condition ($p < 0.001$, $F = 64.033$) and intraoral scanner ($p = 0.013$, $F = 6.452$). Significant interactions were not found between the different variables. Regardless of the type of intraoral scanner and liquid, wet condition showed significantly higher mean RMS values compared to dry condition (all $p < 0.001$) and blow-dry condition ($p = 0.040$, $p < 0.001$, $p = 0.001$, $p < 0.001$, respectively). In contrast, the dry condition showed the lowest mean RMS value among the three conditions. For the two different intraoral scanners, considering the same condition and type of liquid, there were no significant differences in RMS values, except for the scan result of artificial saliva under wet condition ($p = 0.015$). In addition, the RMS value was not significantly different when using the same intraoral scanner under the same condition for two types of liquids.

For precision, Table 2 summarizes the mean and standard deviation of RMS value under different conditions according to the different scanners and the type of liquid used. Three-way ANOVA found that precision was influenced by intraoral scanner ($p < 0.001$, $F = 160.834$), condition ($p < 0.001$, $F = 54.866$), scanner, and condition ($p < 0.001$, $F = 20.577$). Considering the same type of intraoral scanner and liquid, wet condition showed significantly higher mean RMS values compared to dry condition (all $p < 0.001$) and blow-dry condition (all $p < 0.001$), except when using Trios 3, but even in these cases, the mean RMS value of wet condition was the highest numerically. For the two different intraoral scanners, regardless of condition and type of liquid, the mean RMS value of Trios 3 was significantly higher than the mean RMS value of Primescan (all $p < 0.001$). In addition, the mean RMS value was not significantly different for two different types of liquids when using the same intraoral scanner under the same condition.

Figure 2 shows the typical deviation distribution pattern under different scanners, liquids, and conditions. Through comparative observation, the deviations caused by ultra-pure water and artificial saliva were mainly distributed in the pits and fissures of the occlusal surface of premolar and molar (40 / 40), the interproximal area of the teeth (40 / 40) and the margin of the abutments (40 / 40). Notably, that the deviations caused by liquid were almost always positive and can be over 120 μm. However, after the blow-dry operation, the deviations caused by the liquid almost disappeared.

Another area with many deviations was the molar segment (111 / 120), especially the second molar on both sides. Deviations there were mainly distributed horizontally in the buccal or lingual direction. In addition, in most cases, the deviation in the posterior area was greater than that in the anterior segment

Discussion

The results of the present in vitro study indicated a significant difference among scanning conditions. Thus, the first null hypothesis was rejected—that no significant difference would be found in the accuracy of digital scans obtained from different conditions (dry, wet, and blow-dry). Among the three conditions, the dry and the blow-dry condition had prominently higher trueness and precision than the wet condition. Because of the significant difference in the precision of the two intraoral scanners when using different liquids under three conditions, the second null hypothesis—that no significant difference would be found in the accuracy of digital scans obtained using two kinds of intraoral scanners under different conditions—was partially rejected. The third null hypothesis was accepted—that no significant difference would be found in the accuracy of digital scans obtained under the condition of using two kinds of liquids to create liquid-attached scanning objects. Therefore, the difference in the composition of the liquid does not seem to affect the effect of the liquid on the accuracy of the intraoral scanner.

Park et al.[50] compared the accuracy of intraoral scanners at different levels of humidity using an intraoral-environment simulator. However, controlling the amount of liquid and simulating the liquid's attaching pattern on the tooth surface in the mouth still remained challenging. Therefore, in this study, a unique scanning platform was designed to allow liquid to immerse the tooth and then flow out steadily. To a certain extent, this method not only played a role in controlling variables but also helped simulate the state of liquid on the tooth surfaces.

Research on the accuracy of complete arch scanning is still scarce. In previous in vitro studies on complete arch scanning of intraoral digital impressions, Revilla-León et al.[51] also chose Trios 3 as an intraoral test scanner, and they reported mean trueness and mean precision in naturel light conditions (500 lux) of 109.92 µm and 136.94 µm, respectively. Jeong et al.[52] chose CEREC Omnicam and CEREC Bluecam as intraoral test scanners, and they reported mean trueness and precision values of 197 (SD: 4) µm and 58 (SD: 13) µm for CEREC Omnicam and 378 (SD: 11) µm and 116 (SD: 28) µm for CEREC Bluecam. Ender et al.[53] chose Trios 3 and Primescan as test intraoral scanners, and they reported mean trueness and precision values of 47.8 (SD: 20.5) µm and 53.7 (SD: 28.3) µm for Trios 3 and 32.4 (SD: 9.8) µm and 30.1 (SD: 15.8) µm for Primescan. Compared with those values even in different conditions, some of the values reported are consistent with the findings of this study, whereas some showed a significant difference. These differences may be due to different scanning objects, scanning environment and reference scanners.

For precision measurements, another method suitable for this study is to obtain ten consecutive scans by the intraoral scanner while the tooth surface was wet, followed by another 10 scans after drying the tooth. This approach, however, has an unavoidable flaw. The interval between the first and tenth scans is too long, and the evaporation of liquid changes the condition of the tooth surface.

By observing the color map, it is obvious that the deviations caused by ultrapure water and artificial saliva are mainly distributed in the pits and fissures of the tooth surface, the gingival margin and the interproximal area of the teeth. Among them, the deviations of the gingival margin around the abutment were very obvious. These deviations may be due to more liquid remaining caused by the presence of shoulders. Notably, deviations caused by liquid were all positive and were more than 120 μm. The clinically acceptable accuracy of the dental model has been reported to be within 120 μm.[54] In other words, due to the presence of liquid in these areas, many high points appear on the digital models, which would cause misfit in the later restoration.

In the mandibular jaw model scan, the deviations in the posterior teeth, especially the second molars, were large. It is worth noting that these deviations were horizontally distributed. This result is consistent with many other studies on the accuracy of complete arch models, which attribute reason to the 3D model formation algorithm.[55-58] Due to the limitations of the intraoral space, the scan head of the intraoral scanner is often small, which limits the scanning FOV. A stitching algorithm was used during the scanning process to form digital impressions of multiple tooth surfaces. Vág J et al.[59] reported that the stitching process would result in error accumulation when scanning dentitions composed of multiple teeth. If the scanning error of the posterior tooth area can be resolved, the scanning accuracy of the complete arch model may be greatly improved. Thus, it could be an important information for manufacturers to improve the accuracy of intraoral scanner in complete arch scanning.

Because of the complexity of fossae, pits, and ridges on the tooth surface, a complete and detailed digital model places high demands on the scanner. Steinhauser-Andresen et al.[43] reported that CT may be the best choice for scanning the fissure area. The other concern comes from the inaccuracy of the scan of the interproximal part of the teeth. This study used industrial CT to obtain a more accurate reference model based on these problems. Besides, due to the different methods to get reference models, the results of the present study for the accuracy of complete arch scanning cannot be directly compared with other studies.

According to the results of this study, it is necessary to carefully check the tooth surface for liquid residue before using an intraoral scanner. Saliva, blood, or gingival crevicular fluid attached to the tooth surface will affect the accuracy of the scan results. Additionally, using a three-way syringe can eliminate the scanning errors caused by liquid.

This study has some limitations. First, it is an in vitro experiment, so it cannot perfectly reproduce the complex environmental conditions in the oral cavity (such as temperature or humidity). Fluid distribution may change because of the tongue licking the tooth. Second, this study used the best-fit algorithm and RMS value in the Geomagic Control software to evaluate the accuracy. Although this is a classic method to evaluate 3D model accuracy, this method may ignore the location of the scanning starting point. In addition, because there was no frame-by-frame analysis, the overall evaluation can only be done and the error caused by the stitching algorithm may be underestimated.[37] Third, only Trios 3 and Primescan intraoral scanners were tested in this study. The results using more types of intraoral scanners are needed. However, this study can help to standardize procedures performed with intraoral scanners and allow clinical staff to better understand the scanning error caused by liquid. How to best use intraoral scanners for the highest accuracy still requires further exploration. In the future, intraoral scanners that can recognize saliva and blood and perform excellently in the oral environment are expected.

Short conclusion

1. Liquid present on the tooth surface could affect the accuracy of intraoral scanning results.
2. Blow-drying the teeth with a three-way syringe effectively reduced the effects of liquid on intraoral scanning results.

Experiment 2 - Understanding the effect of scan spans on the accuracy of intraoral and desktop scanners

Purpose

The posterior teeth, especially the molar segment, showed large errors in the scans of the full arch span in experiment 1. These errors were attributed to the stitching matching algorithm forming the scan images.

Therefore, to better understand errors caused by scan span, this experiment aimed to measure and compare the accuracy (trueness and precision) of IOSs and desktop scanners for scanning different spans. The null hypothesis was that the scan spans (full arch, half arch, and three teeth) and scanner types (Trios 3, Primescan, LS 3, and D2000) would not affect the accuracy of the IOSs and desktop scanners.

Materials and methods

1. Preparation of the scanning objects

A maxillary typodont (Prosthetic Restoration Jaw Model D16-500A[GSF]-GF, Nissin, Kyoto, Japan) with all teeth replaced with standard abutment tooth models (Abutment Tooth Model A55A-111, A55A-121, A55A-131, A55A-141, A55A-151, A55A-162, A55A-172, A55A-211,

A55A-221, A55A-231, A55A-241, A55A-251, A55A-262, A55A-272, Nissin) was used as the original model. Three plaster models were made to represent different scan spans to eliminate the influence of the reflection and translucent surfaces on the scanning accuracy.[13] Polyvinyl siloxane (addition reaction silicone) impression material (Exafine Putty Type, GC, Tokyo, Japan) with a two-step impression technique was applied to the original model to get three impressions. Type IV dental stone (New Fujirock, GC) was used to produce three plaster models cut with a dental cutting machine to produce the scan objects with different spans (full arch, half arch, and three teeth). A plaster base was made for stable placement of each model. Steel balls were set on each model to facilitate the creation of the trimming plane in the later stage (Figure 3).

2. Scanning procedures

All scanners were calibrated according to the manufacturers' guidelines before scanning. Three plaster models were scanned using a high-accuracy industrial scanner (ATOS III Triple Scan, GOM GmbH, Braunschweig, Germany) to obtain the digital reference model. The scan data obtained were exported in STL format.

Three plaster models were then scanned using two IOSs, the Trios 3 (software version: 1.7.6.1, 3Shape, Copenhagen, Denmark) and Primescan (software version: 5.2.0.247521, Dentsply-Sirona, York, PA, USA), and two desktop scanners, the LS3 (software version: 1.12.3.1, KaVo, Biberach, Germany) and D2000 (software version: 5.1.1.207230, 3Shape). Each scanner (n = 4) was used to take ten scans of each model (n = 3). Thus, 120 scans were obtained and exported in STL format as test models. Based on the different scanners and scan spans, the models were divided into 12 groups for trueness and precision assessment (Figure 4).

The same operator (Y.C.), with two years of user experience with each scanner, conducted all scanning operations. The two IOSs were operated with the same scanning strategy as recommended by the manufacturers: start scanning from the occlusal surface of the right second molar, then sweep along the occlusion to the other end of the dentition. (slowly wiggle the scanner when passing the anterior teeth). Then turn to the buccal side and scan back to the buccal surface of the right second molar. Finally, turn to the lingual side and scan to reach the lingual surface of the left second molar to finish the scan.

To avoid environmental errors caused ambient light, temperature, and humidity, all scanning operations were conducted in a separate room with temperature (23 ± 2 °C), humidity (50 ± 5 %), and illuminance (500 ± 20 lux) measured by a thermo-hygrometer and a digital lux meter (HP-881D, HoldPeak, Zhuhai, China).

3. Processing and comparison of the scanning data

All reference and test models were imported into reverse engineering software (Geomagic Control 2015; 3D Systems Inc., Rock Hill, SC, USA) for analysis. A trimming plane was created for each type of span using pre-set steel balls as marker points on the model surface. All models with the same span were trimmed using the same plane to obtain a common border. The average absolute error between each group of models and the reference model was defined as the trueness of the group. The average absolute error between all models within each group was defined as precision.

For trueness comparison, all models (n = 10) within each group (n = 12) were individually compared with the corresponding reference model using the best-fit algorithm and 3D comparison function in Geomagic Control 2015 (Figure 5). For each pair consisting of a reference model and a test model, the best-fit algorithm was performed so that the two models could achieve the best alignment state. The RMS value was calculated using the formula below using the 3D comparison function, where $X_{1,i}$ represents the reference data, $X_{2,i}$ represents the study data, and n represents the number of all measurement points calculated.

$$RMS = \sqrt{\frac{\sum_{i=0}^{n} \left(X_{1,i} - X_{2,i}\right)^2}{n}}$$

The smaller the RMS value, the smaller the discrepancy between the two models.

For precision comparison, in each group (n = 12), 45 combinations were formed by pairwise matching (Figure 5). A best-fit algorithm and 3D comparison function were then performed on each combination of models to obtain the corresponding RMS value. The mean RMS value of the 45 combinations was used to evaluate the precision of each group.

4. Statistical analysis

G∗Power software (v3.1.9.4, Heinrich-Heine-Universität, Düsseldorf, Germany) was used to detect the appropriate sample size for this study. Ten scans per group were determined as the sample size (actual power = 99.1%; power = 99%; α = 0.05) after conducting five scans as a pilot experiment.

SPSS 25 (IBM, Corp., Armonk, NY, USA) was used for all data analysis with a significance level of α = 0.05. The Shapiro–Wilk test and Levene test evaluated the normality of deviations and homoscedasticity. Two-way analysis of variance (ANOVA) was applied to assess the statistical difference of trueness and precision with the scan span and scanner as two independent factors. The Bonferroni correction was applied to post-hoc multiple pairwise comparisons.

Results

Two-way ANOVA revealed significant differences in the trueness or precision of different scan spans ($p < 0.001$) and different scanners ($p < 0.001$). Furthermore, the interaction effect based on the scan span and scanners was significant ($p < 0.001$). The trueness and precision values are listed in Table 3.

1. Trueness

Figure 6 shows the deviation between the RMS value of different scan spans for the four different scanners. For the D2000, the mean RMS values of the three scan spans (full arch, half arch, and three teeth) were 23.82 ± 0.22 μm, 21.53 ± 0.18 μm, and 21.02 ± 0.27 μm respectively, with no significant difference. The other scanners showed a significant difference in the RMS value of different scan spans. The RMS values of the LS 3, Trios 3, and Primescan for the span of the full arch were significantly higher than those of the half arch and three teeth span. There was no significant difference in RMS values for the LS 3 and Primescan in the half arch and three teeth span. The RMS value of the Trios 3 scan of the half arch span was significantly higher than that of the three teeth span.

Figure 7 shows the deviations between the RMS values of the scanners for the three different spans. For the full arch, there was a significant difference between scanners. The highest mean RMS value was found with the Trios 3 (46.92 ± 9.23 μm), followed by the LS 3 (33.45 ± 0.47 μm) and Primescan (28.73 ± 0.77 μm), with the lowest value found with the D2000 (23.82 ± 0.22 μm). The LS 3 showed a significantly higher RMS value for half arch scanning than the other scanners, while the other scanners did not show significant differences. The Trios 3 and Primescan for three teeth scanning showed significantly lower RMS values than the LS 3 and D2000 scanners.

2. Precision

Figure 8 shows the deviation between the RMS values of different scan spans for the four scanners. For the D2000, the RMS values of the three spans (full arch, half arch, and three teeth) were 7.86 ± 0.83 μm, 7.87 ± 1.11 μm, and 7.82 ± 0.84 μm respectively, with no significant difference. The other scanners showed significantly higher RMS values for the full arch scan than for the half arch and three teeth scans. There was no significant difference between the half arch and three teeth scans in the LS 3 and Primescan. For the Trios 3, the RMS value of the half arch scan was significantly higher than that of the three teeth scan.

Figure 9 shows the deviations between the RMS values of different scanners for the different spans. The RMS value of the Trios 3 was significantly higher than that of the other scanners in any scan span. For full arch scanning, the RMS values of the LS 3 and Primescan were 15.36 ± 3.10 μm and 15.74 ± 2.45 μm respectively, which were not significantly different from each other, but were significantly higher than that of the D2000 (7.86 ± 0.83 μm). For half arch and three teeth scanning, the RMS values of the D2000 and Primescan were not significantly different but were significantly higher than those of the LS 3.

Discussion

In this study, significant differences were found in accuracy among different scan spans ($p < 0.001$) when the same scanner was used and among different scanners ($p < 0.001$) for the same scan span. Therefore, the null hypothesis of this study was rejected, which suggests that both scanner type and scan span affect the accuracy of the scanner.

In the present study, all the scanners except for the D2000 exhibited significantly higher mean RMS values in the full arch scan span than in the half arch and three teeth scan spans, which is consistent with the results of other studies.[60] As the stitching range expands and the stitching time increases, the error accumulation increases, decreasing scanning accuracy. However, there was no significant difference in the trueness and precision of the D2000 for the three different spans. This result is presumably attributable to the D2000 having better optimization and stitching capabilities and a large FOV, so the full arch scan does not require multiple stitching processes. For the other desktop scanner the LS3, regardless of trueness or precision, had no significant difference in the three teeth and half arch spans, which is consistent with the D2000. However, for the full arch span of the LS3, the trueness and precision were significantly lower than that of the three teeth or half arch spans. These results may indicate that when the scan span is larger than half an arch, the imaging process of the LS 3 still requires stitching because of FOV limitations. Therefore, even for some desktop scanners, when the scan span exceeds a certain range, there may be a significant decrease in accuracy which similar to that of IOSs. Bohner et al.[61] compared the accuracy of two IOSs and desktop scanners using a single prepared tooth as the scanning object and concluded that their scanning accuracy was similar. Cai et al.[62] compared the accuracy of a desktop scanner (SHINING) with two types of IOSs (CEREC and TRIOS) by scanning a spherical model designed according to ISO 3290-2:2014, and reported that the CEREC and TRIOS scanners were more accurate than the SHINING scanner. Although the scanned objects and scanners were differed, their results were similar to the present study. The IOS had similar even better accuracy for small scan spans like a single crown or three teeth than a desktop scanner. To assess a longer scan span, Baghani et al.[63] removed four teeth from a full-arch model, prepared the remaining teeth, and compared the accuracy of three IOSs (CEREC Omnicam, TRIOS 3, Carestream CS 3600) with one desktop scanner (Deluxe scanner). The desktop scanner was more accurate than two of the IOSs tested (CEREC Omnicam and Carestream), which is similar to the the present study's finding comparing two IOSs with the D2000 for full arch span. On the basis of the results of the present study, when comparing the accuracy of IOSs and desktop scanners, it is still difficult to conclude whether desktop scanners or IOSs are more accurate, because each scanner has a unique pattern of accuracy variation for different scan spans. However, it is worth noting that compared with the D2000 desktop scanner, the Primescan intraoral scanner showed higher trueness and similar precision when scanning the three teeth span and similar trueness and precision when scanning the half arch span. Additionally, compared with the LS3 desktop scanner, the Primescan showed better trueness and similar precision when scanning the full arch span. Therefore, an intraoral scanner such as the Primescan has accuracy comparable with desktop scanners regardless of the scan span in this study.

In a similar experiment, Park et al.[64] used TRIOS 3 IOS and the FREEDOM HD desktop scanner to scan a full arch plaster model. The results showed that the trueness of the IOS was significantly better than that of the desktop scanner for a single tooth, and there was no significant difference between the trueness of the IOS and the desktop scanner for two teeth. In comparison, the trueness of the IOS was significantly lower than that of the desktop scanner when the span was greater than two teeth. This result partially conflicts with the results of this study, although a similar tendency was evident. In this study, IOSs showed better trueness than the D2000 for the three teeth span and similar trueness for the half arch span. The IOSs showed significantly lower trueness than desktop scanners only for the full arch span. The different results between the present study and Park's study could be explained by the different scanners, scanning objects, and experimental methods. Huang et al.[65] reported that when the gap between two teeth was smaller than 1.5 mm, there was a large error in the adjacent area. In Park's study, full dentition with tight teeth alignment was used, which may result in a more rapid accumulation of errors when the span increases, while in this study, the abutment teeth with were prepared for scanning.

In this study, regardless of intraoral or desktop scanners, all scanners showed trueness and precision values of less than 50 μm. If 120 μm is used as a clinically acceptable accuracy requirement, it is no doubt that the scanning accuracy is acceptable even for the full arch span. Therefore, the scan span may not be the main limiting factor for applying intraoral scanners to larger scanning areas.

A limitation of this study is that the accuracy results obtained from all the scanners relate to intrinsic accuracy, and do not represent accuracy in clinical situations. This experiment did not consider the effects of various environmental factors, such as humidity and saliva in the human mouth, that may affect the accuracy of IOSs. To ensure the standardization of the experiment and to avoid errors caused by the reflection and translucent surfaces of real teeth, plaster models were directly used as the scanning objects instead of human teeth, which disregarding the various errors that might occur during the process of making plaster models using traditional impression methods. To understand the accuracy of digital impressions obtained by desktop scanners in clinical situations, further analysis of the errors occurring during the impression-taking process is needed. Second, only two types of intraoral scanners and two types of desktop scanners were tested by only one experienced operator. The accuracy of other types of IOSs and desktop scanners for various scan spans requires further testing and validation to obtain more comprehensive data for clinicians and manufacturers. However, this study can help clinicians understand the effect of various scan spans on the accuracy of IOSs and desktop scanners, leading to a deeper understanding of digital impression technology. Scanners with higher accuracy, faster speed, and greater applicability require further development and optimization.

Short conclusion

1. The scan span affected the accuracy of the intraoral scanner, but not necessarily the

accuracy of the desktop scanner.

2. For the LS3 and the two IOSs (TRIOS 3 and Primescan), the scanning accuracy of the full arch scan was significantly worse than that of the half arch and three teeth scans. There were no significant differences in the scanning accuracy of different scan spans for the D2000.

Experiment 3 - Impact of internal design on the accuracy of 3D printed casts fabricated by stereolithography and digital light processing technology

Purpose

Although the advent of intraoral scanners has enabled virtual casts to be obtained, physical dental casts remain indispensable in various clinical situations.[66] In the past, dental casts were poured into gypsum, but defects in the casts were a problem for dentists.[67] Cast fabrication can be greatly automated and standardized with 3D printing technology, improving traditional manufacturing in terms of accuracy, time efficiency, and cost.[68, 69]

Information on the effect of the internal design on the accuracy of dental casts made through various 3D printing techniques is sparse. Rungrojwittayakul et al.[70] used DLP and CLIP printing techniques to print dental casts, but only compared the printing accuracy of hollow and solid designs. Revilla-León et al.[71] compared the printing accuracy of three internal designs, but only one printing technology (material jetting) was used.

Different 3D printing technologies are available, including SLA, DLP, FDM, and PolyJet.[72, 73] SLA and DLP are the most well-established and commonly used technologies for cast manufacture.[26] SLA polymerizes materials using an ultraviolet laser point by point, resulting in highly detailed representation and high resolution, while DLP forms the object by polymerizing the resin layer by layer, therefore, with the advantage of high print speed.[74] In this study, these two technologies were selected as representatives to evaluate the accuracy of 3D printing technology for dental cast fabrication.

This study aimed to evaluate the impact of internal design on the accuracy (trueness and precision) of 3D-printed dental casts fabricated by SLA and DLP technology. The null hypotheses were that different internal designs would not affect the trueness and precision of 3D printed casts printed by the same printer and that different 3D printers would not affect the trueness and precision of 3D printed casts with the same internal design.

Materials and methods

1. Construction of the different internal designs

A maxillary typodont (Prosthetic Restoration Jaw Model D16-500A[GSF]-GF, Nissin, Kyoto, Japan) with half of the teeth replaced by standard abutment teeth was scanned with an intraoral scanner (Trios 3, 3Shape, Copenhagen, Denmark) to obtain a STL format digital cast. The digital cast was then imported into an open-source 3D modeler software program (FreeCAD v0.20; Matra Datavision Inc, Massachusetts, USA) for setting on three cylinders (Ø2×3 mm) on the facial side of the two central incisors, left first molar, and right first molar. This cast was used as the digital reference cast, upon which four different types of interior designs were constructed: HWB, HB, S, and SWB (Fig. 10) using two dedicated software programs (Model builder, version: 19.3.0, 3 Shape, Copenhagen, Denmark; Lychee slicer, version: 4.1.000, Mango 3D, Aquitaine, France). For design types HWB, HB, and SWB, the surface thickness was set at 1.5 mm with the drain hole on the base set to Ø2 mm.

2. 3D printing of the dental models

The SLA-based printer (Form 3; Formlabs, Massachusetts, USA) with the specified resin (Model Resin V3; Formlabs, Massachusetts, USA) and the DLP-based printer (Straumann P30+; Institut Straumann AG, Basel, Switzerland) with the specified resin (P pro Master Model; Institut Straumann AG, Basel, Switzerland) were used to print the casts. Both 3D printers were calibrated according to the manufacturer's guidelines before use. To ensure the standardization of the experiment, all cast were manufactured at a 0-degree build orientation and the build layer thickness was set to 50 μm. Each printer printed ten specimens for each type of internal design. The sample size was based on a previous study.[75] Thus, a total of 80 casts were printed. For postprocessing, all the printed casts were first cleaned with a toothbrush in a tank containing 90 % isopropanol and then immersed for 10 minutes ultrasonic bath to remove excess resin. The casts printed by the Form 3 printer were polymerized by using the dedicated post-polymerizing unit (Form Cure; Formlabs, Massachusetts, USA), and the casts printed by the Straumann P30+ were also polymerized using corresponding dedicated polymerizing machine (P Cure; Institute Straumann AG, Basel, Switzerland). The manufacturer's recommendation for the corresponding resin determined the polymerizing time.

3. Scanning procedure and comparison of the scanning results

After post-processing, all the casts were scanned with a calibrated desktop scanner (D2000, 3Shape, Copenhagen, Denmark) with a manufacturer's reported accuracy of 5 μm (ISO 12836:2015) to fabricate the research digital casts. Finally, 80 research digital casts were obtained and exported in STL format. For accuracy evaluation, the research and reference digital casts were imported into a software program (Geomagic Control 2015; 3D Systems Inc, Rock Hill, United States). All the imported casts were trimmed to a common plane defined by three points separately selected from the upper surface of each cast cylinder to ensure a common area for accuracy evaluation. All research digital casts were divided into eight groups according to printer type ($n = 2$) and internal design type ($n = 4$). The best-fit algorithm in the Geomagic Control 2015 software program overlaps the point cloud of the research digital cast and the reference digital cast to achieve the best fit. The deviation between the two point clouds was shown by the RMS value.[9, 76, 77] The larger the RMS value, the greater the deviation between the two casts. This study compared ten research digital casts within each group with the reference digital cast by applying the best-fit algorithm, resulting in ten RMS values. The mean of these RMS values was used to represent the trueness of the group. To evaluate the precision of each group, all unrepeatable pairwise combinations of the ten research digital casts within each group were generated, resulting in 45 combinations ($n = {}_{10}C_2 = 45$). For each combination, one cast was designated as the reference cast and the other as the test cast for the best-fit algorithm. The mean of these 45 RMS values was used to represent the precision of the group.

4. Statistical analysis

All data analysis was conducted in a statistical software (SPSS; IBM, Inc., Armonk, NY, USA) ($\alpha = 0.05$). The Shapiro-Wilk test assessed the data's normality of deviations, which revealed that all the data was not normally distributed ($p < 0.05$). Therefore, the Kruskal-Wallis one-way ANOVA and Dunn test were used to test for significant differences between the different internal design types by comparing mean ranks ($\alpha = 0.05$). The Bonferroni correction was applied to adjusted post hoc multiple pairwise comparisons. The Mann-Whitney U test was used to test significant differences between the two 3D printers in each design type by comparing mean ranks ($\alpha = 0.05$).

Results

Table 4 shows the RMS value (mean ± standard deviation) of trueness and precision for casts with different internal structure designs manufactured by two 3D printers. For both trueness and precision, the Kruskal-Wallis one-way ANOVA revealed significant differences in mean ranks of mean RMS values for different internal design types (all $p < 0.001$) for casts printed by both 3D printers. For the casts printed by both 3D printers, the HB design showed significantly higher mean RMS values than other design types for both trueness (all $p < 0.05$) and precision (all $p < 0.001$) (Fig. 11). There was no significant difference in mean RMS values for HWB and SWB designs in trueness and precision (Fig. 11) for casts printed by both 3D printers ($p > 0.05$). For the casts printed by the Straumann P30+, the S design did not have a significantly different mean RMS value for trueness compared to the HWB and SWB designs ($p > 0.05$). In contrast, for casts printed by Form 3, the S design had a significantly higher mean RMS value for trueness than the HWB ($p = 0.002$) and SWB designs ($p < 0.001$) (Fig. 11A). For the precision of casts printed by both 3D printers, the S design showed a significantly lower mean RMS value than the HWB (all $p < 0.05$) and SWB designs (all $p < 0.05$) (Fig. 11B).

For trueness, the mean RMS values of casts printed by the Straumann P30+ were significantly higher than the mean RMS values of casts printed by the Form 3 regardless of the design type (all $p < 0.05$) (Fig. 12A). For precision, the mean RMS values of casts printed by the Straumann P30+ were significantly lower than the mean RMS values of casts printed by the Form 3 regardless of the design type (all $p < 0.05$) (Fig. 12B).

Discussion

Significant differences were found in trueness and precision among different internal designs (all $p < 0.001$) for casts printed by the same 3D printer, as well as between different 3D printers (all $p < 0.05$) for printing casts with the same internal design. Therefore, the null hypotheses were rejected, indicating that internal design and printer types affected the accuracy of the 3D-printed dental casts.

Four types of internal designs were evaluated to investigate the relationship between the accuracy of 3D printed dental casts and the internal design. Regardless of the 3D printer type, the HB design exhibited significantly lower trueness and precision than the other design types. The main difference between the HB design and the other design types is the absence of a base, which suggests that the base design significantly affects the accuracy of the 3D-printed cast. The lower trueness and precision may have been because the cast was printed starting at the base and progressing to the top. Therefore, the base was the first part to be generated. A complete base not only determines the overall position and size of the cast but also provides sufficient attachment sites for the superstructure.[78] Rungrojwittayakul et al.[70] used a DLP printer to print dental casts and compare the accuracy of hollow (no base) and solid casts. They reported no significant difference in trueness between hollow and solid casts when comparing the median of trueness. However, the mean of the RMS values for the trueness of the hollow cast was 97 μm, which was higher than that of the solid cast (87 μm). Additionally, Revilla-León et al.[71] compared the accuracy of casts printed with three different internal designs (hollow without base, honeycomb, and solid) and reported that the hollow casts had the highest accuracy. This result differs from the present study, possibly because of the different printing technology (material jetting) used and the different methods used for accuracy evaluation (a coordinate measuring machine used to measure and compare linear differences). These differences indicate that the effect of internal design on accuracy may vary for different 3D printing technologies and needs further investigated. Jin et al.[24] compared solid and hollow implant casts printed with LCD technology and reported that the solid casts were better than the hollow casts in terms of trueness and precision. In the present study, the S casts with a solid design were as good or better than the HWB casts with a hollow design in terms of precision for casts printed by both 3D printer used, consistent with Jin et al. [24] However, S casts were not significantly different from HWB casts in terms of trueness for Straumann P30+ casts. S casts were even worse than the HWB casts regarding trueness for the Form 3 casts, suggesting that the solid design does not necessarily lead to higher accuracy. Although these studies cannot be directly compared with the present study because of the different 3D printing technologies used, a common finding has been that the internal design significantly affected the accuracy of 3D printed dental casts. In addition, regardless of the printer type, there was no significant difference in trueness and precision between the HWB and SWB designs, suggesting that the internal support did not affect the accuracy of the printed casts. Based on this analysis, it is feasible to reduce material consumption by changing the internal design without compromising printing accuracy.

Regardless of the internal design, the casts printed with the Form 3 printer exhibited higher trueness than those printed with the Straumann P30+ printer. Abdeen et al.[68] printed implant casts with the same printer as in the present study and reported that the trueness of the casts made by the Form 3 printer was 62.7 ± 10.4 μm, which was significantly better than that of the casts made by the Straumann P30+ printer (88.1 ± 16.5 μm). Their finding was consistent with the present study, and the difference in the trueness values may have been because different cast designs were produced. Additionally, the casts printed by the Form 3 in the present study exhibited less precision than those printed by the Straumann P30+, regardless of the internal design. Kim et al.[69] compared the trueness and precision of dental casts printed by SLA, DLP, FFF, and Polyjet techniques and reported that casts printed by SLA technology had higher trueness and lower precision compared with DLP technology, consistent with the present study. The Straumann P30+ printer uses DLP technology to polymerize the resin layer by layer, whereas the Form 3 uses SLA technology which fabricates casts by polymerizing the resin point by point. Errors may occur when the newly polymerized layer or spot connects with the polymerized layer or spot. DLP technology has a larger volume in a single polymerization than SLA technology when working on the same cast. It, therefore, requires less polymerizing time to complete the print, with fewer opportunities to accumulate errors, leading to higher precision. In addition, in this study, the models printed by SLA and DLP technologies were all less than 120 μm in trueness and precision values, regardless of the type of internal designs. This is in accordance with the clinically acceptable accuracy range. Therefore, from the results of this study, the accuracy of the 3D-printed models can be accepted for clinical use.

Limitations of this study included that only two printers and two resins were tested as representative of SLA and DLP technologies. Additional printer types and materials should be tested to improve the generalization of the study. The best-fit algorithm was used to assess the variation in accuracy, but this method can only compare overall accuracy, while the difference in linear accuracy is not yet known.[77] Additionally, only four internal designs were tested. More internal design types should be tested to determine the optimal design with best accuracy and lower material consumption. The term accuracy in this study can only be understood as printing accuracy and does not account for the accuracy of the 3D printed cast in clinical use. The fabrication of 3D-printed casts for clinical use entails a two-step process involving intraoral scanning of the patient's mouth with an intraoral scanner to obtain a digital cast and subsequently using the digital cast to fabricate a 3D-printed cast with a 3D printer. However, both the scanning and printing processes can introduce errors that affect the accuracy of the final 3D printed cast. In the present study, a pre-created virtual cast was used as a reference cast rather than the actual dentition in the patient's mouth; thus, the errors introduced by the scanning process were ignored to exclude the scanning process and better observe the impact of the printing process on the final 3D printed cast. Future research into the accuracy of 3D printed dental casts considering both scanning and printing errors is essential to provide dentists with a more direct and comprehensive understanding of the accuracy of 3D printed casts. Three-dimensional printing technology has great potential for dentistry; more factors affecting printing accuracy, speed, and cost should be fully investigated to ensure dentists can take full advantage of these technological innovations.

Short conclusion

1. The internal design affected the accuracy of 3D printing.
2. The base was necessary to ensure the accuracy of 3D printed dental casts while the internal support structure did not affect the accuracy of 3D printed dental casts.
3. An all-solid design led to higher precision, but not higher trueness.
4. Dental casts printed with SLA technology had higher trueness and lower precision than those printed with DLP technology.

Summarized discussion

This study evaluated the accuracy of dental models obtained by digital scanning and 3D printing through accessing three specific influencing factors: liquids, scan spans and internal designs.

Experiment 1 evaluated the effect of liquid on the tooth surface on the intraoral scanning accuracy. Results demonstrated that residual liquids on tooth surfaces adversely affected scanning accuracy, with specific areas identified as more susceptible. The experiment concluded that the presence of residual liquids led to positive deviations in intraoral scanning results. In addition, since there was no statistically significant difference in the scan accuracy between dry and blow-dry conditions, it was proved that the blow-dry process is effective in avoiding deviations caused by residual liquids, providing evidence for the necessity of the blow-dry operation before scanning. In experiment 1, the posterior segment of the dental arch (molar region) also showed a large deviation except for the portion affected by residual liquid. The presence of deviation here was attributed to the stitching algorithm used for the intraoral scanner to achieve a large scanning area. Since the stitching process may generate errors, the larger scanning range leads to more stitching, and thereby the scanning accuracy decreases.

Experiment 2 was thus conducted to evaluate the effect of scan span on the scanning accuracy of the IOS and the desktop scanner. By comparing the scanning accuracies of different scanners for three scan spans of the same dentition, it was demonstrated that long scan span decreases the scanning accuracy of the IOS. As for the desktop scanner, based on the experimental results, it was concluded that long scan span does not necessarily cause a decrease in scanning accuracy. To our knowledge, it is the first experiment to evaluate scan accuracy for different spans of the same dental arch, indicating the pattern of changes in accuracy resulted by the extension of scan spans for both intraoral and desktop scanners.

Experiments 1 and 2 focused on the evaluation of scanning accuracy, experiment 3 later investigated the manufacturing accuracy, which to be specific, the accuracy of 3D printed dental models. Four different internal designs were constructed for the same dental model. With the comparison of the models printed with different internal designs, experiment 3 revealed the important role of the base on the bottom in ensuring the accuracy of 3D-printed dental models. In addition, it was found that the all solid design could not lead to a higher degree of trueness. Since there was no significant difference in the accuracy of the models printed by hollow interior without base and internal support structure with perforated base designs, a method was found to utilize the internal hollow design to achieve a reduction in material consumption while maintaining the same accuracy.

Through this study, the accuracy of the scanning and manufacturing processes in the digital dental workflow was preliminarily evaluated. In the future, further studies should be conducted on other factors and aspects that may have an impact on the digital workflow to provide more scientific evidence for the realization of the full process of digital dentistry. Digitization will undoubtedly become a significant driving force behind the development of the dental field.

Conclusion

1. According to the results of this study, dental models obtained through digital scanning and 3D printing could meet the accuracy requirements for clinical use, but their accuracy was significantly affected by liquids, scan spans and internal designs.

2. Liquids on the tooth surface resulted in a positive deviation of more than 120 μm. Blow drying effectively avoided the liquid's effect on the tooth surface on the intraoral scanning results. Full arch span for intraoral scanning led to greater errors than a short scan span (three teeth, half arch). Choosing a suitable scan span for different clinical cases was crucial to improve the accuracy of the scanning results. The lack of a complete base significantly decreased the accuracy of the 3D printed dental models. A proper internal design could help to save printing material while maintaining the accuracy of the 3D-printed dental models.

3. The in vitro experimental method established in this study could help dental clinicians to comprehensively understand and effectively assessed the effect of liquid and scan span on the accuracy of intraoral scanning, as well as the effect of internal design on the accuracy of 3D printed dental models, thus providing evidence for clinical practice of the digital dentistry.

Published articles

As a first author:

1. **Chen Y**, Zhai Z, Li H, Yamada S, Matsuoka T, Ono S, Nakano T. Influence of liquid on the tooth surface on the accuracy of intraoral scanners: an in vitro study. J Prosthodont. 31:59-64. 2022

2. **Chen Y**, Zhai Z, Watanabe S, Nakano T, Ishigaki S. Understanding the effect of scan spans on the accuracy of intraoral and desktop scanners. J Dent. 124:104220. 2022

3. **Chen Y**, Li H, Zhai Z, Nakano T, Ishigaki S. Impact of internal design on the accuracy of 3D printed casts fabricated by stereolithography and digital light processing technology. J Prosthet Dent. Accepted. 2023

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Reference

1. Davidowitz G, Kotick PG. The use of CAD/CAM in dentistry. Dent Clin North Am 2011;55:559-570.
2. Miyazaki T, Hotta Y, Kunii J, et al. A review of dental CAD/CAM: Current status and future perspectives from 20 years of experience. Dent Mater J 2009;28:44-56.
3. Stanley M, Paz AG, Miguel I, et al. Fully digital workflow, integrating dental scan, smile design and CAD-CAM: Case report. BMC Oral Health 2018;18:1-8.
4. CAD/CAM Dentistry: Adopted by the FDI general assembly. August 2017, Madrid, Spain. Int Dent J 2018;68:18-19.
5. Kapos T, Evans C. CAD/CAM technology for implant abutments, crowns, and superstructures. Int J Oral Maxillofac Implants 2014;29:117-136.
6. Beuer F, Schweiger J, Edelhoff D. Digital dentistry: An overview of recent developments for CAD/CAM generated restorations, Brit Dent J 2008;9:505-511.
7. International Organization of Standardization (ISO). Accuracy (trueness and precision) of measurement methods and results. Part1: General principles and definitions. https://www.iso.org/obp/ui/#iso:std:iso:5725:-1:ed-1:v1:en. Accessed 11/07/2023
8. Arakida T, Kanazawa M, Iwaki M, et al. Evaluating the influence of ambient light on scanning trueness, precision, and time of intra oral scanner. J Prosthodont Res 2018;62:324-329.
9. Chen Y, Zhai Z, Li H, et al. Influence of liquid on the tooth surface on the accuracy of

intraoral scanners: An in vitro study. J Prosthodont 2022;31:59-64.

10. Ochoa-López G, Cascos R, Antonaya-Martín JL, et al. Influence of ambient light conditions on the accuracy and scanning time of seven intraoral scanners in complete-arch implant scans. J Dent 2022;121:104138.

11. Revilla-León M, Jiang P, Sadeghpour M, et al. Intraoral digital scans-part 1: Influence of ambient scanning light conditions on the accuracy (trueness and precision) of different intraoral scanners. J Prosthet Dent 2020;124:372-378.

12. Wesemann C, Kienbaum H, Thun M, et al. Does ambient light affect the accuracy and scanning time of intraoral scans?. J Prosthet Dent 2021;125:924-931.

13. Cakmak G, Marques VR, Donmez MB, et al. Comparison of measured deviations in digital implant scans depending on software and operator. J Dent 2022;122:104154.

14. Resende CCD, Barbosa TAQ, Moura GF, et al. Influence of operator experience, scanner type, and scan size on 3D scans. J Prosthet Dent 2021;125:294-299.

15. Zarauz C, Sailer I, Pitta J, et al. Influence of age and scanning system on the learning curve of experienced and novel intraoral scanner operators: A multi-centric clinical trial. J Dent 2021;115:103860.

16. Diker B, Tak Ö. Accuracy of six intraoral scanners for scanning complete-arch and 4-unit fixed partial dentures: An in vitro study. J Prosthet Dent 2022;128:187-194.

17. Donmez MB, Çakmak G, Atalay S, et al. Trueness and precision of combined healing abutment-scan body system depending on the scan pattern and implant location: an in-vitro study. J Dent 2022;124:104169.

18. Li H, Lyu P, Wang Y, et al. Influence of object translucency on the scanning accuracy of

a powder-free intraoral scanner: A laboratory study. J Prosthet Dent 2017;117:93-101.

19. Dutton E, Ludlow M, Mennito A, et al. The effect different substrates have on the trueness and precision of eight different intraoral scanners. J Esthet Restor Dent 2020;32:204-218.

20. Son K, Lee KB. Effect of finish line locations of tooth preparation on the accuracy of intraoral scanners. Int J Comput Dent 2021;24:29-40.

21. Mangano FG, Admakin O, Bonacina M, et al. Accuracy of 6 desktop 3D printers in dentistry: A comparative in vitro study. Eur J Prosthodont Restor Dent 2020;28:75-85.

22. Park JM, Jeon J, Koak JY, et al. Dimensional accuracy and surface characteristics of 3D-printed dental casts. J Prosthet Dent 2021;126:427-437.

23. Dias Resende CC, Quirino Barbosa TA, Moura GF, et al. Cost and effectiveness of 3-dimensionally printed model using three different printing layer parameters and two resins. J Prosthet Dent 2023;129:350-353.

24. Jin G, Shin SH, Shim JS, et al. Accuracy of 3D printed models and implant-analog positions according to the implant-analog-holder offset, inner structure, and printing layer thickness: an in-vitro study. J Dent 2022;125:104268.

25. Ko J, Bloomstein RD, Briss D, et al. Effect of build angle and layer height on the accuracy of 3-dimensional printed dental models. Am J Orthod Dentofacial Orthop 2021;160:451-458.

26. Zhang ZC, Li PL, Chu FT, et al. Influence of the three-dimensional printing technique and printing layer thickness on model accuracy. J Orofac Orthop 2019;80:194-204.

27. de Castro EF, Nima G, Rueggeberg FA, et al. Effect of build orientation in accuracy,

flexural modulus, flexural strength, and microhardness of 3D-printed resins for provisional restorations. J Mech Behav Biomed Mater 2022;136:105479.

28. Tahir N, Abduo J. An in vitro evaluation of the effect of 3D printing orientation on the accuracy of implant surgical templates fabricated by desktop printer. J Prosthodont 2022;31:791-798.
29. Unkovskiy A, Bui PH, Schille C, et al. Objects build orientation, positioning, and curing influence dimensional accuracy and flexural properties of stereolithographically printed resin. Dent Mater 2018;34:324-333.
30. Piedra-Cascón W, Krishnamurthy VR, Att W, et al. 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: A narrative review. J Dent 2021;109:103630.
31. Tian Y, Chen C, Xu X, Wang J, Hou X, Li K, et al. A review of 3d printing in dentistry: Technologies, affecting factors, and applications. Scanning 2021;2021:1-19.
32. Ender A, Mehl A. In-vitro evaluation of the accuracy of conventional and digital methods of obtaining full-arch dental impressions. Quintessence Int 2015;46:9-17.
33. Patzelt SB, Emmanouilidi A, Stampf S, et al. Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig 2014;18:1687-1694.
34. García-Martínez I, Zarauz C, Morejón B, et al. Influence of customized over-scan body rings on the intraoral scanning effectiveness of a multiple implant edentulous mandibular model. J Dent 2022;122:104095.
35. Shin SH, Lim JH, Kang YJ, et al. Evaluation of the 3D printing accuracy of a dental model according to its internal structure and cross-arch plate design: An in vitro study.

Materials 2020;13:5433.

36. Lee JH, Yun JH, Han JS, et al. Repeatability of intraoral scanners for complete arch scan of partially edentulous dentitions: An in vitro study. J Clin Med 2019;8:1187.

37. Maeng J, Lim YJ, Kim B, et al. A new approach to accuracy evaluation of single-tooth abutment using two-dimensional analysis in two intraoral scanners. Int J Environ Res Public Health 2019;16:1021.

38. Rutkunas V, Geciauskaite A, Jegelevicius D, et al. Accuracy of digital implant impressions with intraoral scanners. A systematic review. Eur J Oral Implantol 2017;10:101-120.

39. Seelbach P, Brueckel C, Wostmann B, et al. Accuracy of digital and conventional impression techniques and workflow. Clin Oral Investig 2013;17:1759-1764.

40. Boeddinghaus M, Breloer ES, Rehmann P, et al. Accuracy of single-tooth restorations based on intraoral digital and conventional impressions in patients. Clin Oral Investig 2015;19:2027-2034.

41. Carbajal Mejia JB, Wakabayashi K, Nakamura T, et al. Influence of abutment tooth geometry on the accuracy of conventional and digital methods of obtaining dental impressions. J Prosthet Dent 2017;118:392-399.

42. Flugge TV, Schlager S, Nelson K, et al. Precision of intraoral digital dental impressions with itero and extraoral digitization with the itero and a model scanner. Am J Orthod Dentofacial Orthop 2013;144:471-478.

43. Steinhauser-Andresen S, Detterbeck A, Funk C, et al. Pilot study on accuracy and dimensional stability of impression materials using industrial ct technology. J Orofac

Orthop 2011;72:111-124.

44. Ender A, Mehl A. Accuracy of complete-arch dental impressions: A new method of measuring trueness and precision. J Prosthet Dent 2013;109:121-128.
45. Imburgia M, Logozzo S, Hauschild U, et al. Accuracy of four intraoral scanners in oral implantology: A comparative in vitro study. BMC Oral Health 2017;17:1-13.
46. Mangano FG, Hauschild U, Veronesi, G, et al. Trueness and precision of 5 intraoral scanners in the impressions of single and multiple implants: A comparative in vitro study. BMC Oral Health 2019;19:1-14.
47. Koseoglu M, Kahramanoglu E, Akin H. Evaluating the effect of ambient and scanning lights on the trueness of the intraoral scanner. J Prosthodont 2021 2021;30:811-816.
48. Yang X, Lv P, Liu Y, et al. Accuracy of digital impressions and fitness of single crowns based on digital impressions. Materials (Basel) 2015;8:3945-3957.
49. Geomagic Control 2014 Online Help: https://www.3dsystems.com/software?utm_source=geomagic.com&utm_medium=301. Accessed 11/07/2023
50. Park HN, Lim YJ, Yi WJ, et al. A Comparison of the accuracy of intraoral scanners using an intraoral environment simulator. J Adv Prosthodont 2018;10:58-64.
51. Revilla-León M, Subramanian SG, Özcan M, et al. Clinical study of the influence of ambient light scanning conditions on the accuracy (trueness and precision) of an intraoral scanner. J Prosthodont 2020;29:107-113.
52. Jeong ID, Lee JJ, Jeon JH, et al. Accuracy of complete-arch model using an intraoral video scanner: An in vitro study. J Prosthet Dent 2016;115:755-759.

53. Ender A, Zimmermann M, Mehl A. Accuracy of complete- and partial-arch impressions of actual intraoral scanning systems in vitro. Int J Comput Dent 2019;22:11-19.
54. McLean JW, von Fraunhofer JA. The estimation of cement film thickness by an in vivo technique. Br Dent J 1971;131:107-111.
55. Lim JH, Park JM, Kim M, et al. Comparison of digital intraoral scanner reproducibility and image trueness considering repetitive experience. J Prosthet Dent 2018;119:225-232.
56. Nedelcu R, Olsson P, Nyström I, et al. Accuracy and precision of 3 intraoral scanners and accuracy of conventional impressions: A novel in vivo analysis method. J Dent 2018;69:110-118.
57. Son K, Lee KB. Effect of tooth types on the accuracy of dental 3D scanners: An In Vitro Study. Materials (Basel) 2020;13:1744.
58. Treesh JC, Liacouras PC, Taft RM, et al. Complete-arch accuracy of intraoral scanners. J Prosthet Dent 2018;120:382-388.
59. Vág J, Nagy Z, Simon B, et al. A novel method for complex three-dimensional evaluation of intraoral scanner accuracy. Int J Comput Dent 2019;22:239-249.
60. Su TS, Sun J. Comparison of repeatability between intraoral digital scanner and extraoral digital scanner: An in-vitro study. J Prosthodont Res 2015;59:236-242.
61. Bohner LOL, De Luca Canto G, Marció BS, et al. Computer-aided analysis of digital dental impressions obtained from intraoral and desktop scanners. J Prosthet Dent 2017;118:617-623.
62. Cai HX, Jia Q, Shi H, et al. Accuracy and precision evaluation of international standard spherical model by digital dental scanners. Scanning 2020;2020:1714642.

63. Baghani MT, Shayegh SS, Johnston WM, et al. In vitro evaluation of the accuracy and precision of intraoral and extraoral complete-arch scans. J Prosthet Dent 2021;126:665-670.

64. Park GH, Son K, Lee KB. Feasibility of using an intraoral scanner for a complete-arch digital scan. J Prosthet Dent 2019;121:803-810.

65. Huang MY, Son K, Lee KB. Effect of distance between the abutment and the adjacent teeth on intraoral scanning: An in vitro study. J Prosthet Dent 2021;125:911-917.

66. Jeong YG, Lee WS, Lee KB. Accuracy evaluation of dental models manufactured by CAD/CAM milling method and 3D printing method. J Adv Prosthodont 2018;10:245-251.

67. Wiskott A. Laboratory procedures and clinical implications in the making of casts. Quintessence Int 1987;18:181-192.

68. Abdeen L, Chen YW, Kostagianni A, et al. Prosthesis accuracy of fit on 3D-printed casts versus stone casts: A comparative study in the anterior maxilla. J Esthet Restor Dent 2022;34:1238-1246.

69. Kim SY, Shin YS, Jung HD, et al. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. Am J Orthod Dentofac 2018;153:144-153.

70. Rungrojwittayakul O, Kan JY, Shiozaki K, et al. Accuracy of 3D printed models created by two technologies of printers with different designs of model base. J Prosthodont 2020;29:124-128.

71. Revilla-León M, Piedra-Cascón W, Methani MM, et al. Influence of the base design on

the accuracy of additive manufactured casts measured using a coordinate measuring machine. J Prosthodont Res 2022;66:68-74.

72. Khorsandi D, Fahimipour A, Abasian P, et al. 3D and 4D printing in dentistry and maxillofacial surgery: Printing techniques, materials, and applications. Acta Biomater 2021;122:26-49.
73. van Noort R. The future of dental devices is digital. Dent Mater 2012;28:3-12.
74. Backeris P, Borrello J. Rapid prototyping in cardiac disease. 1st ed. New York: Springer; 2017. p. 41-49.
75. Lo Giudice A, Ronsivalle V, Rustico L, et al. Evaluation of the accuracy of orthodontic models prototyped with entry-level LCD-based 3D printers: a study using surface-based superimposition and deviation analysis. Clin Oral Invest 2022;26:303-312.
76. Chen Y, Zhai Z, Watanabe S, et al. Understanding the effect of scan spans on the accuracy of intraoral and desktop scanners. J Dent 2022;124:104220.
77. Peroz S, Spies BC, Adali U, et al. Measured accuracy of intraoral scanners is highly dependent on methodical factors. J Prosthodont Res 2022;66:318-325.
78. Alammar A, Kois JC, Revilla-León M, et al. Additive manufacturing technologies: Current status and future perspectives. J Prosthodont 2022;31:4-12.

Table 1. Mean root mean square (RMS) values indicate the trueness of different conditions regarding different liquids and intraoral scanners (Unit: µm).

Liquid	Condition	Intraoral scanner	
		Trios 3	Primescan
Ultra-pure water	Dry	109.79(23.05) Aa	106.06(10.05) Aa
	Wet	152.04(31.68) Ba	139.75(14.13) Ba
	Blow-dry	124.27(28.03) Aa	119.93(6.11) Ca
Artificial saliva	Dry	108.78(23.05) Aa	103.37(10.05) Aa
	Wet	166.94(20.75) Ba	145.01(11.59) Bb
	Blow-dry	127.98(11.04) Ca	124.80(7.4) Ca

Different uppercase letters indicate statistical differences among conditions considering the same liquid and intraoral scanner ($p < 0.05$).

Different lowercase letters indicate statistical differences between different intraoral scanners considering the same liquid and condition ($p < 0.05$).

Table 2. Mean root mean square (RMS) values indicate the precision of different conditions regarding different liquids and intraoral scanners (Unit: μm).

Liquid	Condition	Intraoral scanner	
		Trios 3	Primescan
Ultra-pure water	Dry	78.37(28.35) ^{Aa}	41.83(10.05) ^{Ab}
	Wet	88.13(32.68) ^{Aa}	74.13(17.63) ^{Bb}
	Blow-dry	79.36(31.34) ^{Aa}	57.52(9.46) ^{Cb}
Artificial saliva	Dry	77.70(24.88) ^{Aa}	42.64(6.00) ^{Ab}
	Wet	85.06(10.03) ^{Aa}	78.96(15.59) ^{Bb}
	Blow-dry	76.82(13.41) ^{Aa}	62.68(7.96) ^{Cb}

Different uppercase letters indicate statistical differences among conditions considering the same liquid and intraoral scanner ($p < 0.05$).

Different lowercase letters indicate statistical differences between different intraoral scanners considering the same liquid and condition ($p < 0.05$).

Table 3. Trueness and precision of four scanners for three scan spans (unit: μm).

		LS 3			D2000			Trios 3			Primescan		
		Full arch	Half arch	Three teeth	Full arch	Half arch	Three teeth	Full arch	Half arch	Three teeth	Full arch	Half arch	Three teeth
Trueness	Mean	33.35	27.27	24.68	23.82	21.53	21.02	46.92	22.29	16.92	28.73	18.91	15.79
	Median	33.39	27.23	24.61	23.72	21.48	20.91	42.46	22.64	17.08	28.82	19.04	15.94
	SD	0.47	0.43	0.36	0.22	0.18	0.27	9.23	1.50	0.78	0.77	0.70	0.65
	CI (Lower,	31.54,	25.46,	22.87,	22.00,	19.62,	19.21,	45.11,	20.47,	15.11,	26.92,	17.10,	13.98,
	Upper)	35.16	29.09	26.49	25.63	23.24	22.83	48.73	24.10	18.73	30.55	20.72	17.60
Precision	Mean	15.36	5.62	5.29	7.86	7.87	7.82	20.79	14.12	11.95	15.74	7.94	7.68
	Median	15.05	5.62	5.32	7.75	8.04	8.00	20.80	13.82	11.87	16.41	8.01	7.72
	SD	3.10	0.88	0.62	0.83	1.11	0.84	3.08	2.25	2.22	2.45	1.09	0.62
	CI (Lower,	14.81,	5.08,	4.75,	7.32,	7.33,	7.28,	20.24,	13.57,	11.40,	15.20,	7.40,	7.13,
	Upper)	15.90	6.17	5.84	8.41	8.42	8.37	21.33	14.66	12.49	16.28	8.49	8.22

SD: standard deviation, CI: confidence interval.

Table 4. Trueness and precision of 3D printed dental casts fabricated with four internal designs and two 3D printers (μm)

	3D printers	HWB Mean ± SD	HB Mean ± SD	S Mean ± SD	SWB Mean ± SD
Trueness	Straumann P30+	98.06 ± 2.20	114.03 ± 2.75	98.01 ± 4.95	100.75 ± 2.50
	Formlab 3	70.61 ± 2.15	94.06 ± 3.43	85.28 ± 2.49	74.37 ± 2.51
Precision	Straumann P30+	24.38 ± 2.36	29.78 ± 1.90	20.96 ± 0.95	22.77 ± 1.36
	Formlab 3	46.06 ± 3.31	66.65 ± 3.06	42.63 ± 4.09	47.61 ± 5.10

HWB, hollow interior with perforated base; HB, hollow interior without base; S, all solid; SWB, internal support structure with a perforated base. SD, standard deviation.

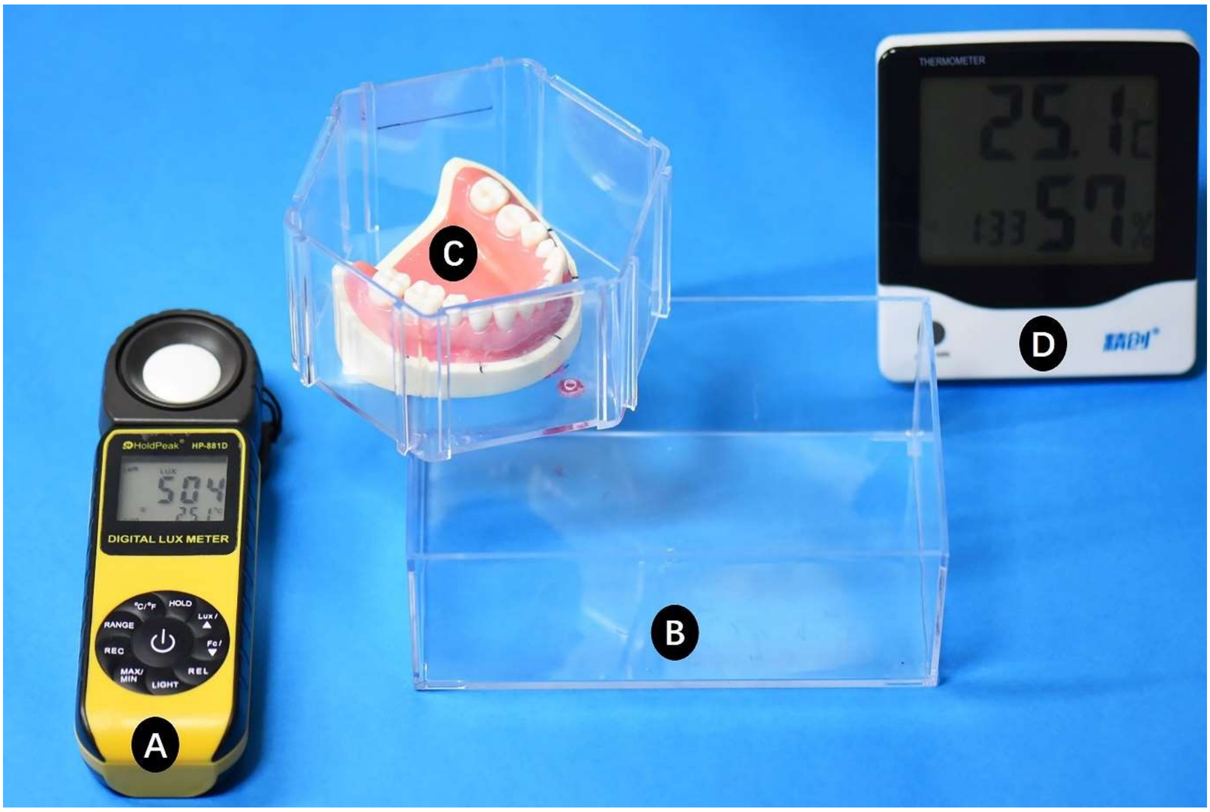


Figure 1. Overall view of scanning platform. (A) Digital lux meter. (B) Scanning platform. (C) Mandibular jaw model. (D) Temperature and humidity indicator

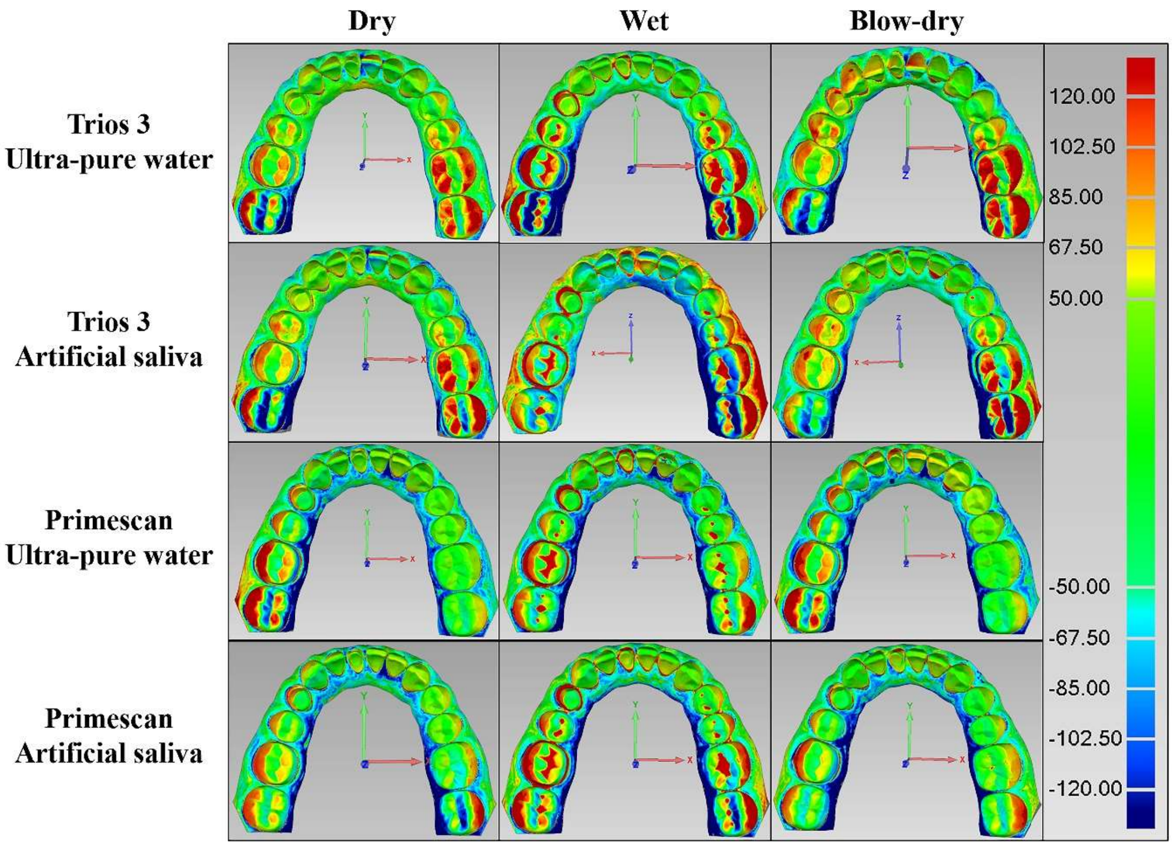


Figure 2. Typical color maps. Color maps showing the typical deviation distribution pattern between the reference the experimental scans in which different scanners and liquids were used under different conditions. The yellow-to-red area represents a positive deviation from the reference scan. The blue area represents a negative deviation from the reference scan. The green area indicates a small deviation between -50μm and +50μm from the reference scan. (Unit for color bar: μm)

Figure 3. The original maxillary jaw and three plaster models representing three spans (full arch, half arch, and three teeth).

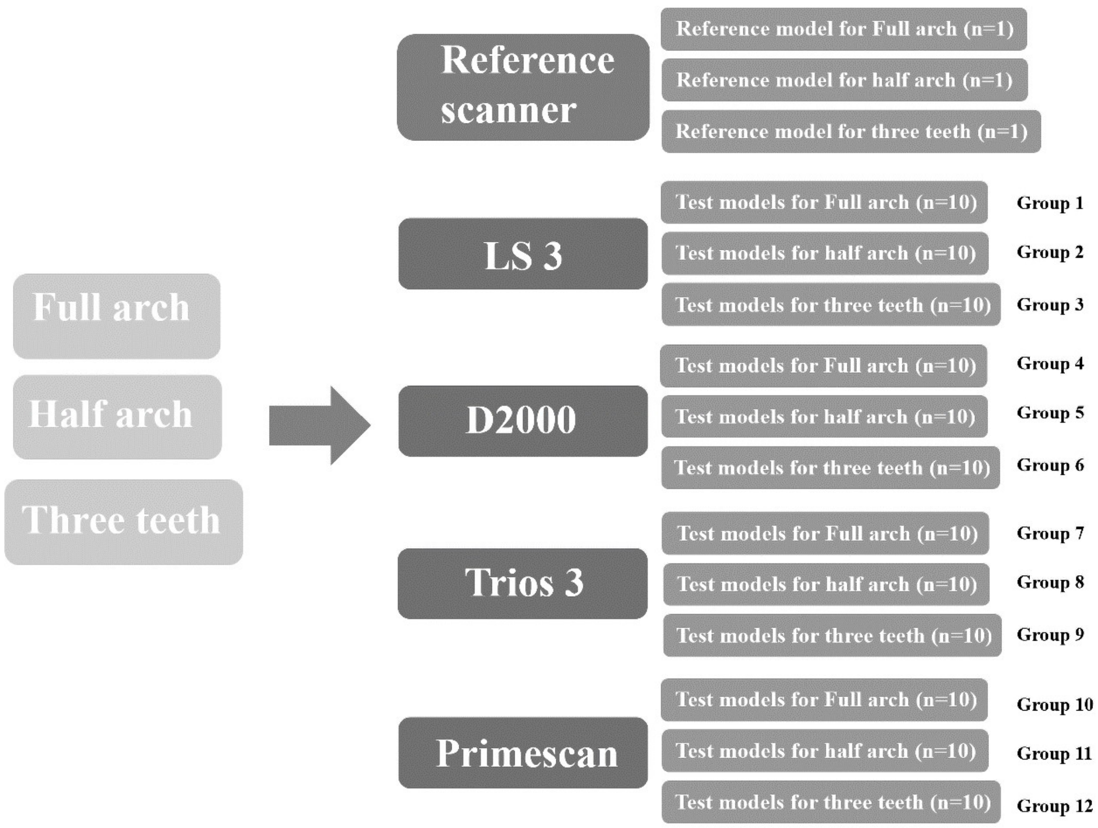


Figure 4. Scanning procedures.

Test model (T)	Reference model (R)
T1	R-T1
T2	R-T2
T3	R-T3
T4	R-T4
T5	R-T5
T6	R-T6
T7	R-T7
T8	R-T8
T9	R-T9
T10	R-T10

Comparison of all test models within one group with reference model (n=10).

Trueness

Test model (T)	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
T1		T1-T2	T1-T3	T1-T4	T1-T5	T1-T6	T1-T7	T1-T8	T1-T9	T1-T10
T2			T2-T3	T2-T4	T2-T5	T2-T6	T2-T7	T2-8	T2-T9	T2-T10
T3				T3-T4	T3-T5	T3-T6	T3-T7	T3-T8	T3-T9	T3-T10
T4					T4-T5	T4-T6	T4-T7	T4-T8	T4-T9	T4-T10
T5						T5-T6	T5-T7	T5-T8	T5-T9	T5-T10
T6							T6-T7	T6-T8	T6-T9	T6-T10
T7								T7-T8	T7-T9	T7-T10
T8									T8-T9	T8-T10
T9										T9-T10
T10										

Comparison of all the test models within one group by pairwise matching (n=45).

Precision

Figure 5. Trueness and precision evaluation.

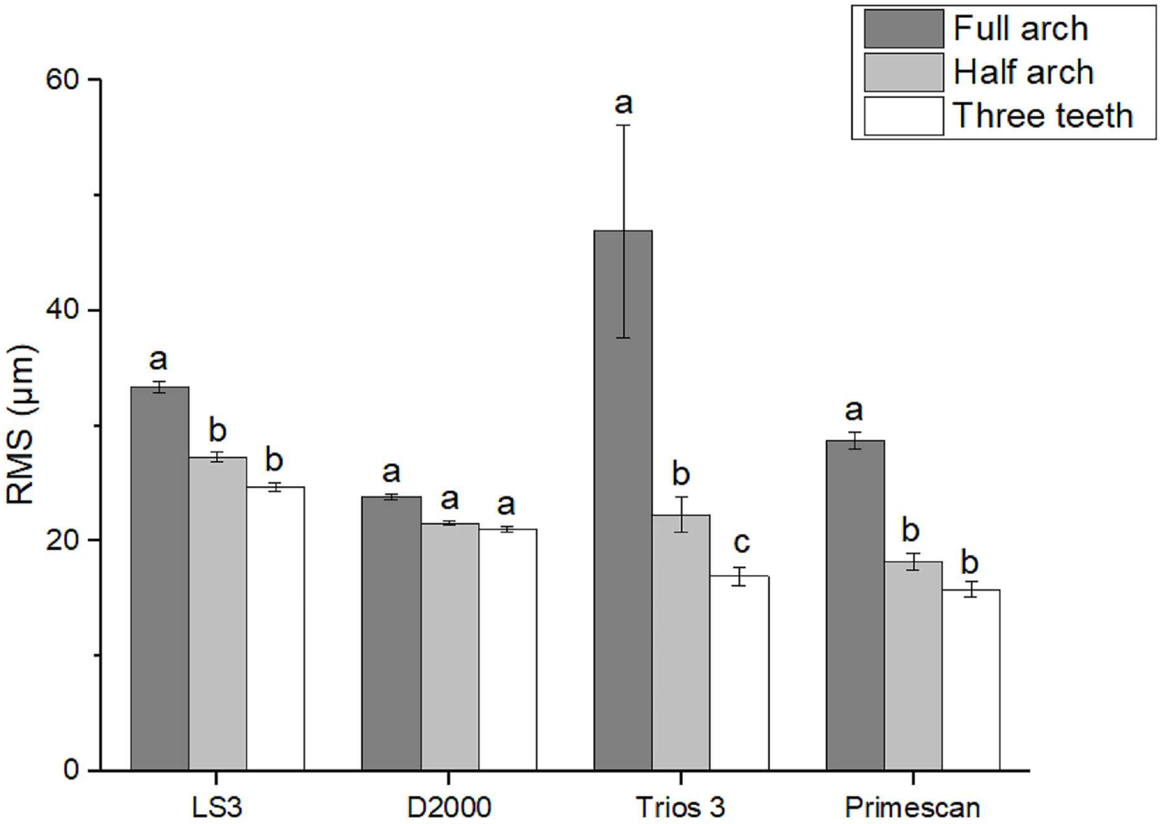


Figure 6. Trueness comparison of three scan spans for four scanners. RMS, root mean square. Groups with different lowercase letters indicate significant differences at $p < 0.05$.

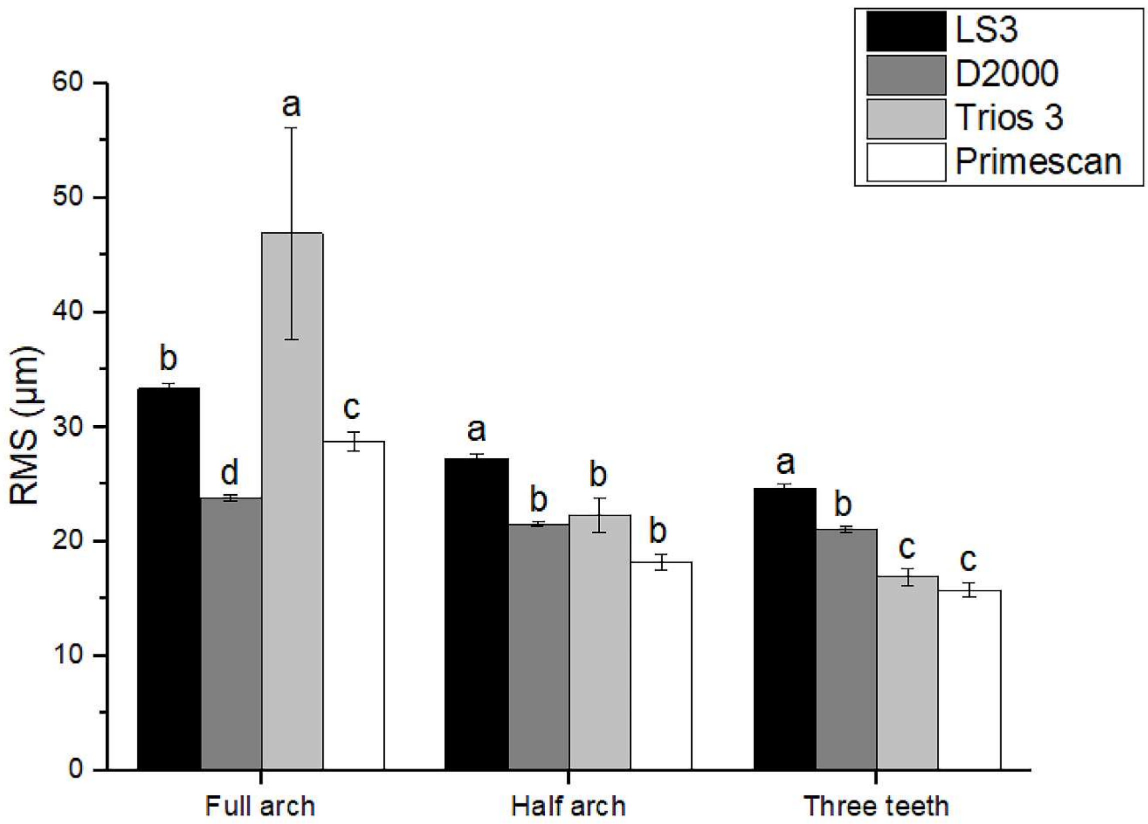


Figure 7. Trueness comparison of four scanners for three scan spans. RMS, root mean square. Groups with different lowercase letters indicate significant differences at $p < 0.05$.

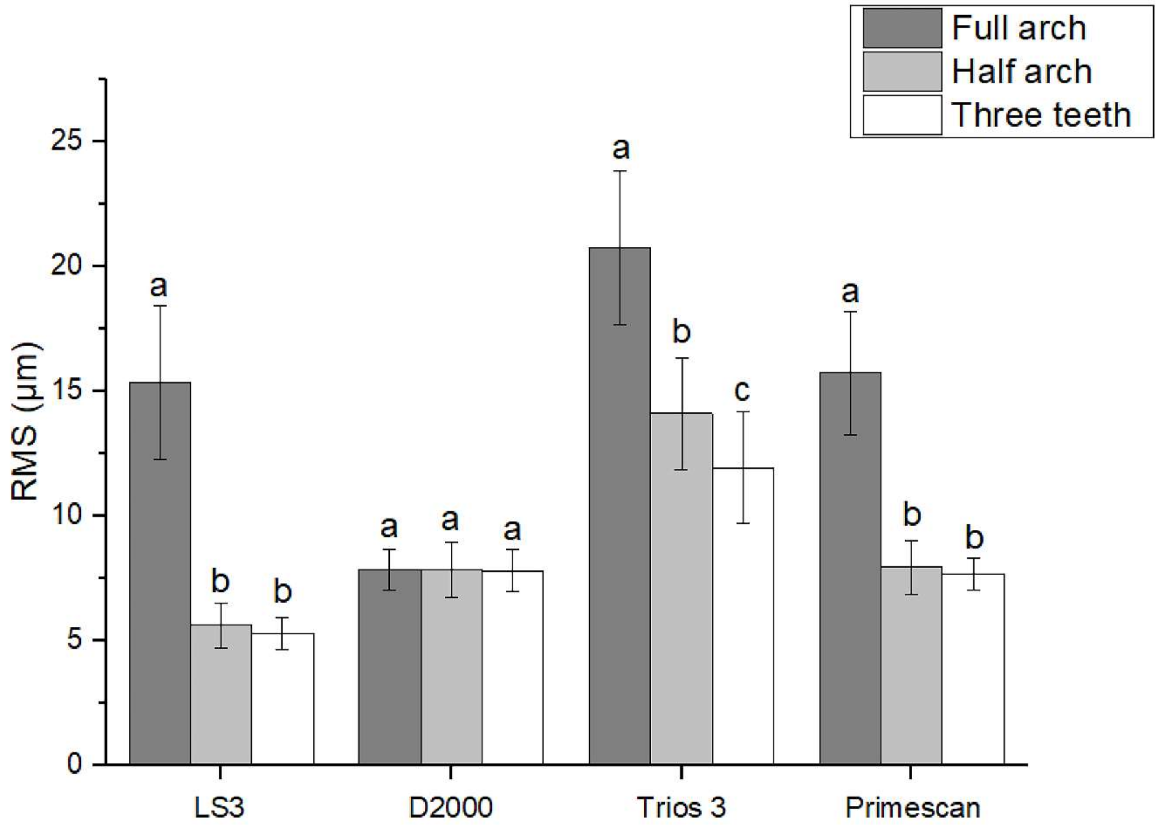


Figure 8. Precision comparison of three scan spans for four scanners. RMS, root mean square. Groups with different lowercase letters indicate significant differences at $p < 0.05$.

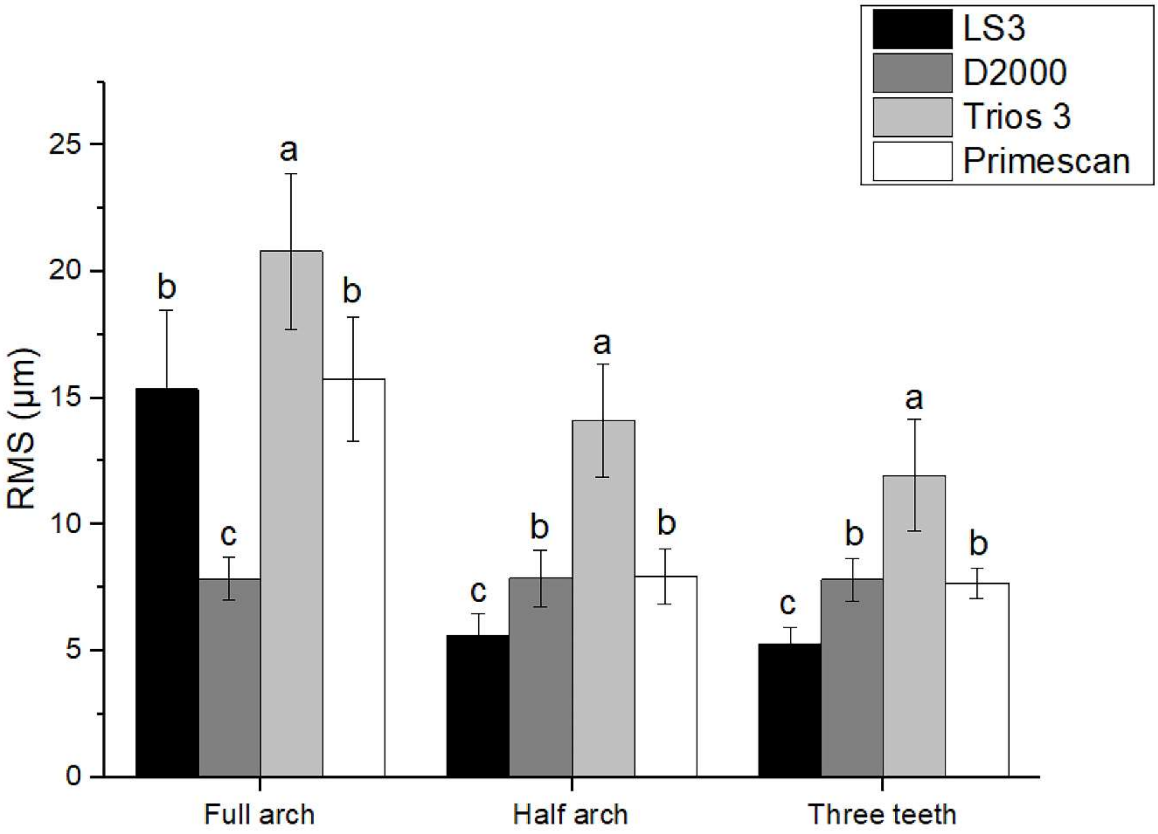


Figure 9. Precision comparison of four scanners for three scan spans. RMS, root mean square. Groups with different lowercase letters indicate significant differences at $p < 0.05$.

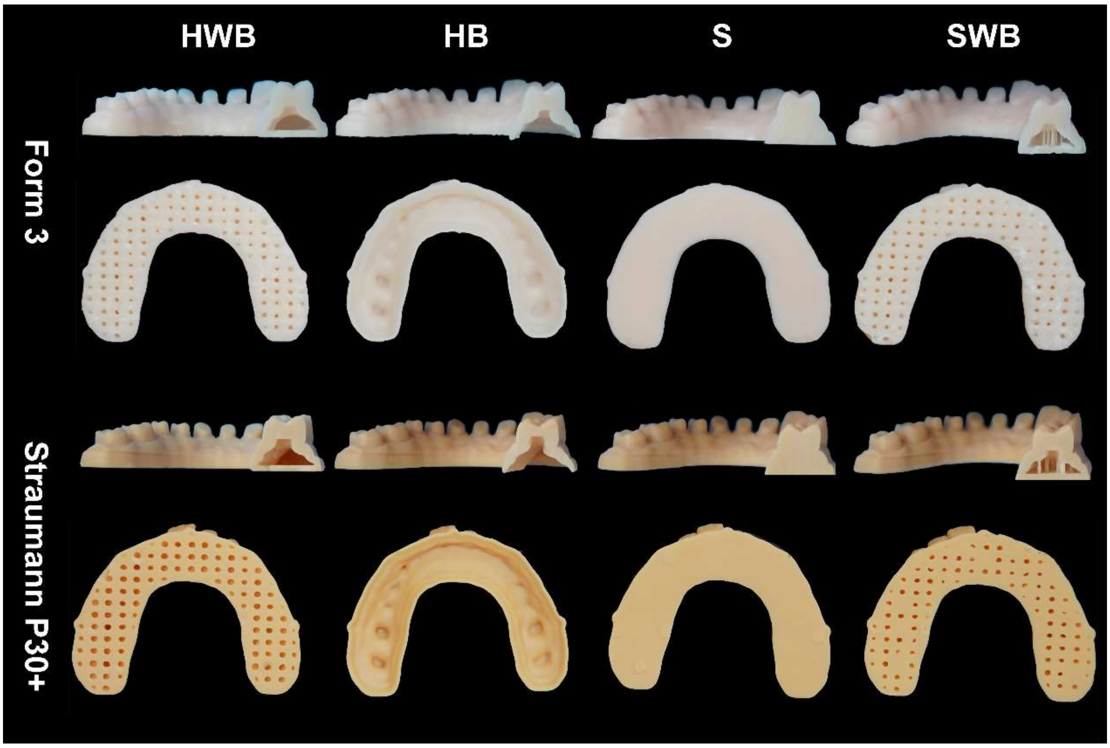
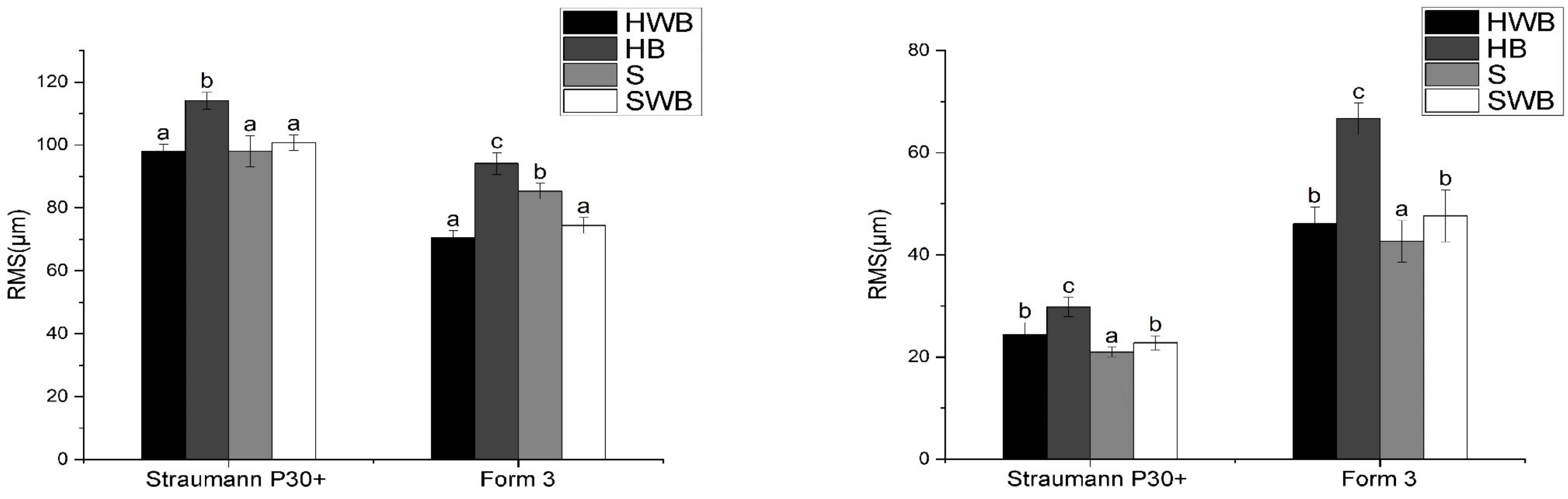


Figure 10. Transverse cross-section and top view of four different internal designs for dental casts printed by two different 3-dimensional printers.

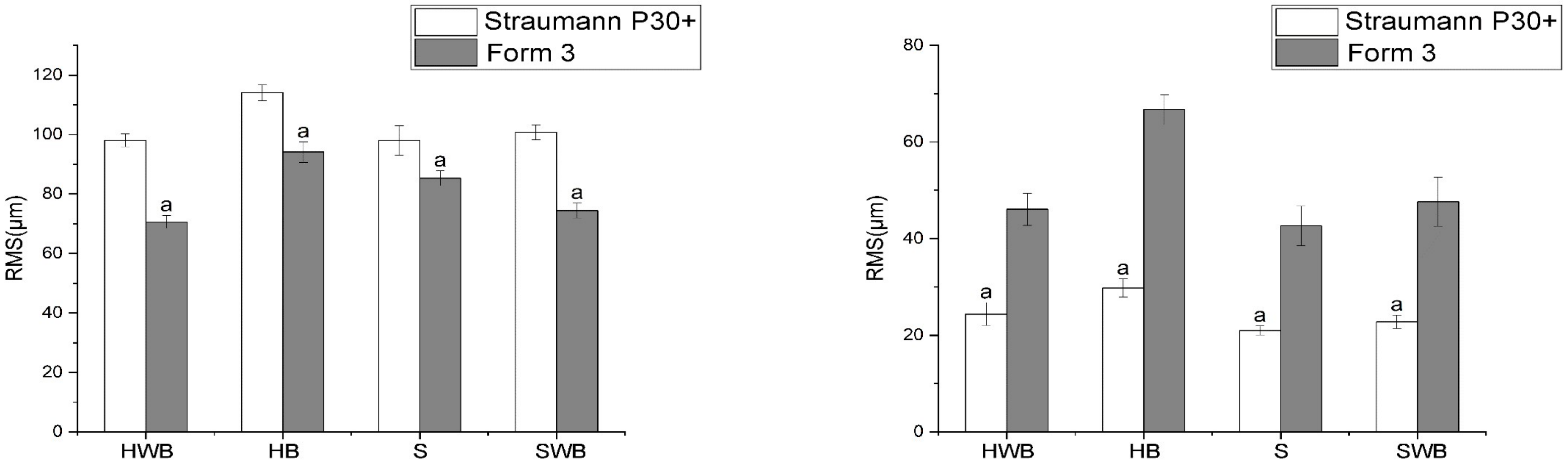


A B

Figure 11. Comparison of internal designs for different 3D printers. A: Trueness. B: Precision.

Groups with different lowercase letters indicate significant differences ($P < 0.05$).

HWB, hollow interior with perforated base; HB, hollow interior without base; S, all solid; SWB, internal support structure with perforated base; RMS, root mean square.



A B

Figure 12. Comparison of 3D printers for different internal designs. A: Trueness. B: Precision.

Groups with different lowercase letters indicate significant differences (P < 0.05).

HWB, hollow interior with perforated base; HB, hollow interior without base; S, all solid; SWB, internal support structure with perforated base; RMS, root mean square.