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Accuracy and Reliability of Ultra Low Dose CBCT Versus CBCT Imaging in Semi-Automated Segmentation of the Mandibular Condyle (A Diagnostic Accuracy Study)

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CBCT,
Condyle,
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Ultra-low dose

ABSTRACT:

Aim: The aim of this study was to evaluate the effect of conventional or ultra-low dose CBCT imaging on the accuracy of semi-automated segmentation of the mandibular condyles, and their effect on volumetric measurements when compared to the actual volumetric measurements of the mandibular condyles as a gold standard.

Methodology: Dry human skulls and dry human mandibles were recruited from the Anatomy Department, Faculty of Medicine, Cairo University. Gutta-percha points were secured horizontally parallel to the lowest part of the sigmoid notch all around the mandibular condyles to locate the condylar area for volumetric assessment. Reference standard for mandibular condyle volumes was calculated by using the Archimedes Principle.The dry skulls and mandibles were scanned in the Oral and Maxillofacial Radiology Department, Faculty Dentistry, Cairo University; using CBCT machine Planmeca ProMax® 3D Mid, using two scan protocols; conventional and ultra-low dose. After applying the index test, DICOM files of both CBCT conventional and ultra-low dose CBCT scanning protocols were imported from Romexis software (Romexis® software (Planmeca- Helsinki-Finland) to 3D slicer free segmentation software and semi-automated segmentation was performed. Volumetric measurements were calculated on the segmented condyles by 3D slicer software and compared to the real gold standard measurements.

Results: There was no clinical significant difference between the volumetric measurements obtained from the semi-automated segmented condyles scanned by using ULD CBCT protocol, in comparison to the measurements obtained from conventional CBCT scanning protocols, as well as the actual real gold standard measurements.

Conclusion: ULD scanning protocols should be considered effective when mandibular condyle semi-automated segmentation to be performed. 3D slicer software is an accurate and reliable free segmentation software for maxillofacial structures segmentation, especially mandibular condyles.

INTRODUCTION

The mandibular condyle is one of the most important osseous parts of the temporomandibular joint (TMJ). Functional abnormalities and aging can lead to morphological and histological alterations in the temporomandibular joint **(Altan Şallı & Öztürkmen, 2021).** Determining the morphology and size of the mandibular condyles is essential for diagnosis since they play a significant role in temporomandibular disorders and certain malocclusions. Therefore, it is critical to have an accurate and trustworthy mandibular condyle assessment tool **(García-Sanz et al., 2017).** The condyles are a challenging anatomical structure to segment, due to their unique and complicated architecture, low condylar bone density, proximity to the articular disc, and overshadowing of the glenoid fossa **(Kim et al., 2020; Xi et al., 2014).**

Cone beam computed tomography (CBCT) is thought to be the best imaging method for osseous components. CBCT is a precise, economical, and generally low-radiation imaging method that provides three-dimensional imaging. Moreover, it is a widely utilized dental technique that poses less radiation risk and permits three-dimensional TMJ assessment as well **(Altan Şallı & Öztürkmen, 2021; Yeung et al., 2019).** Radiation dosage protection has drawn increased attention in dental medicine in recent years. One of the most crucial elements of radiation dose protection is the acceptance of the as low as reasonably achievable (ALARA) principle **(Yeung et al., 2019).**

A semi-automated segmentation methodology has been devised to get around the constraints of automatic condylar segmentation. Using local thresholding methods, this protocol requires a seed point from the observer every few CBCT cuts. The software then automatically fills in the missing grey values corresponding to the pre-set threshold. **(Méndez-Manjón et al., 2019).** Semi-automated segmentation is significant since it is faster than manual segmentation. Furthermore, semi-automatic segmentation, which is crucial for clinical and research applications, is not significantly impacted by intra-observer reliability **(Lo Giudice et al., 2020).**

The current study investigated the application of ultra-low dose CBCT imaging and compared the accuracy and reliability of the segmented condyles to those obtained from conventionally yielded CBCT scans.

MATERIALS & METHODS

The study is a prospective study, as data collection was planned before the index test and reference standard were performed.

Study Population:

Dry human skulls and dry human mandibles were recruited from the Anatomy Department, Faculty of Medicine, Cairo University which were recruited according to the following eligibility criteria: The inclusion criteria were mandibles with sound condyles and skulls with sound glenoid fossae. Exclusion criteria were skulls with fractured glenoid fossa or glenoid fossa with developmental deformities, mandibles with fractured condylar necks or heads, and the presence of pathological lesions, fractures, shipping, or developmental deformities in the condyle.

Real Volumetric Physical Measurements of the Condyles:

Volumetric measurements of the dry human condyles were considered a reference standard where the water displacement method was used (according to Archimedes' principle) by immersion of the condyle under investigation in a water-filled graduated transparent glass container, after being hanged from an L-shaped metal hanger by using a rope, till the complete immersion of the condylar volume, as supported by **García-Sanz et al. (2017) & Kim et al., (2020).**

An L-shaped metal hanger and the rope were used for hanging the condyle to provide more standardized stabilization for the condyle volumetric assessment. The water in the transparent graduated container was colored black. This was done to facilitate the demarcation of a certain level on the condylar neck at which gutta percha points were secured, to standardize the volumetric measurement.

The water level was recognized and recorded before the condyle under investigation was immersed then the condyle was gradually immersed under the water level. The level of water after condyle immersion was again recognized and recorded, and then the displaced amount of water was aspirated by using a graduated clear pipette. The volume of water aspirated was recorded.

As previously mentioned, at the water level where the condyle was completely immersed, gutta-percha points were secured horizontally by a glue tape all around the condyle. Gutta-percha points were used as a radiopaque reference to facilitate condylar volumetric assessment after imaging. Aspirated volume of water was converted from milliliters to cubic millimeters, for each of the investigated condyles, similar to the units of volume in the software.

CBCT imaging for the Dry Skulls and Mandibles:

Each skull was assembled with its corresponding mandible by using a clear wrap to ensure complete stabilization during the imaging procedures. Dry human skulls and assembled mandibles were scanned in the Oral and Maxillofacial Radiology Department, Faculty of Dentistry, Cairo University; using the CBCT machine Planmeca ProMax® 3D Mid.

Exposure Parameters:

Scanning was performed using the CBCT machine as follows:

I1 (Index test):: CBCT imaging with conventional dose using the following exposure parameters:

- Kilovoltage: 90 kV.
- Milliampere: 8 mA.
- Field of view: 20 x 6 cm.
- Voxel size: 0.4 mm.
- Exposure time: 13.5s

I2: CBCT imaging with ultra-low dose using the following exposure parameters:

- Kilovoltage: 90 kV.
- Milliampere: 5 mA.
- Field of view: 20 x 6 cm.
- Voxel size: 0.4 mm.
- Exposure time: 4.5s

Image Processing:

Primary reconstruction and processing of the scans, as well as image analysis, were done using Romexis® software (Planmeca, Helsinki, Finland). For each skull, two CBCT scans were acquired: one with a conventional dose and the second with an ultra-low dose (ULD), as mentioned previously.

Image Analysis:

After applying the index test, DICOM files of both CBCT conventional imaging and ultra-low dose CBCT imaging were imported from Romexis software (Romexis® software Planmeca- Helsinki-Finland) to 3D Slicer open-source segmentation software (https://www.slicer.org/), to generate the whole volume of the condyle by using the semi-automated segmentation tool.

Semi-automated Segmentation and Condylar Volume Generation:

In 3D Slicer software, the DICOM files were first imported in “DICOM files” format. After importing the CBCT scan, volume orientation was done to allow the condyle under investigation to be clearly seen and investigated in the software window.

The “Paint” tool was activated, and the brush diameter was selected to be 3 mm for ease and convenient painting of the condyle, also “Sphere brush” & “Edit in 3D” options were selected to allow application of the painting action in the two second cuts (coronal & sagittal) other than the working one (axial).
Painting of the condyle included the whole condylar area till the radiopaque gutta percha markers already secured before imaging.

The “Grow from Seeds” tool was activated for the semi-automated segmentation process to occur and to generate the 3D condylar volume.

Smoothening of the condyle was performed slice by slice until complete smoothening of the segmented condylar volume. The smoothening aims to remove any extra condylar painted areas

The same steps were performed for all the condyles for both the conventional & ULD imaging protocols.

Volumetric Measurements for the Segmented Condyle:

Volumetric measurements for each condyle on the software were calculated by the 3D slicer software, and the following steps on the software took place: The “Markups” module on the 3D slicer software was switched to the “Quantification” module, and the “Segmentation Statics” option was selected. By pressing the “Apply” option in the same module, the volume of the segmented condyle was automatically calculated and tabulated. The volume of the condyle was presented in the software in different units, including the cubic millimeter, automatically by the software. The volumetric measurements calculated by the software were documented. The same steps were done for all the condyles for both the conventional & ULD imaging protocols

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Blinding & Inter- and Intra-Observer Agreement

All scanning results for all the different index tests were reviewed by two oral radiologists with different experiences ranging from 5 to 18 years. One of the two oral radiologists assessed the radiographs twice, with a two-week interval between the two sessions to assess intra-observer agreement.

RESULTS

1- Volumetric measurements descriptive statistics Intergroup comparisons:

The **highest value** was measured at conventional semi-automated group measurements (2243.43±365.79 mm^3), followed by ULD semi-automated group measurements (2158.10±395.49 mm^3), while the **lowest value** was found at real measurements (2126.67±383.21 mm^3). Post hoc pairwise comparisons showed conventional semi-automated group measurements to be significantly higher than values measured at other groups (p<0.001). **Table (1), Figure (1).**

Table (1): Intergroup comparison of volumetric measurements in mm^3.

Measurement	Volumetric measurements (Mean±SD)			p-value
	Real measurements	Software measurements (Conventional semi-automated)	Software measurements (ULD semi-automated)	
Volume (mm^3)	2126.67 ± 383.21^B	2243.43 ± 365.79^A	2158.10 ± 395.49^B	**<0.001***

Values with different superscript letters within the same horizontal row are significantly different *; Significant (p<0.05).

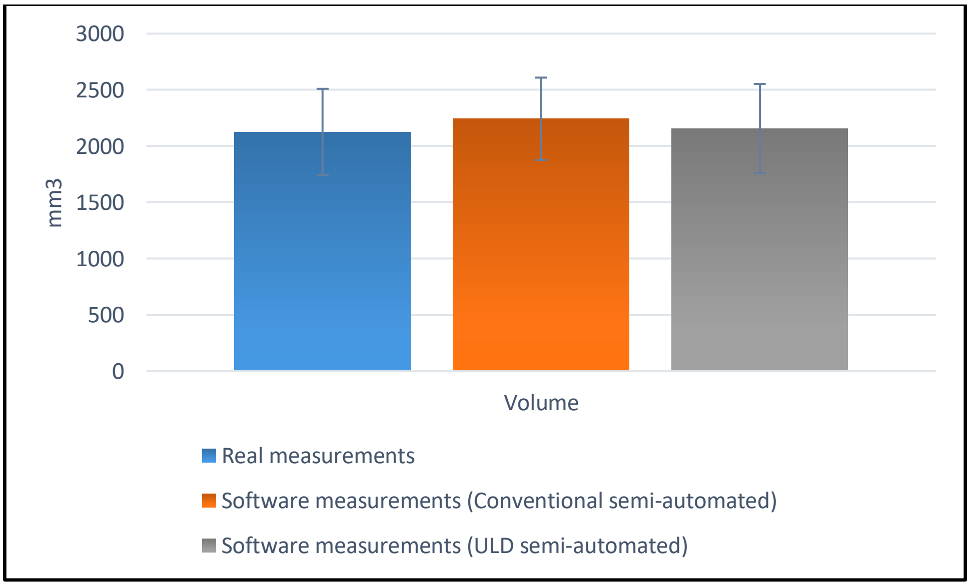

Figure (1): Bar chart showing mean and standard deviation (error bars) values for volumetric measurements.

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2- Volumetric measurements Agreement of Software Measurements:

Both modalities had an **excellent agreement** with real measurements that were statistically significant (ICC>0.9, $p<0.001$). **Table (2).**

Table (2): Agreement analyses for software measurements for volumetric measurements in mm^3.

Measurement	ICC (95% CI)	
	Real-Software (Conventional semi-automated)	**Real-Software (ULD semi-automated)**
Volume (mm^3)	0.959 (0.550:0.988)*	0.978 (0.954:0.990)*

*; Significant ($p<0.05$)

3- Measurements Errors Descriptive statistics

For conventional semi-automated measurements, the mean was (134.17 mm^3) with a 95% confidence interval of (107.64:160.69 mm^3), the standard deviation was (74.13 mm^3), the minimum value was (19.00 mm^3), and the maximum value was (344.00 mm^3).

For ULD semi-automated measurements, the mean was (93.43 mm^3) with a 95% confidence interval of (69.55:117.31 mm3), the standard deviation was (66.74 mm3), the minimum value was (0.00 mm^3), and the maximum value was (250.00 mm^3). **Table (3), Figure (2).**

Table (3): Descriptive statistics of linear and volumetric measurement error in mm^3.

Measurement	Group	Mean	95% CI		SD	Min.	Max.
			Lower	Upper			
Volume (mm^3)	**Software measurements (Conventional semi-automated)**	134.17	107.64	160.69	74.13	19.00	344.00
	Software measurements (ULD semi-automated)	93.43	69.55	117.31	66.74	0.00	250.00

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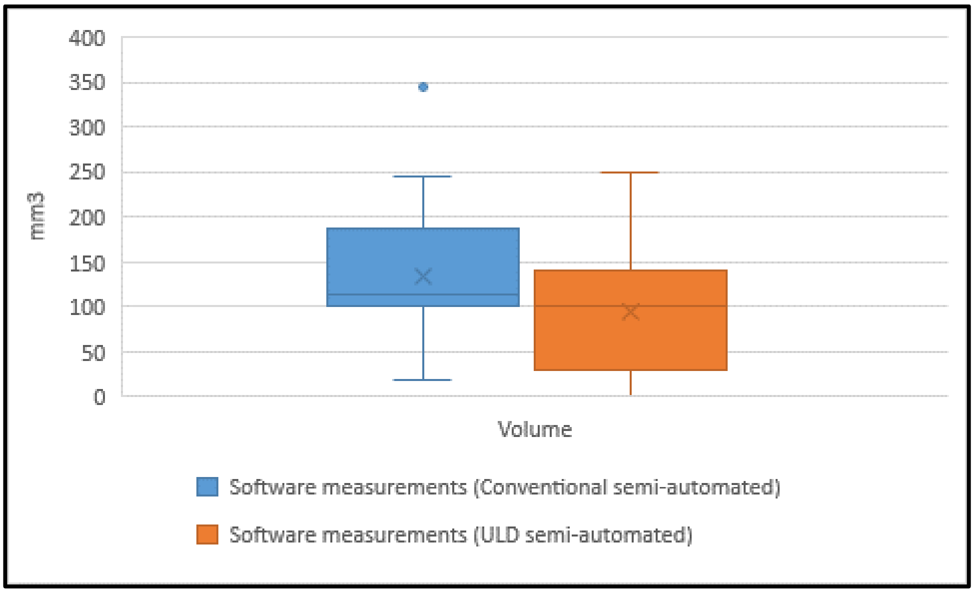

Figure (2): Box plot for volumetric measurement error values.

4- Inter and Intra-observer Reliability:

There was an **excellent agreement** between both observers and observations that was statistically significant (ICC>0.9, p<0.001).

DISCUSSION

Segmentation, along with the resulting 3D model, opens up a range of possibilities for various clinical applications. Traditional segmentation processes for anatomical structures have been manual, involving laborious slice-by-slice labeling, or semi-automatic, where software delineates the region of interest based on user-defined thresholds or inputs. However, these common methods, including thresholding and semiautomatic techniques, are fraught with limitations such as missing intricate bony details, being time-consuming, having a steep learning curve, observer variability, and necessitating manual adjustments **(Alrashed et al., 2024).**

Volumetric measurements from the dry human condyles were considered a reference standard where the water displacement method was used (according to Archimedes' principle) by immersion of the condyle under investigation in a water-filled graduated transparent glass container, after being hanged from an L-shaped metal hanger by using a rope, till the complete immersion of the condylar volume (which was demarcated by using the gutta-percha points) under the water level. This provided more standardization. Then, the displaced amount of water was observed and then aspirated by a graduated pipette to calculate its volume in cubic millimeters.

Archimedes' principle for measuring the condylar volume by the water displacement method was supported by Bayram et al., (2012), García-Sanz et al., (2017); Kim et al., (2021) in their studies **(Bayram et al., 2012; García-Sanz et al., 2017; Kim et al., 2021).**

Yeung et al., (2021) aimed to determine whether or not observers gave significantly different ratings to the CBCT image quality acquired pre- and post-root canal treatment using different exposure protocols: ultra-low-dose (ULD), standard (SM), and high-resolution mode (HR). The ULD does not appear to have a negative impact on the diagnostic quality of the CBCT images based on the observers' ratings **(Yeung et al., 2021)**. That was supportive evidence for using ultra-low-dose CBCT protocols in the current study.

3D Slicer software is an open-source segmentation software that was used in the segmentation of many maxillofacial structures such as teeth, mandibular segmentation, and airway segmentation with reported accuracy and reliability **(Herren et al., 2022; Lo Giudice et al., 2022).** To the best of our knowledge, it hasn't been used in the segmentation of mandibular condyles before, which is considered a gap of knowledge to be covered by the current study.

Volumetric measurements for each condyle were calculated and measured by using the 3D Slicer software tools according to the reference taken and measured on the real condyles. The same was performed by García-Sanz et al., (2017) in their study to assess the accuracy of cone-beam computed tomography (CBCT) on linear and volumetric measurements of condyles on dry skulls **(García-Sanz et al., 2017).**

For the volumetric descriptive analysis, the results were as follows:Intergroup comparison results showed that the **highest value** was measured at conventional exposure protocol measurements (2243.43±365.79 mm^3), followed by ULD exposure measurements (2158.10±395.49 mm^3), while the **lowest value** was found at real gold standard measurements (2126.67±383.21 mm^3), showing **no statistically significant difference** neither between both exposure protocols nor with the real gold standard. Both modalities had an **excellent agreement** with **real measurements that were statistically significant.**

To the best of our knowledge, no previous study has assessed the volume of the segmented condyles using different CBCT dose protocols. However, the current study results are found in agreement with Alrashed et al., (2024) whose study aimed to evaluate the effects of exposure protocol, voxel sizes, and artifact removal algorithms on the trueness of segmentation in various mandible regions using an artificial intelligence (AI)-based system. This study used conventional and ULD exposure protocols of the CBCT scans for dry human mandibles, sharing almost the same methodology as the current study except for the segmentation type. The results of this study showed that the exposure protocol did not affect root mean square (RMS) values for mandibular condyles ($p = 0.114$).

The mean error for conventional semi-automated measurements was (134.17 mm^3), while that of ULD semi-automated measurements was (93.43 mm^3). The difference measured in the conventional measurements was **higher** than the difference measured in the ULD measurements, yet the difference **was not statistically significant.** Regarding the measurements error and intergroup comparisons of the volumetric measurements, there was **no statistically significant difference** nor **clinical significant difference,** neither between both exposure protocols nor with the real gold standard.

In a study by García-Sanz et al., (2017)**,** regarding the volume calculations. CBCT was found to be highly accurate, with a mean difference between CBCT-scanned condyle and the gold standard real condylar measurements of 0.010 ± 0.095 cm^3 and a strong linear correlation (R2 = 0.922). Despite showing less mean difference than the current study and sharing the same outcomes, this study did not use the semi-automated segmentation technique to calculate the condylar volume as the current study, but instead used a 3D scanner to obtain STL surface models of the twelve condyles, and then each surface model was imported and superimposed onto its corresponding DICOM reconstruction using the manual superimposition tool included in the Dolphin Imaging® software. These differences in the methodology make the difference in the results easily apprehended **(García-Sanz et al., 2017)**.

CONCLUSION

CBCT is an accurate and reliable imaging modality for maxillofacial structures segmentation and ULD CBCT protocols can be used for the purpose of segmentation of various maxillofacial structures without compromising image quality.

RECOMMENDATIONS

In vitro studies, such as the current setting, allowed variables to be precisely controlled. Although this setting does not exactly reproduce clinical practice, it is important as a reference point for future clinical studies, which we highly recommend. Further clinical studies are needed to assess the effect of ULD CBCT imaging protocols as well as their effect on the accuracy and reliability of semi-automated segmentations.

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