Original Article

Accuracy of three-dimensional printed models derived from cone-beam computed tomography

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ABSTRACT

Objectives: To determine the accuracy of three-dimensional (3D) printed models fabricated from cone-beam computed tomography (CBCT) scans of human mandibular dry skulls in comparison with models derived from intraoral scanner (IOS) data.

Materials and Methods: Six human mandibular dry skulls were scanned by IOS and CBCT. Digital models (DMs) constructed from the IOS and CBCT data were fabricated physically using a 3D printer. The width and thickness of individual teeth and intercanine and molar widths were measured using a digital caliper. The accuracy of the DMs was compared between IOS and CBCT. Paired *t*-tests were used for intergroup comparisons.

Results: All intraclass correlation coefficient values for the three measurements (mesial-distal, buccal-lingual, width) exceeded 0.9. For the mandibular teeth, there were significant discrepancies in model accuracy between the IOS (average discrepancies of 0.18 $\pm$ 0.08 mm and 0.16 $\pm$ 0.12 mm for width and thickness, respectively) and CBCT (0.28 $\pm$ 0.07 mm for width, 0.37 $\pm$ 0.2 mm for thickness; $P < .01$). Intercanine ($P = .38$) and molar widths ($P = .41$) showed no significant difference between groups.

Conclusions: There was a statistically significant difference in the accuracy of DMs obtained from CBCT and IOS; however, this did not seem to result in any important clinical difference. CBCT could be routinely used as an orthodontic diagnostic tool and for appliance construction. (*Angle Orthod.* 2022;92:722–727.)

KEY WORDS: 3D printed model; CBCT

INTRODUCTION

In general, the data required for orthodontic diagnosis are in the form of photographs, cast models, and radiographs, including panoramic and cephalometric radiographs, and recently, digital models (DMs) derived using an intraoral scanner (IOS) have become popular. The DM has several advantages over a cast model made from alginate impressions, including less physical space required for storage, cost-effectiveness, ready applicability for teledentistry, and more satisfied patient responses.[1,2] The use of DMs has expanded from diagnosis to treatment planning, including construction of set-up models[3] and indirect bonding systems.[4,5] From recent studies,[4,5] the use of three-dimensional (3D) printers has been reported in constructing indirect bonding trays; it would be useful if cone-beam computed tomography (CBCT) images could be used to construct these trays. Numerous studies have demonstrated the accuracy, validity, and reproducibility of DMs in comparison with cast models.[6–8]

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CBCT is another 3D technology commonly used in the specialty of orthodontics. Panoramic and cephalometric radiographs can be constructed from CBCT, but it also provides additional important 3D data such as root structure, position of the roots within bone, and cortical bone quantity, which cannot be obtained from two-dimensional radiographs. However, the ionizing radiation of CBCT may, in some settings, limit its use to patients such as those with impacted canines or those requiring orthognathic surgery. There must be strong evidence that CBCT can provide substantial information for diagnosis and treatment planning if it is to be routinely used in the orthodontic clinic.

Many studies have shown that CBCT can also provide accurate DMs for dental measurements.[9–11] Thus, model analysis can be performed on CBCT-derived DMs. However, no study has investigated the accuracy of actual models printed from CBCT-derived DMs. If CBCT data could be used to print DMs accurately, appliance construction could be possible from the CBCT data without the need for an IOS. However, because there may be some errors in the 3D printing procedure, 3D printed models may not be accurate enough to use for the same purposes as cast models.

The null hypothesis of this study was that there would be no significant differences in tooth size and arch width measurements between IOS- and CBCT-based 3D printed models of human mandibular dry skulls.

MATERIALS AND METHODS

Six human (three male and three female) mandibular dry skulls of ages ranging from 40.0 to 58.0 years (average age ± standard deviation [SD], 50.6 ± 7.6 years) donated to The Ohio State University College of Medicine were used in this study. All mandibles had at least 12 permanent teeth (a maximum of two missing teeth, excluding third molars). The mandibles were scanned using a TRIOS scanner (3Shape, Copenhagen, Denmark), and the DMs (IOS DM) were created with OrthoAnalyzer software (3Shape, Copenhagen, Denmark). The same mandibles were also scanned with CBCT (ProMax 3D Mid; Planmeca, Roselle, Ill) using an ultra-low dose (ULD) setting with 90 kV, 7.1 mA, 12.389 seconds, and a 200-μm voxel size. Images in CBCT Digital Imaging and Communications in Medicine format were then segmented using ITK-SNAP (Penn Image Computing and Science Laboratory) to construct the CBCT DMs. The IOS DMs and CBCT DMs were superimposed in 3D slicer (an open-source platform for medical image analysis published by the Slicer Community) via the SlicerCMF project (http://cmf.slicer.org).[12] The mesh deviations (vertex distances) between the two DMs were evaluated using the Visualization Toolkit (http://www.vtk.org/doc/release/6.2/html/) and visualized by subsequent color displacement maps ranging from −1 mm to 1 mm constructed using Paraview,[13] as shown in Figure 1. The mean and SD of the between-DM vertex distances within the range from −1 mm to 1 mm were calculated.

Then, both the IOS DM and CBCT DM images were converted to stereolithography (STL) format for 3D printing using Form2 (Formlabs, Somerville, Mass) with Grey V4 resin. The printer was maintained on a regular basis following Formlabs' guides. The printing layer thickness was 50 μm. The postprocessing operation and setting (ie, washing uncured resin and second curing) were followed according to Formlabs' instructions. The width and thickness of individual teeth and intercanine and molar widths were measured directly from the right second molar to the left second molar (Figure 2) at a resolution of 0.01 mm using a Mitutoyo (Kawasaki, Japan) electronic vernier digital caliper.

Statistical Analysis

All data were analyzed using SPSS (version 16.0; IBM Corp., Armonk, NY). Two examiners followed the same measurement procedures for the six dry skulls. Repeated measurements were performed after a 2-week interval by both examiners. Intraclass correlation coefficients (ICC) were calculated to determine inter- and intraexaminer reliability. After determining the interexaminer reliability, the tooth widths of the same teeth measured by the two examiners were collected, and the mean values were calculated. Measurements of each tooth from the actual mandibles (direct measurement) were compared with those from the 3D printed models based on IOS and CBCT DMs. Paired *t*-tests were used to compare values measured from human mandibles, printed IOS DMs, and CBCT DMs. The significance level was set at $P < .05$.

RESULTS

The ICCs for intraexaminer reliability were 0.995, 0.988, 0.963, and 0.993 for mesial-distal, buccal-lingual, intercanine, and intermolar widths, respectively, whereas the corresponding values for interexaminer reliability were 0.995, 0.958, 0.937, and 0.984, respectively.

Superimposition

The superimpositions of the IOS and CBCT DMs showed an average difference of 0.19 ± 0.03 mm

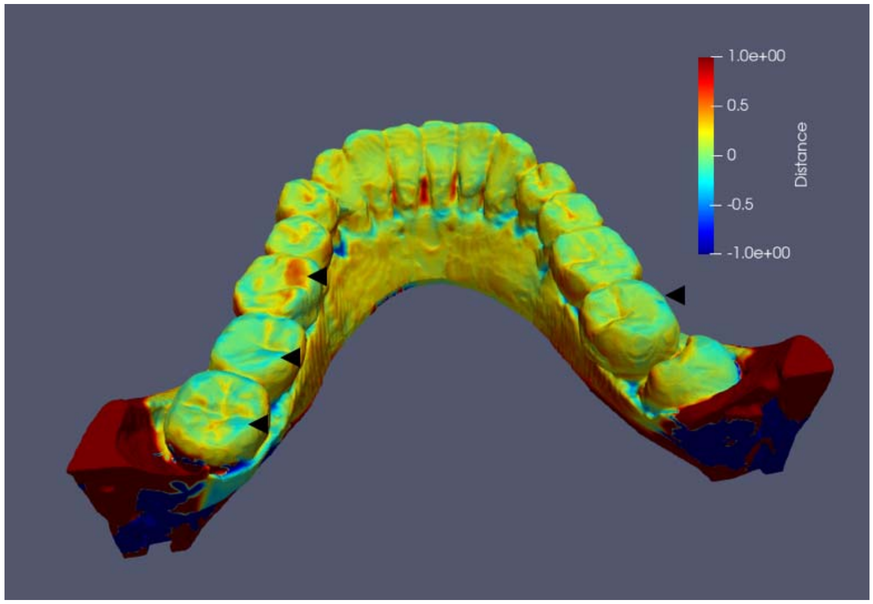

Figure 1. Color map superimposition between IOS and CBCT DMs. Notice the deviation from 0.5–1.0 mm (arrowhead) mainly at the molar area.

(Figure 1). Most of the deviation was observed in the molar area.

Comparison of Tooth Size

The average differences in mesial-distal width and buccal-lingual width measurements between the mandibular dry skulls and the IOS DM were 0.18 $\pm$ 0.08 mm and 0.16 $\pm$ 0.12 mm, respectively, whereas between the dry skulls and CBCT DM, they were 0.28 $\pm$ 0.07 mm and 0.44 $\pm$ 0.18 mm ($P < .05$), respectively (Table 1). The average difference in mesial-distal width and buccal-lingual width measurements between the IOS DM and CBCT DM were 0.10 $\pm$ 0.10 mm and 0.29 $\pm$ 0.08 mm, respectively. Both mesial-distal and buccal-lingual measurements showed significant differences between the printed ISO and CBCT DMs ($P < .05$).

Comparison of Width Analysis

The measured intercanine and intermolar widths were 0.29 $\pm$ 0.29 mm and 0.29 $\pm$ 0.37 mm, respectively, for ISO DMs, and 0.50 $\pm$ 0.49 mm and 0.44 $\pm$ 0.48 mm for CBCT DMs (Table 2). None of the differences were statistically significant ($P > .05$).

DISCUSSION

Clinical studies demonstrated that 3D printing can be used for fabrication of orthodontic appliances.[14,15] Studies also indicated that the accuracy of a 3D printed model largely depended on the type of printing device and that errors attributed to discrepancies in the model were mostly not of clinical significance.[16,17] In the contemporary digital era, orthodontists begin with an IOS, construct a DM, and then print the DM and fabricate custom appliances, including clear aligners, indirect bonding trays, and removable intraoral appli-

Figure 2. Canine and molar width (red line) was measured from the mandibular dry skulls (A), printed IOS DMs (B), and CBCT DMs (C).

Table 1. Differences in Tooth Size

	Mesial-distal Width (mm)						Buccal-lingual Width (mm)					
	Direct Scan		Direct CBCT		CBCT Scan		Direct Scan		Direct CBCT		CBCT Scan	
Tooth No.	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
47	0.27	0.22	0.28	0.26	0.02	0.05	0.27	0.34	0.49	0.55	0.11	0.21
46	0.14	0.18	0.35	0.31	0.22	0.12	0.10	0.14	0.73	0.49	0.78	0.35
45	0.17	0.12	0.25	0.30	0.10	0.18	0.05	0.06	0.26	0.21	0.20	0.14
44	0.35	0.63	0.40	0.92	0.18	0.30	0.09	0.09	0.46	0.22	0.38	0.13
43	0.13	0.11	0.37	0.36	0.24	0.25	0.11	0.04	0.27	0.20	0.15	0.16
42	0.11	0.10	0.21	0.23	0.12	0.12	0.10	0.03	0.41	0.19	0.23	0.16
41	0.14	0.07	0.24	0.22	0.10	0.14	0.29	0.64	0.48	0.21	0.19	0.43
31	0.16	0.13	0.22	0.17	0.06	0.04	0.41	0.76	0.41	0.17	0.00	0.59
32	0.13	0.13	0.22	0.22	0.07	0.09	0.20	0.38	0.53	0.55	0.31	0.17
33	0.13	0.07	0.33	0.35	0.20	0.27	0.11	0.16	0.30	0.17	0.19	0.01
34	0.29	0.40	0.35	0.13	0.05	0.27	0.12	0.06	0.47	0.34	0.34	0.28
35	0.10	0.11	0.20	0.15	0.06	0.04	0.11	0.08	0.35	0.21	0.24	0.13
36	0.17	0.20	0.32	0.27	0.16	0.07	0.09	0.03	0.68	0.30	0.54	0.27
37	0.23	0.25	0.23	0.23	0.00	0.02	0.16	0.06	0.33	0.20	0.27	0.14
Mean	0.18	0.08	0.28[a]	0.07	0.10	0.10	0.16	0.12	0.44[a]	0.18	0.29	0.08

[a] Statistically significant difference between scanned digital model ($P < .05$).

ances. Improvements in practice workflow and efficiency in the clinical setting are key features provided by the DM.

As imaging modalities, IOS and CBCT help to improve the orthodontist's diagnostic ability and boost practice capabilities. The current results showing high intrarater and interrater reliability demonstrated that both IOS- and CBCT-based 3D printed models allow reliable and reproducible tooth size and arch width measurements. These results were in agreement with those of a recent study that investigated the accuracy of printed DMs obtained from an IOS and suggest that the methods are clinically acceptable and could be considered viable options for clinical applications.[17]

There was an average difference of 0.18 mm in mesial-distal width and 0.16 mm in buccal-lingual width produced by the IOS DM compared with the actual teeth. In general, most of the measurements of the printed DM were slightly larger than those made on the actual teeth. This was also shown in a past study that compared tooth width between plaster and printed models.[16] These findings indicated that printed models tend to be produced slightly larger than actual size. The difference in the current study also seemed to be somewhat larger than that observed in a past study, which showed mean differences of 0.09 mm in mesial-distal width and 0.10 mm in buccal-lingual width between plaster models and digital printed models made using the same type of printer (STL).[18] The reason for the larger measurements in the current study may have been because the previous study used an extraoral model scanner, which is more accurate than an IOS.[19] In addition, accuracy seems to vary even with the same type of SLA printer. However, it was noted that a mean difference of 0.27 mm in a DM would not have an important clinical impact.[20] Other studies indicated that, for orthodontic purposes, a difference of 0.3 mm could be considered as clinically insignificant,[21] whereas a threshold difference of 0.5 mm in tooth size would be clinically relevant.[22]

Table 2. Differences in the Intercanine and Intermolar Width[a]

	Direct Scan		Direct CBCT		
	Average	SD	Average	SD	Statistic
Intercanine distance (mm)	0.29	0.29	0.50	0.49	NS
Intermolar distance (mm)	0.29	0.37	0.44	0.48	NS

[a] NS indicates not significant.

Interarch widths measured on the IOS DM resulted in a 0.29-mm difference in both intercanine and intermolar distances. The interarch distance values measured were always greater than those of tooth width, as reported in a past study that found intercanine and intermolar width discrepancies of 0.07 mm and 0.18 mm, respectively.[18] Again, the use of an IOS rather than an extraoral scanner and differences in the type of printing devices may have resulted in the discrepancies between the results of the two studies. Sweeney et al. stated that an interarch distance with an error of less than 0.5 mm was acceptable.[23] In addition, because the error of TRIOS is known to be about 40–90 μm,[24] and the printer error of Form2 is approximately 70 μm,[25] the data were similar if these two errors are additive (0.1–0.2 mm).

No previous study has investigated the accuracy of printed CBCT DMs. High accuracy of CBCT printed models is important because, if models can be obtained directly from CBCT for cast analysis and appliance construction, an IOS may not be necessary.

The voxel size is the major factor in CBCT segmentation and affects the accuracy of reconstructed models significantly. To minimize its influence on the accuracy of printed CBCT DMs, the voxel spacing was set to 200 μm isotopically, which was the finest resolution available in the CBCT scanner used in this study. This value could be considered as a high-quality setting in CBCT images. The current study assessed the average differences in mesial-distal and buccal-lingual widths to be 0.28 mm and 0.44 mm, respectively, for the CBCT DM. The width measurements based on CBCT DMs also resulted in larger values than the actual tooth widths, with significant differences in both mesial-distal and buccal-lingual widths compared with the IOS DM, indicating that the CBCT DMs were less accurate than the IOS DMs. A past study observed differences of −0.45 to 0.14 mm between DM and direct measurements of CBCT images.[26] Another study that compared linear measurements between CBCT DMs and OrthoCad (3Shape, Copenhagen, Denmark) DMs found maximum mean differences between 0.44 and 0.62 mm.[11,27,28] In the current study, an average difference of 0.2 mm was found in the superimposition data between the IOS DMs and CBCT DMs. As the CBCT DMs required segmentation to convert the imaging data to an STL file for printing, this process may have been responsible for some of the errors compared with the IOS DMs. However, the differences measured in this study were similar to those reported in previous studies, indicating that the errors from the 3D printing of the CBCT DMs were minimal and would be without substantial clinical impact.

The CBCT DM resulted in a 0.5-mm difference in intercanine width and a 0.44-mm difference in intermolar width compared with the actual width of the mandibular arch. The accuracy of the linear measurements between the CBCT-derived DM and OrthoCad DM for the mandible ranged from 0.34 to 0.61 mm, with a median of 0.44 mm in a previous study.[28] If the amount of error of the printer (Form2) of about 70 μm[25] was added in, the total would be similar to the values in the current results. Thus, the current data from the printed CBCT DMs were also consistent with linear measurements in a previous study. In another study, the differences between CBCT measurements and a DM derived from IOS were 1.65 mm for intercanine width and 1.13 mm for intermolar width.[26] The larger discrepancies in linear measurements may be related to the use of different CBCT scanner (the previous study used an i-CAT (Imaging Sciences International, Hatfield, PA) system) and also the lower resolution (400 μm) used in the previous study compared with that used in the current study (200 μm). A voxel resolution of at least 200 μm is recommended to provide an acceptable degree of accuracy for the printed DM. However, it must be considered that radiation exposure should be maintained to be as low as possible while increasing the resolution. The CBCT scanner used in the current study provides a setting called ULD, which reduces the radiation exposure to one-fifth that of the normal setting.

Limitations of this Study

A limitation of the study was that dry skulls were used instead of live samples. In live patients, soft tissue and other variables associated with the intraoral environment may influence the accuracy of DMs. The soft tissue especially causes scattering radiation, affecting the gray-level value differentiation, and may lower bone image quality. A past study that compared the measurements of human dry skulls between cadavers concluded that the difference was less than a generally accepted level of clinical significance of about 1.0 mm in the mandible.[29] From an ethical point of view, it is difficult to obtain full jaw (maxilla and mandible) CBCT data from patients. However, if CBCT-derived DMs are shown to be accurate enough to be used as diagnostic tools and for constructing appliances, it may be justifiable to obtain the necessary CBCT scans in routine practice.

CONCLUSIONS

- The results of this study showed that there were significant differences in individual tooth measurements between IOS- and CBCT-derived DMs but that these differences would not be clinically important or affect their use in orthodontic diagnostic models.
- Therefore, accurate model analysis and appliance construction could be possible from CBCT images without the use of IOS.

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