10.5005/jp-journals-10024-1844

ORIGINAL RESEARCH

the Journal of CONTEMPORARY DENTAL PRACTICE
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The Accuracy and Reproducibility of Linear Measurements Made on CBCT-derived Digital Models

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ABSTRACT

Objective: To evaluate the accuracy and reproducibility of linear measurements made on cone-beam computed tomography (CBCT)-derived digital models.

Materials and methods: A total of 25 patients (44% female, 18.7 ± 4 years) who had CBCT images for diagnostic purposes were included. Plaster models were obtained and digital models were extracted from CBCT scans. Seven linear measurements from predetermined landmarks were measured and analyzed on plaster models and the corresponding digital models. The measurements included arch length and width at different sites. Paired t test and Bland–Altman analysis were used to evaluate the accuracy of measurements on digital models compared to the plaster models. Also, intraclass correlation coefficients (ICCs) were used to evaluate the reproducibility of the measurements in order to assess the intraobserver reliability.

Results: The statistical analysis showed significant differences on 5 out of 14 variables, and the mean differences ranged from –0.48 to 0.51 mm. The Bland–Altman analysis revealed that the mean difference between variables was (0.14 ± 0.56) and (0.05 ± 0.96) mm and limits of agreement between the two methods ranged from –1.2 to 0.96 and from –1.8 to 1.9 mm in the maxilla and the mandible, respectively. The intraobserver reliability values were determined for all 14 variables of two types of models separately. The mean ICC value for the plaster models was 0.984 (0.924–0.999), while it was 0.946 for the CBCT models (range from 0.850 to 0.985).

Conclusion: Linear measurements obtained from the CBCT-derived models appeared to have a high level of accuracy and reproducibility.

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Keywords: Accuracy, Cone-beam computed tomography-derived digital models, Plaster models, Reproducibility, Study models.

How to cite this article: Maroua AL, Ajaj M, Hajeer MY. The Accuracy and Reproducibility of Linear Measurements Made on CBCT-derived Digital Models. J Contemp Dent Pract 2016;17(4):294-299.

Source of support: Nil

Conflict of interest: None

INTRODUCTION

Orthodontic diagnosis and treatment planning depend on analyzing and understanding of clinical examination, photographs, radiograph, and dental models.[1] Dental models are an essential part of the orthodontic diagnostic records and they provide clinicians with a three-dimensional (3D) view of occlusion and give more details than clinical examination solely. Also they are used to document the original condition and measure treatments effects.[2]

For many decades, plaster models have been the only way to accurately visualize and evaluate patients occlusions. However, plaster study models are well known for being prone to breakage or fracture and the difficulty in their storage, retrieval, transportation, and their use in telecommunication.[3] Recently, the advancement of imaging and computer technology has introduced digital 3D models to the orthodontic specialty, which has overcome the limitations of traditional plaster models.[4] Digital models are not subject to physical damage and they can be easily transferred or retrieved at multiple locations. In addition, digital storage alleviates the physical storage problem of plaster models.[5]

The 3D digital models of the upper and lower dental arches are produced by two different methods.[6] The first one is indirect and requires impressions that are scanned in a later step or plaster models that are scanned by LASER or cone-beam computed tomography (CBCT). The second method is a direct without the need for taking impressions, but it depends on scanning the dentition with an intraoral scanner or by extracting the digital models from CBCT scans.[6–8]

With the advent of CBCT in the early 2000s, a significant change occurred in many aspects of the daily practice of oral and maxillofacial imaging.[9] This new technique is more comfortable and cheaper than traditional computed tomography (CT).[10] Although CBCT radiation dosage is higher than traditional two-dimensional (2D) technologies (e.g., panoramic and cephalometric radiographs), it is still significantly lower than the radiation dosage associated with traditional CT.[9] The possibility of extracting digital models directly from CBCT scans[11] may eliminate the need for impressions and save the orthodontist's chair-time and materials.[8] Extracting digital models from CBCT involves segmenting the scanned data, removing the unwanted anatomical structures, and retaining dental arches only.[12]

The accuracy of CBCT images has been confirmed with various CBCT scanners;[13,14] however, the accuracy of CBCT-derived digital models is not the same.[15] The segmentation process can be time-consuming and laborious for an orthodontist and the employed programs may not be available within his/her hands. To overcome this problem, a commercially available technique has been recently introduced (i.e., Anatomage™, San Jose, California, USA), which now offers this service using CBCT data. The 3D digital models acquired from CBCT images have been assessed and found acceptable for clinical purposes,[4,11,16–19] but it still be very time consuming and costly for the clinicians.[20] To overcome these shortcomings, a new custom-made and manually constructed CBCT-derived digital modeling has been developed at the Orthodontic Department of University of Damascus. The accuracy of CBCT 3D models is mainly influenced by the segmentation approach that has been employed.[21] Therefore, this study aims to evaluate the accuracy and reliability of linear measurements performed on these custom-made CBCT digital models, to those measurements taken directly from the corresponding plaster models.

MATERIALS AND METHODS

Sample Size Calculation

Twenty-five patients participated in the current study who had attended the orthodontic clinic. The sample size was calculated using G*power 3.1.9.2© (Kiel University, Kiel, Germany) with effect size $|p| = 0.5$ mm as suggested by Luu,[22] $\alpha = 0.05$, and power of 85%; the total sample size was 24 subjects.

Patients' Recruitment

Patients who had been diagnosed as having impacted lower third molars with abnormal positions or with the possibility of injuring the neighboring structures during the surgical removal were asked to have a CBCT image before scheduling their operation at the Department of Oral and Maxillofacial Surgery.

Patients who were referred to have their CBCT images taken constituted our sampling frame. A simple random sampling was used to withdraw 25 patients who were asked to participate in this research project. The inclusion criteria were as follows: The presence permanent dentition from first molars to first molars; absence of anomalies in number, size, and shape of the teeth; absence of any restorations or any prostheses. Upon agreement, alginate impressions were taken and a wax bite registration was performed. The response rate for participation was 100%.

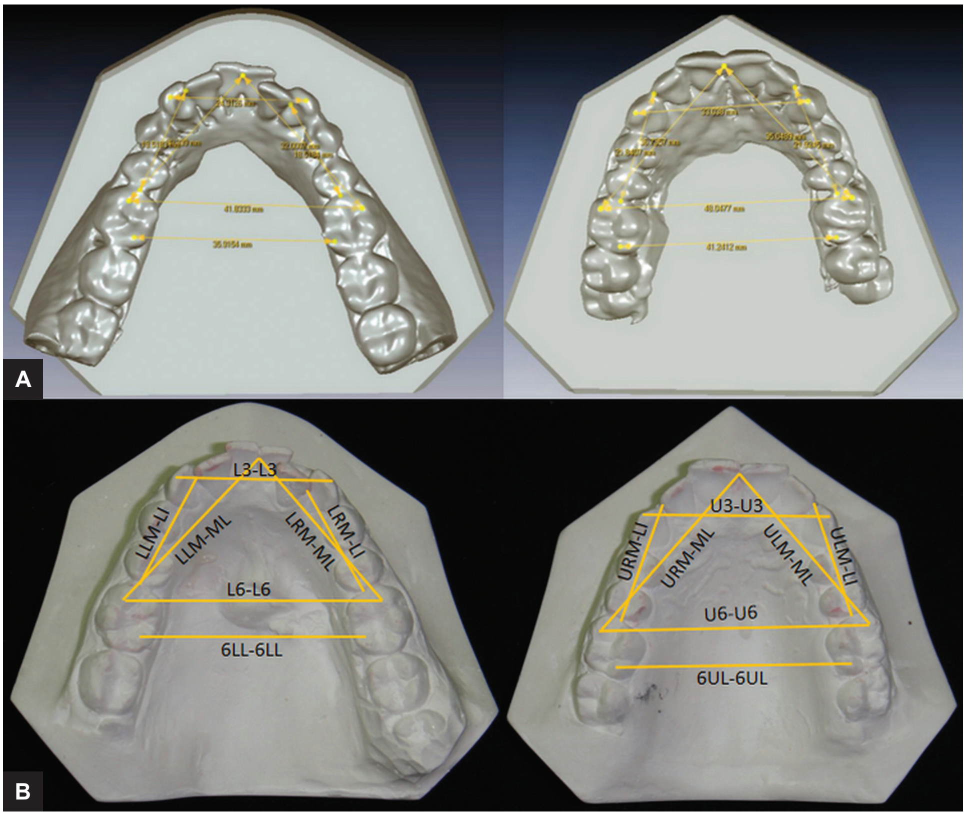
CBCT Imaging

Patients were scanned with an interocclusal separation of about 1 to 2 mm using a wax bite as suggested by Hernández-Soler et al[6] to allow for later segmenting of the upper and lower teeth. The CBCT device that employed in this study was Scanora 3D™ (Scanora 3D, Sordex, Finland) with a large 75 × 145-mm field of view (FoV) at a voxel size of 0.25 mm and an exposure time of 15 seconds.

Plaster and Digital Model Construction and their Analysis

The plaster models were fabricated by pouring the alginate impressions with type II orthodontic plaster (Kimberlit™, Protechno©, Girona, Spain). Digital models were acquired by segmenting the upper and lower arches from DICOM data of the CBCT scans manually using 3D-Doctor® program (Able Software Corp, Lexington, USA); then the models were exported as STL files and were opened by Rapidform program (Rapidform® Software, Inus Technology, South Korea). The models mesh was rebuilt using "Global remesh" command in order to retriangulate the poly-faces of the mesh and produce equilateral triangles, which is believed to improve the quality of each poly-face. Then the command "smooth" was applied to reduce the surface roughness. Finally, the models' bases have been constructed and added to imitate the ordinary plaster models' bases (Figs 1A and B).

Seven linear measurements on the lower jaw and seven similar ones on the upper jaw were undertaken as defined in Table 1. The measurements on the plaster models were taken manually with digital calipers of an accuracy of 0.01 mm, whereas those on digital models were taken on-screen using the Rapidform™ software. Measurements were rounded to the nearest 0.01 mm on the plaster and digital models. One operator (A. M.) completed all the measurements on plaster models



Figs 1A and B: Illustration of the linear measurements performed on the two types of dental models studied: (A) CBCT models, and (B) plaster models

Table 1: Definitions of the variables used in this study

Variable	*Definition*
Maxillary	
URM-ML	Mesiobuccal cusp tip of the upper right first molar to the midline between the central incisors.
ULM-ML	Mesiobuccal cusp tip of the upper left first molar to the midline between the central incisors.
URM-LI	Mesial edge of upper right first molars to the distal edge of the upper right lateral incisor.
ULM-LI	Mesial edge of upper left first molars to the distal edge of the upper left lateral incisor.
U3-U3	Cusp tip of the upper right canine to the same point on the upper left canine
U6-U6	Mesiobuccal cusp tip of the upper right first molar to the same point on the upper left first molar.
6UL-6UL	Distolingual cusp tip of the upper right first molar to the same point on the upper left first molar
Mandible	
LRM-ML	Mesiobuccal cusp tip of the lower right first molar to the midline between the central incisors.
LLM-ML	Mesiobuccal cusp tip of the lower left first molar to the midline between the central incisors.
LRM-LI	Mesial edge of lower right first molars to the distal edge of the lower right lateral incisor.
LLM-LI	Mesial edge of lower left first molars to the distal edge of the lower left lateral incisor.
L3-L3	Cusp tip of the lower right canine to the same point on the lower left canine
L6-L6	Mesiobuccal cusp tip of the lower right first molar to the same point on the lower left first molar.
6LL-6LL	Distolingual cusp tip of the lower right first molar to the same point on the lower left first molar

consecutively before moving to the digital models. All measurements on both types of models were repeated for the second time after 2 weeks to assess the intraobserver reliability.

Statistical Analysis

All data were entered into an Excel file (Excel, Microsoft® Office 2013, USA) and analyzed using SPSS v21 (SPSS, IBM Corp©, NY, USA) and Graphpad v5.03 (Graphpad, Prism©, CA, USA). All data were checked using Kolmogorov–Smirnov tests to examine the normality of data distribution. Paired t tests were used to assess systematic error. Bland and Altman's method of assessing agreement was used.[23] Intraclass correlation coefficients (ICCs) were used to determine the intraobserver reliability for each type of models.[24]

RESULTS

There were significant differences in five out of the fourteen measurements evaluated between the digital models and gold standard readings. The mean differences between the measurements on plaster models and those on digital models ranged from –0.48 to 0.51 mm (Table 2). The results of the Bland–Altman analysis are summarized in Table 3. In the maxilla, the overall mean difference between the two types of models for all measurements was 0.14 ± 0.56 mm and the limits of agreement

Table 2: Paired samples t test: Mean differences (in mm) with standard deviations (SD) for the measurements made on plaster models and CBCT models (n = 25)

	Differences		*95% Confidence interval*	
Variables	*Mean*	*SD*	*Lower*	*Upper*
Maxilla				
URM-ML	–0.20	0.50	–0.41	0.001
ULM-ML	0.08	0.58	–0.15	0.32
URM-LI	–0.21*	0.44	–0.39	–0.02
ULM-LI	–0.48*	0.69	–0.77	–0.20
U3-U3	-4×10^{-4}	0.43	–0.18	0.17
U6-U6	–0.40*	0.53	–0.62	–0.18
6UL-6UL	0.22*	0.34	0.07	0.36
Mandible				
LRM-ML	-8×10^{-4}	0.31	–0.13	0.12
LLM-ML	–0.16	0.60	–0.41	0.08
LRM-LI	–0.05	0.32	–0.18	0.08
LLM-LI	0.07	0.31	–0.05	0.20
L3-L3	0.51	2.19	–0.39	1.41
L6-L6	–0.27	0.80	–0.61	0.05
6LL-6LL	0.29*	0.48	0.08	0.49

*statistically significant difference at p-value < 0.05

were –1.2 and 0.96 mm. In the mandible, the overall mean difference between the two methods for all variables was 0.05 ± 0.96 mm and limits of agreement were –1.8 and 1.9 mm (Figs 2 and 3).

Regarding reliability, the overall mean ICC value for the plaster models was 0.984 (0.924–0.999) and was 0.946 (0.850–0.985) for the CBCT-derived models, indicating an overall excellent agreement between the first and second measurements in both types of models.

DISCUSSION

In the present study, the plaster models were chosen as the reference standard, although direct measurements on plaster models is inevitably associated with some degree of inaccuracy. To overcome this problem, some studies have used artificial models permitting more accurate measurements.[25,26] However, we preferred to simulate the clinical situation where the practitioner routinely uses his/her own calipers to perform direct measurements in the orthodontic office.

As usual, CBCT scans are taken with the teeth in occlusion, but that makes the segmentation process (separation between the maxilla and the mandible) more difficult since there is some overlap of the upper occlusal surfaces with the lower occlusal surfaces. For this reason, the teeth were separated during the scanning by a 2-mm thickness using wax bite. This would prevent the distortion of occlusal surfaces, but still causing a little effect to the vertical dimension.[6] However, in the present study, the CBCT images were used for presurgical diagnosis of impacted lower third molars and to assess the relationship with the adjacent structure, especially the mandibular canal.[27]

Although there were significant differences between the linear measurements on CBCT models and on the corresponding plaster models, these differences are not of a paramount effect and the produced digital models can be accepted for clinical use since all the mean differences were below the clinical threshold of 0.5 mm as suggested by Luu et al.[22] The Bland–Altman analysis showed that the accuracy of linear measurements on CBCT models

Table 3: The Bland–Altman analysis

		95% Limits of agreement	
	Bias	*Lower limit*	*Upper limit*
Maxilla	–0.14	0.96	–1.2
Mandible	0.05	1.9	–1.8

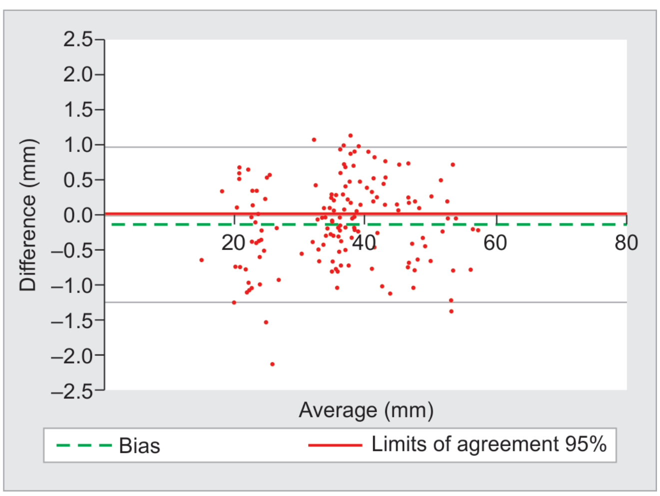


Fig. 2: Bland–Altman plots for accuracy of linear measurements in the maxilla. Difference plot of CBCT models compared with plaster models

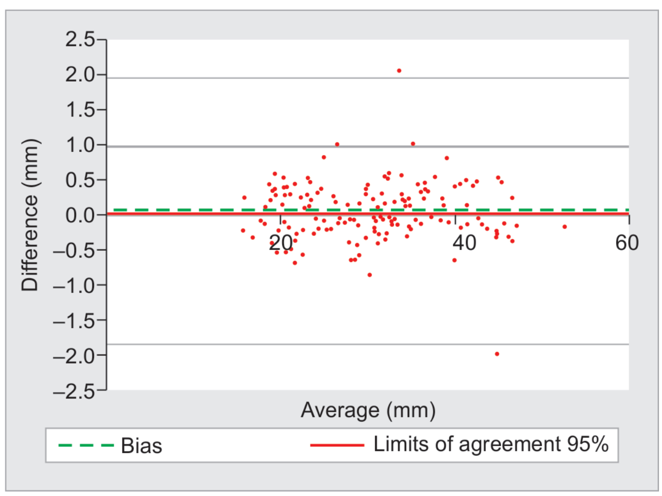


Fig. 3: Bland–Altman plots for accuracy of linear measurements in the mandible. Difference plot of CBCT models compared with plaster models

were within 1.5 mm in the maxilla and within 2 mm in the mandible.

The differences between measurements on CBCT models and plaster models may be explained by several possible reasons: Dimensional changes in the alginate impressions before plaster pouring, the lack of familiarity in manipulating 3D models, and the imprecision of the employed algorithms of the software in calculating interlandmark distances.[25]

Earlier studies evaluated the accuracy and reproducibility of digital models acquired from CBCT by Anatomage™ software (San Jose, Calif, USA) and this was the only company to produce such digital models. Creed et al compared CBCT-derived digital models with OrthoCAD models using linear measurements and found that the mean differences ranged between –0.62 and 0.44 mm. However, their study lacked the presence of the gold standard readings (i.e., those obtained from actual plaster models); therefore, the assumption that OrthoCAD measurements were the reference values is questionable. Another two studies superimposed CBCT-derived models onto digital models produced by OrthoCAD™ and E-models® techniques (employing Rapidform® program for this superimposition) and concluded that CBCT-derived models had adequate accuracy for clinical purposes.[4,16] On the contrary, two recent studies have demonstrated that CBCT-derived models were less accurate than other non-CBCT-based models when compared to the plaster models (i.e., their gold standard),[16,18] and this was attributed basically to the quality of the CBCT images.

Cone-beam computed tomography images' quality can be affected mainly by the artifacts that could emerge from several sources. Physics-based artifacts result from the acquisition processes of the CBCT data, whereas patient-based artifacts are caused by possible patient movements or metal objects in the dental arches. Metallic dental restorations in the scan field can lead to streaking artifacts, which occur because the density of the metal is beyond the normal range that can be handled by the computer, resulting in an incomplete attenuation profile, and as CBCT models were fabricated directly from CBCT scans, so they might be affected by scanning artifacts, and for that reason patients with any restorations were excluded in this study.[28] Another factor that might have affected the quality of CBCT image is the voxel size. Decreasing the voxel size might enhance the quality of the scans and may result in a better correlation between the measurements on the CBCT models and that those on plaster models.[4] In addition, the choice of large FoV reduced the visibility of the occlusal surfaces in comparison with the small or medium FoVs selections.[21]

Roberts and Richmond[29] suggested that an ICC value below 0.4 indicates poor reliability, between 0.4 and 0.75 fair to good, and above 0.75 indicates excellent reliability. All ICC values in this study were excellent and above of 0.9 with the exception of two variables on digital models (LRM-ML and LLM-ML), which had ICC values of 0.850 and 0.888, respectively. This could be attributed to the difficulty in identifying the midline between the central incisors on digital models. Some degree of deformation between the lower incisors' anatomical contacts was noticed in some CBCT models. This deformation could be probably due to the scanning, rendering, segmentation, or smoothing processes. As has been suggested by Houston,[24] the most important reason for the random error in any measurement is the difficulty in identifying the relevant landmarks, and this can arise clearly when measuring digital models from the fact the a 3D structure was being viewed as a still 2D image on the screen; therefore, identifying landmarks was more difficult than the traditional way despite the ability to manipulate the models in 3D.[30]

It is a good idea to take all diagnostic records from a single CBCT scan. On the contrary, according to the ALARA principle "As Low As Reasonably Achievable," it is early to make CBCT scan as part of our daily practice, because CBCT exposes the patient to considerably more (4–5 times) dosage than a regular 2D radiograph.[31] But with constantly improving CBCT technology, this daily implementation could happen. Consequently, plaster models might no longer be required. Similarly to other studies, the current work suggests that linear measurements on CBCT-acquired digital models are accurate and reproducible from the clinical point of view. Further studies comparing the produced models by the current methodology with the commercially available technique are suggested. In addition, the evaluation of accuracy and reproducibility can be expanded to include additional linear measurements such as mesiodistal and labio-lingual tooth dimensions, Bolton ratios, and tooth-size-arch-length analysis that have been undertaken by other researchers.[16,18–20,32]

CONCLUSION

The following conclusions can be drawn from the present study:

- Linear measurements carried out on digital models acquired from CBCT images were in a similar level of accuracy compared to plaster models. The accuracy might be adequate for initial diagnosis and treatment planning in clinical orthodontics.
- High reproducibility was found when linear measurements were repeated with an interval of 2 weeks' time.

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