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Original Article

Linear accuracy of 3D-printed mandibular models fabricated from cone-beam computed tomography scans with two different voxel sizes

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ABSTRACT

Background: This study assessed the linear accuracy of three-dimensionally (3D)-printed mandibular models from cone-beam computed tomography (CBCT) scans with two voxel sizes.
Materials and Methods: In this *in vitro* study, five dry human mandibles underwent CBCT with 0.2- and 0.3-mm voxel sizes. The images were converted to STL format, and the distances between (I) mental foramen (MF) and alveolar ridge crest, (II) MF and inferior border of the mandible (IBM), and (III) alveolar crest and IBM at the midline, as well as the (IV) left central incisor socket depth, (V) left second premolar buccolingual socket width, and (VI) right third molar buccolingual socket width were measured on the CBCT scans, 3D-printed models, and dry mandibles. Two observers recorded the measurements twice, 1 week apart. We analyzed the data using the intraclass correlation coefficient and Pearson's correlation test. Statistical significance was set at $P < 0.05$.
Results: Since the interobserver agreement was high, the mean data was used for the comparisons. The linear accuracy was high for MF-IBM, MF-alveolar crest, and alveolar crest-IBM distances, and second premolar and third molar buccolingual socket width. CBCT scans demonstrated reliable accuracy for left central incisor socket depth measurement, but a lack of significant correlation was found between the 3D-printing and gold-standard measurements of this variable.
Conclusion: The linear accuracy of CBCT scans taken with 0.3- and 0.2-mm voxel sizes was comparable, and they may be used for the fabrication of linearly accurate 3D-printed models of mandible. 3D-printed models demonstrated high precision in all measured parameters except socket depth.

Key Words: 3D Printing, cone-beam computed tomography, dimensional measurement accuracy, imaging, mandible, three-dimensional

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INTRODUCTION

Cone-beam computed tomography (CBCT) is currently the most widely used three-dimensional (3D) imaging

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modality in dentistry with extensive applications in orthodontics, endodontics, pediatric dentistry, oral and maxillofacial surgery, and implantology.[1-3] CBCT has several advantages over CT; for instance, the voxel of CBCT scanners can be changed mechanically or electronically in horizontal and vertical dimensions.[4] Evidence shows that the CBCT scanning and image reconstruction parameters such as the voxel size and field of view (FOV) can significantly affect the quality of the reconstructed images of the 3D model of dental arch.[5,6]

Three parameters of length, width, and height define the size of each voxel. The CBCT voxels are usually isotropic (the aforementioned three parameters are the same). The voxel size of a 3D image is equal to the pixel resolution of a 2D image. For instance, 300 ppi resolution corresponds to 0.085 mm voxel size. Smaller voxel sizes produce sharper images but expose patients to higher radiation doses than those taken with a larger voxel size; nonetheless, the final diagnosis may be the same as that made according to lower resolution images.[7]

The pixel size is often smaller in smaller FOVs; thus, images have a higher resolution; such images are suitable for endodontic purposes. A previous study assessed the effect of different voxel sizes of CBCT scanners on the linear accuracy and found no significant difference in measurement accuracy of different scanners; however, due to higher radiation dose of scanners with a smaller voxel size, their application must be done with caution.[8] Whyms *et al*.[9] reported high linear and angular accuracy of measurements made on 3D-printed models of mandible from CT scans, irrespective of FOV, slice thickness, and other parameters. Vijayan and Allareddy[8] found no significant difference in accuracy of measurements made on 3D-printed models from CBCT data with different voxel sizes. However, to the best of the authors' knowledge, no previous study with a sample size larger than 2 is available on the effect of voxel size on linear accuracy of 3D-printed models from CBCT scans.[8] Therefore, this study aimed to assess the linear accuracy of 3D-printed models from CBCT scans with two different voxel sizes. The null hypothesis is there is no statistically significant difference in the linear accuracy of 3D-printed mandibular models fabricated from CBCT scans using different voxel sizes (0.2 mm vs. 0.3 mm).

MATERIALS AND METHODS

This *in vitro* experimental study included five dry human mandibles. Ethics approval was obtained from the Isfahan University of Medical Sciences (Approval Code: IR. MUI. RESEARCH. REC.1400.394).

Sample size

The sample size was calculated to be 10 assuming alpha = 0.05, beta = 0.2, and study power of 80% using the sample size calculation formula.

Cone-beam computed tomography

The dry mandibles underwent CBCT (Scanora; Soredex, Finland) with 61 mm × 78 mm FOV once with a 200-µm voxel size and once with a 320-µm voxel size. The 3D data were then converted to STL format by the Slicer software, and 3D-printing was performed by Umbriel3d 300 × 3D printer (Iran) by the fused deposition modeling technique.

To assess the linear measurement accuracy, the following six distances were measured on each 3D-printed model [Figure 1], on CBCT scans in OnDemand software (Cybermed, Seoul, South Korea) [Figure 2], and also on dry human mandibles by a digital caliper (abzarsharif, Tabriz, Iran) [Figure 1].

(I) Distance between mental foramen (MF) and alveolar ridge crest
(II) Distance between MF and inferior border of the mandible (IBM)
(III) Distance between alveolar crest and IBM at the midline
(IV) Socket depth of the left central incisor
(V) Buccolingual width of the left second premolar tooth socket
(VI) Buccolingual width of the right third molar tooth socket.

Two observers made the measurements twice in consecutive weeks and the intra- and interobserver agreements were calculated.

Statistical analysis

We analyzed the data by SPSS version 22 (IBM, NY, USA) using the interclass correlation coefficient and the Pearson's correlation test at 0.05 level of significance.

RESULTS

Table 1 presents the mean linear distances measured on 3D-printed models and CBCT scans with small

Figure 1: Measurements made on cross-sectional cone-beam computed tomography images.

Figure 2: Measurements made on dry human mandible and 3D printed model by a digital caliper and manual file.

and large voxel sizes. The intra- and interobserver agreements were >0.990 ($P < 0.05$). Thus, the mean data of the two observers were calculated and used for subsequent statistical analyses [Figure 3].

Distance between mental foramen and inferior border of the mandible

Measurement of the distance between MF and IBM had high precision on 3D-printed models and CBCT scans with different voxel sizes [Table 2].

Distance between mental foramen and alveolar ridge crest

Measurement of the distance between MF and alveolar ridge crest had high precision on 3D-printed models and CBCT scans with different voxel sizes [Table 2].

Left central incisor socket depth

Measurement of the left central incisor socket depth had high precision on CBCT scans with different voxel sizes. However, the measurements recorded on other modalities had a lack of significant correlation with each other ($P > 0.05$, Table 2).

Distance between alveolar crest and inferior border of the mandible

Measurement of the distance between alveolar crest and IBM had high precision on 3D-printed models and CBCT scans with different voxel sizes [Table 2].

Second premolar buccolingual socket width

Measurement of the second premolar buccolingual socket width had high precision on 3D-printed models and CBCT scans with different voxel sizes [Table 2].

Third molar buccolingual socket width

Measurement of the third molar buccolingual socket width had high precision on 3D-printed models and CBCT scans with different voxel sizes [Table 2].

DISCUSSION

This study assessed the linear accuracy of 3D-printed models from CBCT scans with two different voxel sizes. The results showed acceptable linear accuracy of CBCT scans taken with large and small voxel

Table 1: Mean linear distances (mm) measured on three-dimensional-printed models and cone-beam computed tomography scans with small and large voxel sizes

Distances (mm)	Dry mandible (mm)		CBCT-small voxel size (mm)		CBCT-large voxel size (mm)		3D-printed model-small voxel size (mm)		3D-printed model-large voxel size (mm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
MF-IBM	13.86	1.58	12.70	1.48	12.82	1.55	13.78	1.57	13.75	1.53
MF-alveolar crest	15.18	1.14	13.60	1.11	13.73	1.12	14.58	1.12	14.55	1.21
Left central incisor socket depth	12.55	0.88	12.53	0.94	12.55	0.82	5.42	0.82	5.43	0.08
Alveolar crest-IBM	32.90	5.19	32.93	5.10	32.80	5.06	32.91	5.08	32.88	5.13
Buccolingual width of second premolar socket	6.93	1.27	6.46	1.17	6.89	1.28	6.48	1.48	6.46	1.42
Buccolingual width of third molar socket	9.27	0.25	9.25	0.32	9.3	0.29	9.36	0.22	9.35	0.26

MF: Mental foramen; IBM: Inferior border of the mandible; SD: Standard deviation; CBCT: Cone-beam computed tomography; 3D: Three-dimensional

Table 2: Coefficient of agreement between different modalities for the measured linear distances

Compared modalities	MF-IBM		MF-alveolar crest		Left central incisor socket depth		Alveolar crest-IBM		Second premolar buccolingual width		Third molar buccolingual width	
	Coefficient of agreement	*P*	Coefficient of agreement	*P*	Coefficient of agreement	*P*	Coefficient of agreement	*P*	Coefficient of agreement	*P*	Coefficient of agreement	*P*
CBCT with small voxel size-gold standard	0.998	0.000	0.997	0.000	0.986	0.001	0.999	0.000	0.822	0.062	0.952	0.006
CBCT with large voxel size-gold standard	0.999	0.000	0.996	0.000	0.996	0.000	0.998	0.000	0.999	0.000	0.987	0.001
3D-printed model with small voxel size-gold standard	0.999	0.000	0.920	0.016	0.36	0.513	0.999	0.000	0.993	0.000	0.908	0.020
3D-printed model with large voxel size-gold standard	0.999	0.000	0.955	0.005	0.048	0.482	0.999	0.000	0.997	0.000	0.947	0.007
CBCT with small voxel size-CBCT with large voxel size	0.999	0.000	0.999	0.000	0.989	0.000	0.999	0.000	0.823	0.061	0.960	0.004
CBCT with small voxel size-3D printed model with small voxel size	0.999	0.000	0.934	0.011	0.013	0.505	0.999	0.000	0.779	0.086	0.845	0.049
CBCT with large voxel size-3D printed model with large voxel size	0.999	0.000	0.970	0.003	0.075	0.471	0.999	0.000	0.997	0.000	0.963	0.004

MF: Mental foramen; IBM: Inferior border of the mandible; CBCT: Cone-beam computed tomography; 3D: Three-dimensional

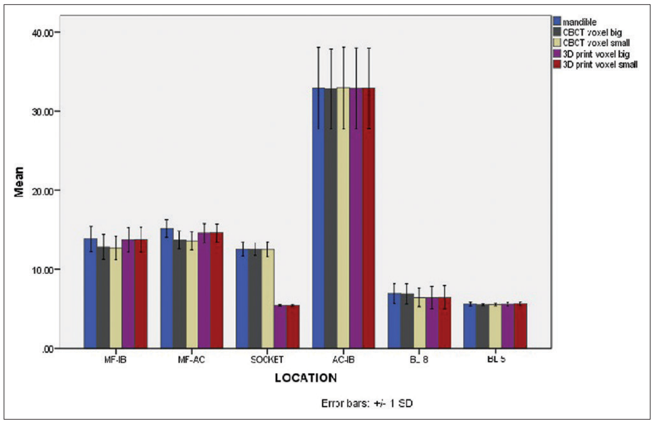

Figure 3: Mean distances measured on dry human mandibles, 3D printed models, and cone-beam computed tomography scans with small and large voxel sizes.

sizes, and also the 3D printed models; the only exception was the left central incisor socket depth for which the measurement made on the 3D-printed model did not match the measurements recorded on dry mandibles and CBCT scans. Therefore, our results report that the null hypothesis was rejected for socket depth measurements but accepted for all other linear measurements.

Al-Ekrish and Ekram[3] compared the accuracy and reliability of CBCT with 0.3 mm voxel size and large FOV for evaluation of implant site dimensions. They reported that measurements made on CBCT scans were significantly more accurate than those made on CT scans. The present results regarding the acceptable linear accuracy of CBCT were in agreement with their findings. Sharifi *et al*.[10] compared the diagnostic accuracy of CBCT and periapical radiography for detection of internal root resorption defects and reported that CBCT measurements were in complete agreement with the actual values in all parameters; however, periapical radiography had a moderate agreement and significant differences with the actual values in some cases, especially in defects located in the apical third of the root. Their results regarding optimal accuracy of CBCT measurements were in line with the present findings. Kamburoğlu *et al*.[11] evaluated the effect of CBCT voxel size (0.1, 0.2, and 0.3 mm) on detection of occlusal caries in experimental models, and reported comparable accuracy of all tested voxel sizes for this purpose with no significant difference among them, which was in accordance with the present results. Liedke *et al*.[12] observed CBCT images of 59 teeth taken with 0.2-, 0.3-, and 0.4-mm voxel sizes for detection of external root resorption defects and concluded that CBCT is a reliable imaging modality for detection of external root resorption defects, and 0.3 mm voxel size appeared to be the most suitable for this purpose due to optimal diagnostic accuracy and lower radiation exposure. Hekmatian *et al*.[13] evaluated the effect of voxel size (0.15 and 0.3 mm) on measurement accuracy of mandibular thickness in 16 mandibles and 7 different landmarks on CBCT scans. They found no significant difference in measurement accuracy of the two voxel sizes and therefore recommended the larger voxel size to minimize unnecessary radiation exposure. Their results were also in agreement with the present findings. Primo *et al*.[14] assessed the accuracy of 3D-printed models from multislice-CT (0.3 mm pixel size) and CBCT (0.25- and 0.4-mm voxel sizes). They found no significant difference in the mean dimensional accuracy of the models, and all models had acceptable dimensional accuracy. Their results were in accordance with the present findings, confirming the acceptable linear accuracy of CBCT. Zhang *et al*.[15] evaluated the accuracy of 3D-printed models from CBCT scans. The models were printed by the fused deposition modeling technique. They measured the tooth width, length and width of maxillary and mandibular dental arches, and length of posterior alveolar crest. They reported higher accuracy of 3D-printed models than the conventionally poured dental casts; however, no statistically significant difference was found between the two groups. They concluded that the 3D-printed casts have high precision and are suitable for clinical use.

Elmahdy *et al*. assessed the accuracy of 3D-printed dental models derived from CBCT scans using 0.125 mm and 0.3 mm voxel sizes, reporting no significant differences compared to stone casts. Their findings are consistent with our results and support the use of different voxel sizes in generating accurate models. While their study focused on dental casts and standard linear measurements, our use of dry human mandibles and additional anatomical landmarks such as socket depth and buccolingual width offers a complementary perspective with broader clinical relevance, particularly for surgical and implant planning.[16] Mukhia *et al*. investigated the dimensional accuracy of 3D models generated from CBCT scans with different voxel sizes and found no significant differences in linear measurements, supporting the reliability of models produced from various scan settings. Their study reinforces our findings and adds to the growing evidence that lower-resolution scans may be sufficient for clinical use. While their work focused on overall dimensional accuracy, our study complements it by including additional anatomical landmarks specific to the mandible, offering further insight into the clinical applicability of 3D-printed models.[17] Yousefi *et al*. compared the accuracy of maxillofacial prototypes fabricated using different 3D printing technologies and imaging modalities, including CBCT with varying voxel sizes. Their results showed that smaller voxel sizes generally produced more precise models, although all tested combinations yielded clinically acceptable accuracy. These findings align with our results in confirming the reliability of 3D-printed models across different voxel sizes.[18] Our study adds to this by focusing specifically on mandibular anatomical landmarks and comparing voxel sizes within a single CBCT system, further supporting the practical use of larger voxel sizes in routine clinical workflows. Domingos *et al*. evaluated the dimensional accuracy of 3D models generated from CBCT scans of dry human mandibles using 0.2 mm and 0.4 mm voxel sizes. Measurements were compared to a white-light surface scan as a reference, and no significant differences were found between the voxel groups. Their study supports the reliability of different voxel resolutions in capturing external anatomical contours. While their approach is similar in assessing voxel size influence and using dry mandibles, it focused on global surface deviations, whereas our study assessed internal anatomical distances relevant to clinical applications.[19] Maret *et al*. examined how voxel size affects the geometric accuracy of CBCT reconstructions by scanning extracted teeth at three voxel settings (76, 200, and 300 μm) and comparing them to high-resolution micro-CT. They found that measurements deviated more significantly at 300 μm. Their findings emphasize voxel size as a factor in fidelity of digital models. Although they investigated voxel-dependent accuracy similar to our study, their focus was on isolated teeth and volumetric data rather than anatomical measurements on 3D-printed mandibular models.[20] In a systematic review, Spin-Neto *et al*. analyzed how varying voxel sizes affect diagnostic outcomes in CBCT imaging across dental applications. They concluded that increased voxel size can introduce measurement error and image degradation, particularly if not paired with proper segmentation thresholds. Their findings highlight voxel size as a key parameter in image quality, though the studies they reviewed focused on digital diagnostic accuracy.[7] Kamburoğlu *et al*. evaluated how voxel size affects the repeatability and accuracy of linear and volumetric measurements of pulp and tooth structures on CBCT scans. They used CBCT images of extracted human teeth taken at three different voxel sizes (0.125 mm, 0.2 mm, and 0.3 mm), and measurements were made of tooth length, volume, and pulp chamber dimensions using dedicated software. The study found that while the average measurements remained similar across voxel sizes, the repeatability of those measurements, particularly for smaller internal structures, declined with increasing voxel size. This suggests that smaller voxel sizes may offer more consistent data when fine anatomical detail is important. Although their work shares our interest in voxel resolution, it focused on in-software measurements of endodontically relevant structures rather than on external anatomical landmarks measured on 3D-printed mandibular models, as done in our study.[21]

In vitro design was a limitation of the present study, which limits the generalizability of the findings to the clinical setting. Small number of models due to high cost of 3D-printing was another limitation. Future studies with a larger sample size are required on the linear accuracy of models fabricated by the computer-aided design and computer-aided manufacturing technology. Moreover, the linear accuracy of 3D-printed models from CBCT scans taken by different CBCT scanners should be evaluated and compared.

CONCLUSION

The linear accuracy of CBCT scans taken with 0.3- and 0.2-mm voxel sizes was comparable, and they can be used for the fabrication of linearly accurate 3D-printed models of mandible. The 3D-printed models had high linear accuracy in all measured parameters except socket depth.

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Conflicts of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, financial or nonfinancial in this article.

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