Reliability of Linear Measurements on STL Models Obtained from CBCT Images Using Artificial Intelligence and Different Softwares

Abstract

Objective: The aim of this study was to compare the reliability of linear measurements using 2 software programs and a web-based artificial intelligence (AI) dental diagnostic tool using standard Tessellation Language (STL) models.

Materials and Methods: 100 CBCT scans were analyzed and enrolled in this study retrospectively. Firstly, DICOM files were imported into MAXILIM® software to create a 3D hard tissue representation. Besides this, a convolutional neural network-based machine learning algorithm and MIMICS software program were used to generate STL images. Five mandibular and four maxillary linear measurements were performed using MIMICS software STL images, MAXILIM software, and AI-generated STL files using 3D-matic. Bonferroni adjustment was used for pairwise comparisons. Absolute agreement among three programs and between pairs of programs was assessed by the intraclass correlation coefficient (ICC).

Results: Overall, ICC values demonstrated reliable reproducibility. The Distance between Coronoid Process (DCP) values was significantly higher in the MAXILIM group compared to the other groups ($p<0.05$). The Distance between Mental Foramens (DMF) values were significantly lower in the Diagnocat STL (DC STL) group compared to the other groups ($p<0.05$). The D. Foramen Infraorbitalis (DFI) values were significantly higher in the MAXILIM group compared to the other groups ($p<0.05$). The D. Foramen Palatinum Majus (DFPM) values were significantly lower in the Diagnocat STL (DC STL) group compared to the other groups ($p<0.05$). The D. Spina

Nasalis Anterior and Spina Nasalis Posterior (DSN) values were significantly higher in the MAXILIM group compared to the other groups ($p<0.05$).

Conclusion: More research needs to be done in the literature because CBCT-derived STL models are now widely used in dentistry, including in orthodontics, AI-based research, and dentomaxillofacial radiology. This study has demonstrated that 3D models derived from CBCT provide higher measurement values than models derived from AI. Additionally, the results demonstrate a significant difference in the STL model reconstruction for maxilla measurements, which may indicate that one should proceed with caution when using the measurements.

Introduction

A cone-shaped X-ray beam is used as the basis for the medical image capture technology known as cone-beam computerized tomography (CBCT), which is focused on a two-dimensional (2D) detector. A single rotation of the item by the source-detector system results in a string of 2D pictures [1] . A modified version of the original cone-beam algorithm created by Feldkamp et al. in 1984 is used to rebuild the images in a three-dimensional (3D) data set.[2]

Cone Beam Computed Tomography (CBCT) has revolutionized the diagnostic process of dentomaxillofacial imaging and orthodontics by delivering precise, high-resolution 3D imaging using easy and cost-effective equipment since it was first used in dentistry in 1998.[3]–[5] CBCT, in particular, has played a significant role in dentistry recently because of its lower radiation doses compared to multi-slice computed tomography (MSCT).[6]

For detecting dentofacial abnormalities and deformities, an important step is to develop accurate virtual 3D models of the head and face anatomic structures from the CBCT scans. As a result, CBCT is now being used more commonly for diagnosing and planning orthodontic surgical therapy for craniofacial skeletal abnormalities, impacted teeth, and cleft lip and palate.[3], [7] To store and transmit 3D data, CBCT pictures are transformed into Digital Imaging and Communications in Medicine (DICOM) files. DICOM is the most commonly used file format that provides a series of 2D cross-sections of the 3D anatomical structures.[8]

DICOM files must be converted to the Standard Tessellation Language (STL) format, which creates a user-friendly visualization of raw data. STL files, which allow 3D industrial and medical product printing, are accessible from any computer running a standard operating system like Microsoft Windows. Additionally, in the head and neck region, STL files can be generated automatically from CBCT data of the teeth and jaws. [9] On the other hand, the rapid and incessant progress in the field of computer science has engendered a surge in the application of novel technologies across various strata of contemporary society. This paradigm shift has also left its imprint on orthodontics, which has undergone a transformational phase by incorporating computer-based records as a routine practice in many of its offices. In addition, the availability of digital models has witnessed a steady upswing, providing reliable and qualified diagnostic images at a justifiable expense.[10] Artificial intelligence (AI) has the capability to rapidly segment the distinct anatomical structures present in a three-dimensional (3D) digital imaging and communications in medicine (DICOM) package obtained from computed tomography (CT) scan, specifically in the domain of dental radiology.[11] STL files may be used to make diagnoses and plan treatments; however, model accuracy is a serious problem that needs to be considered and addressed.[12]

The aim of this study was to evaluate the precision of linear measurements by analyzing the STL models of dental structures using two different software programs and a web-based artificial intelligence (AI) diagnostic tool. The study's null hypothesis was that there is no significant difference in the measurements obtained from the STL models using the three different tools, namely Diagnocat STL, MAXILIM, and the standard STL software. The study aimed to test this hypothesis across three different scenarios, namely (1) comparison between STL and Diagnocat STL measurements, (2) comparison between MAXILIM and STL measurements, and (3) comparison between MAXILIM and Diagnocat STL measurements.

Materials and methods

Data from CBCT scans of 100 patients, who had been referred to Department of Dentomaxillofacial Radiology during an 8-year period, were retrospectively analyzed and enrolled in this study. Patients with evidence of craniofacial deformities, bone disease, anamnesis of surgical procedures in the mandible, syndromes, and pathological disorders of the mandible were excluded from the study.

All modifications and alterations to the study protocol were made in accordance with the rules outlined in the Helsinki Declaration. The collected data was only accessible to the researchers. Written informed consent was obtained from the patient or their legal guardians before the CBCT imaging. The faculty's institutional ethical board examined and approved the work.

With the Newtom 3G (Quantitative Radiology s.r.l., Verona, Italy) and a 12-inch field of view, CBCT scans were taken. All images were recorded at 120 kVP and 3–5 mA with a scan time of 36 s, an isotropic voxel, and a 0.3 mm axial slice thickness. All CBCT scans were performed in accordance with our clinic's strict, standardized scanning protocol while the patients were lying horizontally with the Frankfurt horizontal plane perpendicular to the floor, having their mouths checked to make sure they were closed in a normal, natural occlusive position, and being told to remain still throughout the scan. The axial images were exported in a 512 × 512-matrix DICOM file format and then imported into MAXILIM® software (Medicim – Medical Image Computing, Mechelen, Belgium). An oral and maxillofacial radiologist (SA) creates a 3D hard tissue representation computed from several stages of the patients' CBCT datasets (figure 1), a technique that had been determined by Oz et al. study. [13]

Besides this, a Convolutional Neural Network-based deep learning algorithm (Diagnocat (DC)) (figure 2) and MIMICS STL module were used to generate STL images. For the maxilla, 3 anatomic landmarks were identified and three linear measurements were performed as follows; distance between the left and right infraorbital foramen, distance between the left and right major palatine foramen, and distance between anterior nasal spine and posterior nasal spine.

On the other hand, the mandible had ten anatomical landmarks that could be used to measure five linear dimensions. These measurements included the distance between the right and left angulus mandibulae, the distance between the right and left coronoid processes, the distance between the right and left fovea pterygoidea, the distance between the right and left incisura mandibulae, and the distance between the right and left mental foramen. All linear measurements were performed using MAXILIM software. MIMICS software STL images and AI-generated STL file measurements were performed using 3D-Matic (Materialise, Leuven, Belgium) (figure 3). The distributions of distance measurements were examined by Shapiro-Wilk's test, normality plots, and skewness-kurtosis statistics.

Distance measurements were performed by the same observer (IE) in three programs and compared by repeated measures ANOVA. Bonferroni adjustment was used for pairwise comparisons. Absolute agreement among three programs and between pairs of programs was assessed by the intraclass correlation coefficient (ICC) and 95% confidence interval (CI) based on single-rating and two-way mixed-effects models.

A p-value of less than or equal to 0.05 was considered statistically significant. All statistical analyses were performed via IBM SPSS Statistics 22.0 (IBM Corp., released 2013). IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.

Result:

Based on the ANOVA results shown in Table 1, there was a statistically significant difference between the mean values of the distance measurements for the different imaging software and the anatomical landmarks. In particular, all three imaging software programs showed statistically significant differences in the distance between the coronoid process (DCP), with the MAXILIM software displaying the highest mean value. The three imaging software also demonstrated statistically significant differences in the distance between the mental foramen (DMF) and distance between the foramen infraorbitalis (DFI), with the MAXILIM software once again exhibiting the highest mean values. The distances between left and right foramen palatinum major (DFPM) and distance between spina nasalis anterior and spina nasalis posterior (DSN) showed statistically significant differences between the 3D-Matic STL and Diagnocat STL software, with the 3D-

Matic STL software showing the highest mean values. The other measurements did not show statistically significant differences between the different imaging software.

Table 2 demonstrates the reliability and validity of digital measurements of six different anatomical landmarks on mandible models using two different types of STL files, 3D-Matic STL and Diagnocat STL, as well as a reconstructed model derived from MAXILIM. The results show that the ICC for all measurements were high, indicating excellent reliability. Additionally, all p-values for the ICCs were less than 0.05, suggesting that the results are statistically significant. The 95% confidence intervals for the ICCs were also narrow, indicating good precision. Overall, the digital measurements of the anatomical landmarks on mandible models using both types of STL files and the physical model showed high reliability and validity, making them useful tools in orthodontic treatment planning.

Table 3 showed the ICC for maxillary anatomical structures. For the distance between left and right Foramen Infraorbitalis, the ICC values were 0.712 and 0.542 for the 3D-Matic STL-Diagnocat STL and Diagnocat STL- MAXILIM imaging methods pairings, respectively. These values were statistically significant with p-values of 0.0001.

For distance between left and right foramen palatinum majus measurement, the ICC values were 0.362 and 0.369 for the 3D-Matic STL and Diagnocat STL imaging methods, respectively, and both were statistically significant with p-values of 0.011 and 0.008, respectively. The ICC values for this structure measured using MAXİLİM were not reported for both imaging methods, except for the 3D-Matic STL which showed a non-significant ICC value of 0.116 and p value of 0.696 which shows that it is not statistically significant. ($p>0,05$)

For the distance between spina nasalis anterior and spina nasalis posterior structures, the ICC values were 0.149 and 0.359 for the 3D-Matic STL imaging method, while for the Diagnocat STL method, the ICC values were 0.414 and not reported for the 3D-Matic STL (STL) and MAXILIM, respectively. The only statistically significant ICC value for this structure was obtained using the Diagnocat STL method for the MAXILIM measurement.

Overall, the statistical analysis suggests that the level of agreement between the programs varies for different anatomical structures. Some structures showed good agreement (higher ICC values) between the methods, while others did not.

Table 4 shows the results of the interobserver agreement for measurements of anatomical landmarks in 3D digital models of the mandible using three different software programs: 3D-Matic STL, Diagnocat STL, and MAXILIM. The agreement was assessed using the intraclass correlation coefficient (ICC) with its lower and upper bounds and p-value.

For the distance between the left and right angulus mandibula (DAM), all three software programs showed excellent interobserver agreement with ICC values ranging from 0.984 to 0.994 ($p<0.0001$).

For the distance between the left and right coronoid process (DCP), 3D-Matic STL and MAXILIM showed good interobserver agreement with ICC values of 0.981 and 0.991, respectively, while Diagnocat STL showed excellent agreement with an ICC value of 0.992 ($p<0.0001$).

For the distance between left and right Fovea Pterygoidea (DFP), 3D-Matic STL and Diagnocat STL showed moderate to good interobserver agreement with ICC values of 0.916 and 0.953, respectively, while MAXILIM showed almost perfect agreement with an ICC value of 0.999 (p<0.0001).

For the distance between left and right incisura mandibulae (DIM), all three software programs showed good to an excellent interobserver agreement with ICC values ranging from 0.985 to 0.996 (p<0.0001). For the distance between left and right mental foramina (DMF), 3D-Matic STL and Diagnocat STL showed moderate interobserver agreement with ICC values of 0.922 and 0.902, respectively, while MAXILIM showed almost perfect agreement with an ICC value of 0.997 (p<0.0001).

For the distance between left and right foramen infraorbitalis (DFI), 3D-Matic STL and Diagnocat STL showed poor to moderate interobserver agreement with ICC values of 0.643 and 0.882, respectively, while MAXILIM was not evaluated for this measurement. Overall, the results indicate that MAXILIM showed the highest interobserver agreement for most of the measurements, followed by Diagnocat STL and 3D-Matic STL. The results also demonstrate that the different software programs can affect the interobserver agreement for certain measurements.

Table 5 provides the results of the inter-observer agreement for the assessment of various anatomical structures using different imaging techniques. The intra-class correlation coefficient (ICC) values, lower and upper bounds, as well as the p-values are presented. For the distance between left and right Foramen Infraorbitalis (DFI) and the distance between left and right Foramen palatinum Majus (DFPM) structures assessed with MAXILIM software, the ICC values were 0.997 and 0.997, respectively, indicating excellent inter-observer agreement. The p-values were also highly significant (p<0.0001). For the distance left and right Foramen palatinum Majus (DFPM) and distance between Spina nasalis anterior and spina nasalis posterior (DSN) structures assessed with Diagnocat STL software, the ICC values were 0.517 and 0.897, respectively, indicating moderate to excellent inter-observer agreement. The p-values were significant for both structures ($p=0.044$ and $p<0.0001$, respectively). For the distance between left and right Foramen palatinum Majus (DFPM) structure assessed with 3D-Matic STL software, the ICC value was 0.456, indicating moderate inter-observer agreement. The p-value was not significant ($p=0.071$). For the distance between Spina nasalis anterior and spina nasalis posterior (DSN) structure assessed with 3D-Matic STL software, the ICC value was 0.741, indicating good inter-observer agreement. The p-value was highly significant ($p=0.001$).

Overall, the results suggest that the inter-observer agreement for the assessment of anatomical structures using different imaging techniques varies from moderate to excellent, depending on the structure and software used. The findings have important implications for the reliability and reproducibility of these techniques in clinical and research settings.

Discussion:

Since a statistically significant difference was present between the two STL models and MAXILIM software measurements, the first null hypothesis of the study was rejected. The reliability of the measurements obtained with cephalometric analysis using 3D CBCT data is very important for the correct diagnosis and proper treatment planning. Huotilainen et al. used a patient’s CBCT data who was undergoing a surgical tumoral operation in their study. According to their preferences, three different institutions were asked to automatically reconstruct the patient's

CBCT data into an STL file. Three actual medical skull models were created using these STL data to determine the variances and inaccuracies brought about by the DICOM to STL conversion procedure. They evaluated the geometric discrepancies between the models and found significant changes between the three rebuilt skull models. [8]

For 3D printing of an organ or anatomic structures, DICOM datasets should be extracted and segmented that are recognized by the 3D printer. For this purpose, STL files are the most common for 3D printing. Kamio et al. in their study, used a dry mandible with two metal balls as a phantom and performed a CT imaging. DICOM images of the phantom were exported to the STL files using nine different software packages. They found that the STL model's form changed slightly between different software programs. The quality of the STL data has an impact on 3D printing, and bad STL data might result in the failure of 3D model fabrication.[14] In a different investigation, Ferry et al. used bone sounds, DICOM data alone, and DICOM+STL registrations to estimate soft tissue thickness and compare the results to histomorphological values. Their findings showed that among the three techniques, DICOM+STL registrations had the best agreement with the histology measures.[15] On the other hand, D'Addazio et al. investigated the DICOM-DICOM vs. DICOM-STL surgical template clinical accuracy in the inserted implants and found no statistically significant differences between the two protocols. [16] However, the findings of our study imply that the selection of imaging software may have an impact on the precision of the distance measurements for specific anatomical landmarks. Barker et al. assessed the dry skull and its STL replicas as part of their inquiry into the accuracy of STL models in human anatomy, and they recommended STL models as an accurate replica of the complex anatomy. However, they reported that smaller pixel resolution in CT images may improve accuracy if higher accuracy is required for planning intricate surgical operations.[17]

Shahbazian et al. segmented and generated a STL tooth replica from the CBCT images of a dry mandible. They obtained reasonable results with acceptable accuracy, but in some areas the deviation was up to 2.5 mm. [18] In comparative studies using open source software, Wallner et al. (2018) used the "GrowCut" open-source algorithm to segment the mandible of 10 CT images using the three-dimensional Slicer software. They then compared this segmentation to slice-by-slice segmentation on the same data sets using the MeVisLab software as the ground truth. Several parameters, including segmentation volume, dice similarity coefficient (DSC), and Hausdorff distance (HD) (voxel value), were used to evaluate the accuracy of the segmentation. Their findings showed that HD fell below 33.5 voxels on average, average DSC values were over 85%, and there was no discernible difference in segmentation volumes. [19]

The three-dimensional reconstruction of the mandible segmented using MIMICS and open-source medical imaging interaction toolkit (MITK) software on five CT images was compared by Abdullah et al.. The results of the geometric differences showed that there were no significant discrepancies in the measurement of the landmarks and that the average errors of two three-dimensional models employing HD were less than 1%. These analyses, however, focused on the mandible rather than the entire skull.[20] In another study, Van Steenberghe et al. discovered a 2.7 mm maximum linear deviation while analyzing the variation between implanted implants using a surgical guide made from STL and planned implants. However, the positioning of the surgical guide may have had an effect on the deviation inaccuracy rather than the accuracy of the STL model itself.[21] According to Jardini et al., a virtual three-dimensional model of the human body's interior structures—in this example, the skull—is required for the final creation of a three-dimensional physical model. To maintain its accuracy, it needs very accurate segmentation with high resolution and relatively small-sized pixels.[22]

Santana et al. measured the anterior loop length (ANLL) of the mental nerve using CBCT and STL models and compared these measurements with direct anatomic measurements. They found the STL model ANLL measurements were significantly different from both CBCT and direct anatomic measurements. The ANLL was over and under-estimated in the STL model by up to 1.83 and 1.51 mm, respectively. [23] DICOM data from CT scans were segmented and reconstructed into three-dimensional models in the research by Abdullah et al. utilizing MIMICS and InVesalius software. Without any manual editing from users for either software, the processes of segmentation, postprocessing, and three-dimensional reconstruction were all automated. Users were provided with the same methodology and a step-by-step manual to follow. The human mistake was thus reduced to a minimum. Using InVesalius software, segmenting the skulls required fewer steps than using MIMICS software—six steps as opposed to 19 steps using InVesalius software and MIMICS software, respectively. This demonstrated that, in comparison to proprietary software, open-source software may offer faster processes.[24]

Conclusion

More research needs to be done in the literature because CBCT-derived STL models are now widely used in dentistry, including in orthodontics, AI-based research, and dentomaxillofacial radiology. This study has demonstrated that 3D models derived from CBCT provide higher measurement values than models derived from AI. Additionally, the results demonstrate a significant difference in the STL model reconstruction for maxilla measurements, which may indicate that one should proceed with caution when using the measureme

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