ASDJ
AINSHAMS DENTAL JOURNAL

Print ISSN 1110-7642
Online ISSN 2735-5039

AIN SHAMS DENTAL JOURNAL
Official Publication of Ain Shams Dental School
June 2022 • Vol. 26

Dimensional accuracy of 3D printed models using different voxel size CBCT (Comparative Experimental Study)

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Aim: To evaluate the influence of different imaging protocols (voxel sizes) of CBCT on linear measurements accuracy of different printed 3d models.
Methods and Material: Ten intact casts with complete dentition were selected and anonymously numbered from 1-10. Casts were prepared with round bur size 2 at certain specific points to be used as fixed measurement limits. Casts were then scanned with the same CBCT machine using two voxel size protocols (0.125mm and 0.3mm). Each scan was then imported into ondemand3d app software, segmented by thresholding, and exported as STL file to be transferred to the 3d printer. Each set of reference cast and two printed copies were compared with considering cast as gold standard.
Results: Different linear measurements throughout the three basic planes were taken using digital caliper of 0.01mm accuracy on each set by two radiologists of nine years' experience after having set for standardization measures. Each observer had three readings to assess intra-rater variability and resulted in no statistically significant difference and excellent agreement between conventional cast readings with models 0.125 and 0.3. Although measurements taken on models 0.125 were slightly close to the gold standard than measurements of model 0.3.
Conclusion: Using 0.3 mm voxel size in scanning cast models to obtain 3d printed models showed no statistical significance difference from using 0.125mm voxel size.

Keywords: 3d printing, voxel size, stone model

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Introduction

Because of technological advancements, dental models can now be produced in digital format [1], so we can replace stone casts with three-dimensional (3D) digital models.[2] However, their accuracy in comparison to stone casts must be assessed, as the linear accuracy with a digital caliper in plaster models is considered the gold or reference standard in most dental researches.[3] Stone casts also have the advantage of being simple and inexpensive to produce.[4]

As for their advantages over stone casts, the use of these various types of digital models has grown significantly. They are not easily damaged or degraded, and the digital archive facilitates communication between dentists and patients while it saves money, effort, and space needed for physical storage.[5] In addition, when it comes to orthodontic treatment, it is now possible to use virtual simulation setups to mimic the results of orthodontic treatment; [6] use specific qualitative measuring tests, as orthodontic scales or indexes [5], and digitally superimpose images to track progression and follow up the treatment results.[4]

One of the major disadvantages of digital models is complicated data acquisition; it is dependent on expensive, but highly developed technology. Furthermore, it has limitations in terms of privacy and security, also there is a high risk of losing electronic data files.[4]

Digital Scanning of stone casts could be either direct or indirect; Direct scanning is done with the help of cone-beam computed tomography (CBCT) [7] while indirect scanning is obtained when a laser scanner is used to scan physical impression or stone cast then the scanned data is exported as STL digital file. During data acquisition using digital scanners for stone casts, many cameras are used in different directions with a light source as laser or light-emitting diode (LED).[7]

It is critical to remember that comparing various CBCT imaging protocols of different resolutions is related to complete awareness of the influence of image quality parameters on the reliability and accuracy of the final diagnosis.[8] Using high-resolution images from small voxel sizes will not guarantee a better final diagnosis than using low-resolution high voxel size protocols, even though the small voxels provide sharper and clearer image quality yet it is not biologically safe as the radiation dose on the patient is higher.[9]

The construction of a 3D printed object usually refers to additive manufacturing. An object is fabricated by adding layers of printing material until the complete height of the object is reached. Each layer represents a cross-section slice of the object. It is also known as rapid prototyping.[10] 3d printing is the inverse of the milling process which is commercially known as subtractive manufacturing.[11] In this process, one piece of metal or plastic is cut down to the desired shape with the help of a milling machine. 3d printing is considered more accurate and can produce more complex shapes.[12]

Many authors have focused in their publication on the accuracy of digital models scanned by computed tomography (CT) machines either conventional multislice CT or CBCT using different imaging protocols and voxel sizes,[13-16] but few have compared the accuracy of 3d printed models with the original plaster stone model.[17, 18]

So, in our study, we aimed to evaluate the influence of different imaging protocols (voxel sizes) of CBCT on linear measurements accuracy of different printed 3d models.

Subjects and Methods

A convenient number of ten (10) anonymous maxillary or mandibular stone models were obtained from the orthodontic department, faculty of dentistry, Ain shams university. The models were selected according to a few inclusion criteria as having a full dentition of permanent teeth (from left the first molar to right first molar) and showing complete intact surfaces (no voids on the plaster models and no fractures on the teeth). Stone models with the presence of deciduous teeth, multiple permanent teeth extraction, fractured or destructed models, models with bond orthodontic retainers, attachments, appliances, or prostheses were excluded from the study. The selected casts were subsequently numbered from 1 to 10 with no personal data written on them.[18]

The study was approved by the Research Ethics Committee of the Faculty of dentistry, Ain Shams University with approval number FDASU-Rec IM011906.

Multiple small pinpoint holes were done on the surface of casts and models at the determined endpoints of our study measurements and acted as a surface guidance point to prevent easy caliper tips slippage on casts or models surfaces (figure 1).[19] These points were applied by using round bur size 2 (low-speed motor) on the following locations bilaterally (right RT, left LT); the mesial incisal tip of the central incisor (1), the cusp tip of canine (2), the labial gingival margin of canine (3), and mesiobuccal cusp tip of 1st molar (4).

Each cast was scanned two times with different voxel sizes by the same CBCT machine. In our study, we used iCAT next-generation imaging machine (Imaging sciences international, Hatfield, PA, USA). A fixed field of view (FOV) was performed for both scans (4cm height x 16cm diameter) while the resolution was different in each scan as the first scan used 0.125mm voxel size with a 26.9-sec duration of the scan while the second scan used 0.3mm voxel size with an 8.9-sec duration of the scan. Casts were set on the scanning table horizontally and aligned at the midline on its center.

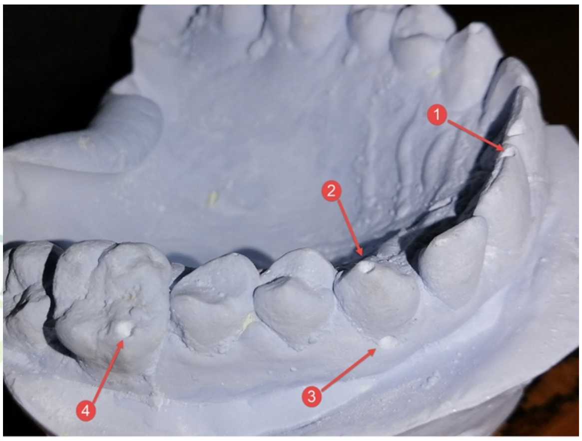

Figure 1 - Cast preparation with round bur size 2 on specific locations

After CBCT scan construction, they were imported directly to third-party image analysis software "Ondemand3D App" (Cybermed, Korea) in a form of DICOM files (digital imaging and communications in medicine). Each cast is separated from the image volume using a semi-automatic segmentation tool (thresholding). By selecting the suitable range of voxel values (0-3000), thresholding was applied, and the casts were segmented (figure 2).[19]


Figure 2 - Cast segmentation by thresholding values 0-3000

After segmentation, the 3D cast surface of each case was exported as STL (Stereolithography) format without the use of any digital smoothing tools to maintain its raw volume measurement.[16]

Files were sent after free-forming and aligning to a 3D printer "Dent2 3D Printer (Mogassam Co., Egypt)", which deposits and then fuses successive 2D layers of polyacrylic material (figure 3).[20] The highest printing resolution (layer thickness of 50um) was used. Finally, the printed two copies (copy from each voxel size) of each cast were marked by numbering concerning their plaster one.

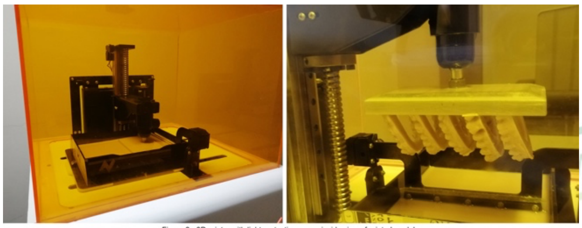

Figure 3 - 3D printer with light protection cover, inside view of printed models

Different linear measurements throughout the three basic planes (X, Y, and Z) were taken on each stone model and its printed 3d copies physically with a digital caliper (figure 4) of 0.01mm accuracy (Mitutoyo Co, Kanagawa, Japan).[14] The measurements were taken by two radiologists with nine-year experience, three times with two weeks intervals. The two observers were preset for standardization measures. Measurements that were taken on the plaster models were considered the gold standard.[21]

Figure 4 - Using caliper for measuring 1Rt-2Rt distance

The linear measurements were selected regarding X, Y, and Z planes as follows; X-plane as the inter-canine distance (distance between the incisal tips of canines) from point 2Rt to point 2Lt, Y-plane as the distance between the incisal tip of the canine and mesio-buccal cusp of the first molar of the same side from point 2Rt to point 4Rt and from point 2Lt to point 4Lt, Z-plane as the height of the clinical crown of canine from point 2Rt to point 3Rt and from point 2Lt to point 3Lt, and mixed XY distance as the distance between the mesial incisal tip of the central incisor and cusp of canine of the same side from point 1Rt to point 2Rt and from point 1Lt to point 2Lt.[18]

The measurement values of the ten casts and their printed models were tabulated, recorded in a Microsoft Excel sheet for data analysis, and then statistically compared to determine the relation between printed models of different scanning resolutions and the conventional plaster cast.

Data were analyzed by IBM SPSS Corp. 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp. Numbers and percentages were used to describe qualitative data. Quantitative data were described using mean and standard deviation for parametric data after testing normality using Shapiro–Wilk test. The obtained results were judged for significance at the 0.05 level.

Results

No statistically significant differences were found between the models 0.3, 0.125 at any measurement when comparing their accuracy after obtaining them from CBCT scans of 0.3mm and 0.125mm voxel sizes. The accuracy was defined as the mean deviation of each measurement from the measurement on the reference cast model. The mean of each reading (taken three times by each observer) was as shown in figure 5.

The first observer had three readings to assess intra-rater variability and resulted in no statistically significant difference between conventional cast readings with models 0.125 and 0.3. There was excellent agreement between the cast and models with different voxel sizes. However, there was a slightly higher agreement between conventional cast and model 0.125 than with model 0.3 (All interclass correlations during the first reading, second reading, and third reading were high).

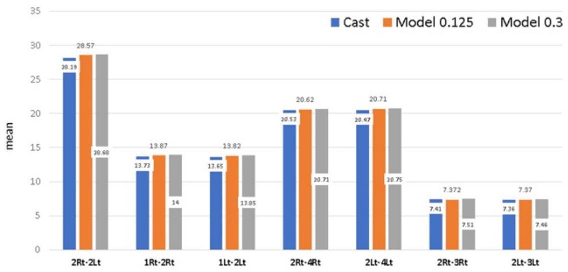

Figure 5 - Mean values comparison of different distances

Also, the second observer had three readings to assess intra-rater variability and resulted in no statistically significant difference between conventional cast readings with models 0.125 and 0.3. There was excellent agreement between the cast and models with different voxel sizes. However, there was a slightly higher agreement between conventional cast and model 0.125 than with model 0.3 (All interclass correlations during the first reading, second reading, and third reading were high except for interclass correlation for model 0.3 which was moderate).

The Inter-rater agreement between both observers for first, second, and third readings showed high agreement.

Student t-test as a parametric analysis was used to compare two independent groups. Agreement between continuous variables was detected using Inter-class correlation (ICC) considering a correlation coefficient of more than 0.7 to be accepted. The ICCs were classified by McGraw and Wong as; Less than 0.75 is considered poor agreement, 0.75 to less than 0.90 is considered moderate agreement, while 0.9 or greater is considered high agreement.

Discussion

Selecting an appropriate CBCT acquisition protocol is mandatory to obtain an image with appropriate resolution and minimal radiation exposure.[22] Among all the variables that affect image quality, voxel size is of great importance as it is directly related to radiation dose.[8]

There is a lack of knowledge in the literature concerning the assessment of 3d printed models dimensional accuracy from different CBCT scanning voxel sizes, so we aimed to compare the geometric accuracy and to measure the reliability of 3d printed models of casts created from 0.3mm, 0.125mm voxel size CBCT images and the reference cast models. The result of our study spotted that, there was no statistically significant difference between each set (plaster cast and its two printed copies) although there was a slight increase of correlation with the high-resolution group.

This means, it is needed to use lower resolution scans with reduced-dose exposure protocols while obtaining the needed diagnostic results following the principle of ALARA (As Low As Reasonably Achievable) of dose optimization.[23]

Regarding the accuracy of 3D printed dry mandible models from CBCT scans with 0.3mm, 0.25mm, and 0.2mm voxel size; it was proved that there was no statistically significant difference between the dry skull mandible as a reference and the printed models.[24]

In the same way, changing the voxel size from 0.3mm to 0.15mm did not improve linear, volumetric, or geometric accuracy of 3D teeth reconstructions as stated by Yan-Hui Sang et al.[25]

Also, no statistically significant difference was noted regarding linear vertical and horizontal measurement accuracy of bone [26], tooth and root length [27], using the same iCAT CBCT machine (Imaging Sciences International Inc., Hatfield, PA, USA) and different voxel sizes (0.4mm, 0.3mm, 0.25mm, 0.2mm).

The agreement between these studies and ours assumes that different voxel sizes that were used were of insignificant difference regardless of the type of CBCT machine or the scanned study model.

In contrast, CBCT images evaluating measurements of alveolar crest level showed good accuracy for 0.3mm and 0.2mm voxel sizes. Meanwhile, the only significant difference found was on 0.4mm voxel size while assessing the mandibular lingual plate of bone of incisors.[22]

In another study evaluating bone thickness linear accuracy, 0.25mm images were found to be closer to the gold standard measurements than 0.4mm images. Also, measures from both voxel sizes were different from the gold standard when the bone walls were thinner than the voxel size.[28]

A study with a special focus on the accuracy of 3D printed models derived from multidetector computed tomography (MDCT), CBCT systems with 0.2mm, 0.4mm voxel sizes, different FOV, and different 3D printer machines showed that smaller voxel size results in a higher precision of 3D reconstructions and printed models.[29]

The disagreement between these studies and ours was mainly related to the usage of a larger voxel size (0.4mm) that proved to have less resolution and fewer image details.

Limitations

The small sample size is one of our study limitations so we recommend future studies with larger sample size which can give more representative results.

Also, using specific voxel values with one 3d printer and one printing technique might have limited the assessment of models' accuracy; which is recommended for further investigation to measure the effect of different voxel sizes associated with different CBCT systems on the accuracy of 3d printed models; aiming to reach a justified scanning protocol following the ALADA (As Low As Diagnostically Acceptable) concept [30] that aims to obtain a diagnostically sufficient image with minimal radiation dose.

Conclusion

Finally, we concluded that using 0.3 mm voxel size is recommended in scanning cast models as there was no statistical significance between voxels sizes up to 0.3 mm.

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