Reliability and accuracy of a method for measuring temporomandibular joint condylar volume

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Objective. The aim of this study was to develop and validate a technique for mandibular condyle segmentation and volume determination by using cone beam computed tomography (CBCT).
Study Design. A dry skull was used to generate 3 dimensional (3-D)−printed mandible models that were then imaged by using CBCT. Semiautomatic segmentation of condyles was completed. The Frankfurt plane was established and translated to the most inferior point of the sigmoid notch, and the condylar volume superior to the plane was determined. This procedure was repeated on 3-D-printed mandibles by using physical landmarks and the water displacement method to obtain the physical volume. This was repeated 3 times to evaluate reliability. Sensitivity analysis was performed to demonstrate the effect of discrepancies in locating landmarks in the Frankfurt plane. Condylar volume measurements obtained from CBCT were compared with physical measurements through repeated-measures analysis of variance (ANOVA) to determine accuracy.
Results. Condylar volume obtained from CBCT and physical measurements resulted in an intraclass correlation coefficient of 0.988 (0.918, 0.998) ($P < .01$) with both modalities, demonstrating excellent intrarater reliability. The mean difference of volume measurements between the modalities was not statistically significant ($P = .365$). Potential discrepancies in porion coordinates had minimal impact on condylar volume change.
Conclusions. The condylar segmentation technique proved to be a reliable and accurate method for evaluating condylar volume. (Oral Surg Oral Med Oral Pathol Oral Radiol 2021;131:485−493)

Advancement of 3-dimensional (3-D) imaging modalities has enabled clinicians and researchers to analyze various craniofacial structures to an extent that was not possible with 2-dimensional (2-D) radiographic images.[1] Cone beam computed tomography (CBCT) has become an increasingly important adjunctive diagnostic tool in assessing dentofacial structures and helping clinicians establish accurate diagnoses and treatment plans.[1] This is primarily attributed to its ability to provide linear and volumetric measurements on 3-D skeletal models[2] while exposing patients to a relatively low radiation dose in comparison with conventional computed tomography (CT).[3] CBCT is often used in imaging of the temporomandibular joint (TMJ), where this technology shows promise in assessing condylar shape and volume for both physiologic and pathologic condylar changes.[4,5]

The comprehensive assessment of a particular dentofacial structure from a CBCT image requires an accurate and reliable segmentation procedure to isolate the structure with a known resolution.[6] TMJ condylar segmentation with the use of CBCT images is more difficult than segmentation of other osseous structures because of the presence of the articular disk, proximity to the glenoid fossa, and the typical voxel size employed in the scans.[6-8] As a result of this complexity, the need to establish reliability and accuracy in segmentation and analysis methods is critical before their use in clinical decision making. Several 3-D condylar segmentation methods have been studied. Volume threshold-based segmentation is the most widely used and exhibits high degrees of reliability and accuracy when performed by an experienced technician or clinician; however, the results are poorer when performed by an operator with limited experience.[6] Other segmentation methods have been designed to minimize operator subjectivity. The manual segmentation technique achieves this objective by having the operator outline the condylar border for each CBCT slice.[9] Although manual segmentation demonstrated high accuracy compared with physical measurements (the gold standard) on cadaveric mandibles in a previous study, it is a tedious process that may be clinically unfeasible when multiple condylar segmentations are required with time constraints.[9]

Statement of Clinical Relevance

The study describes a semiautomatic method for segmenting the mandibular condyle. The results demonstrated that this clinically relevant method is a reliable and accurate means to measure condylar volume and, thus, facilitate the study of condylar changes in various clinical scenarios.

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Received for publication Apr 23, 2020; returned for revision Jul 29, 2020; accepted for publication Aug 14, 2020.

2212-4403/$-see front matter
https://doi.org/10.1016/j.oooo.2020.08.014

Semiautomatic segmentation methods require some level of user input to specify bulk parameters (e.g., threshold values) that are applied to all 2-D slices comprising 3-D reconstruction. In this method, the operator selects the global threshold range, and the computer algorithm determines the volume of interest (VOI) based on preselected gray-scale cutoff values.[10-12] Recent studies have demonstrated the reliability of segmentation methods but have not provided comparisons with a validated reference model (gold standard) to establish numerical accuracy for linear and/or volumetric measurements.[10-13]

Evidence is lacking regarding the reliability (i.e., the ability to repeat a process using a prescribed method) and accuracy (i.e., comparison of a measurement to a known reference value) of semiautomatic condylar segmentation techniques with respect to condylar volume and associated measurements. Establishing a reliable and accurate method to segment the mandibular condyle from CBCT images could further advance knowledge of the different ways condylar remodeling, whether pathologic or physiologic in nature, can occur. The objective of this study was to develop and validate a semiautomatic condylar segmentation technique from CBCT images.

MATERIALS AND METHODS

Fabrication and scanning of mandibular models

A well-preserved dry human skull, used for educational and research purposes, was obtained from the Department of Anatomy, University of Alberta (Edmonton, Alberta, Canada). The mandible was isolated from the skull and scanned by using an i-CAT Next Generation CBCT unit (Imaging Sciences International, Hatfield, PA) at 120 kVp, 7 mA, 9.1 seconds exposure time, and 0.25 mm voxel size. The volume was saved in Digital Imaging and Communications in Medicine (DICOM) format and was converted to the stereolithography (STL) file format by using Dolphin imaging software (Dolphin Imaging and Management Systems, Chatsworth, CA). Three mandibular models were 3-D printed by using an Objet Eden350 V printer (Stratasys, Eden Prairie, MN) with Vero gray material at a resolution of 16 microns in the z-axis (vertical). Six radiopaque markers were placed for each 3-D-printed model at the following locations: the most superior point of the right and left coronoid processes, the right mental foramen, and 3 tripod areas along the inferior border of the mandible physically contacting the surface when the model was placed on a flat surface.

For CBCT scans, the 3-D-printed mandibular models were fitted back into the dry skull and placed into a double-layered Plexiglas box with water-filled compartments situated between 2 layers of Plexiglas to simulate soft tissue attenuation, as shown in Figure 1. The full skull was imaged in this case to allow for condylar segmentation by using the Frankfurt horizontal (FH) plane, as will be discussed below. CBCT scanning was performed on the i-CAT scanner, following the normal clinical full field of view protocol at 8.9 seconds exposure time, 0.3 mm voxel size, and a 640 × 640 mm field of view to replicate the clinical scenario. These settings were chosen instead of settings that would have produced the highest possible spatial resolution; these settings are not commonly used in clinical practice because of increased radiation exposure of the patient. Images were then converted to the DICOM format. CBCT images regenerated from the 3-D-printed models now served as the digital format from which reliability and accuracy could be determined through comparison with the physical models.

Fig. 1. Dry skull and 3-dimensional (3-D)−printed mandible placed in a Plexiglas box with water-filled compartments simulating soft tissue attenuation during cone beam computed tomography (CBCT).

Semi-automatic segmentation of CBCT images

DICOM files of the scanned CBCT images were imported and analyzed by using the Avizo software Standard Edition, Version 9.1 (Mercury Computer Systems Inc., Chelmsford, MA). Although Dolphin is the most commonly used software in clinical practice, Avizo was used to assess the CBCT volume because this software, unlike Dolphin, maintains raw voxels without any smoothing algorithm, thereby allowing segmentation of the desired structure slice by slice without compromising the accuracy of the resulting segmented condylar volume. Additionally, Dolphin's segmentation function is limited to the threshold-based volume segmentation with the use of sculpting tools. Once the isosurface volume of scanned CBCT images was established, the threshold range was adjusted by the operator for the best-fit condylar outline in an axial slice through the condyle (Figure 2A). Thereafter, a seed-point was selected by the operator for every axial

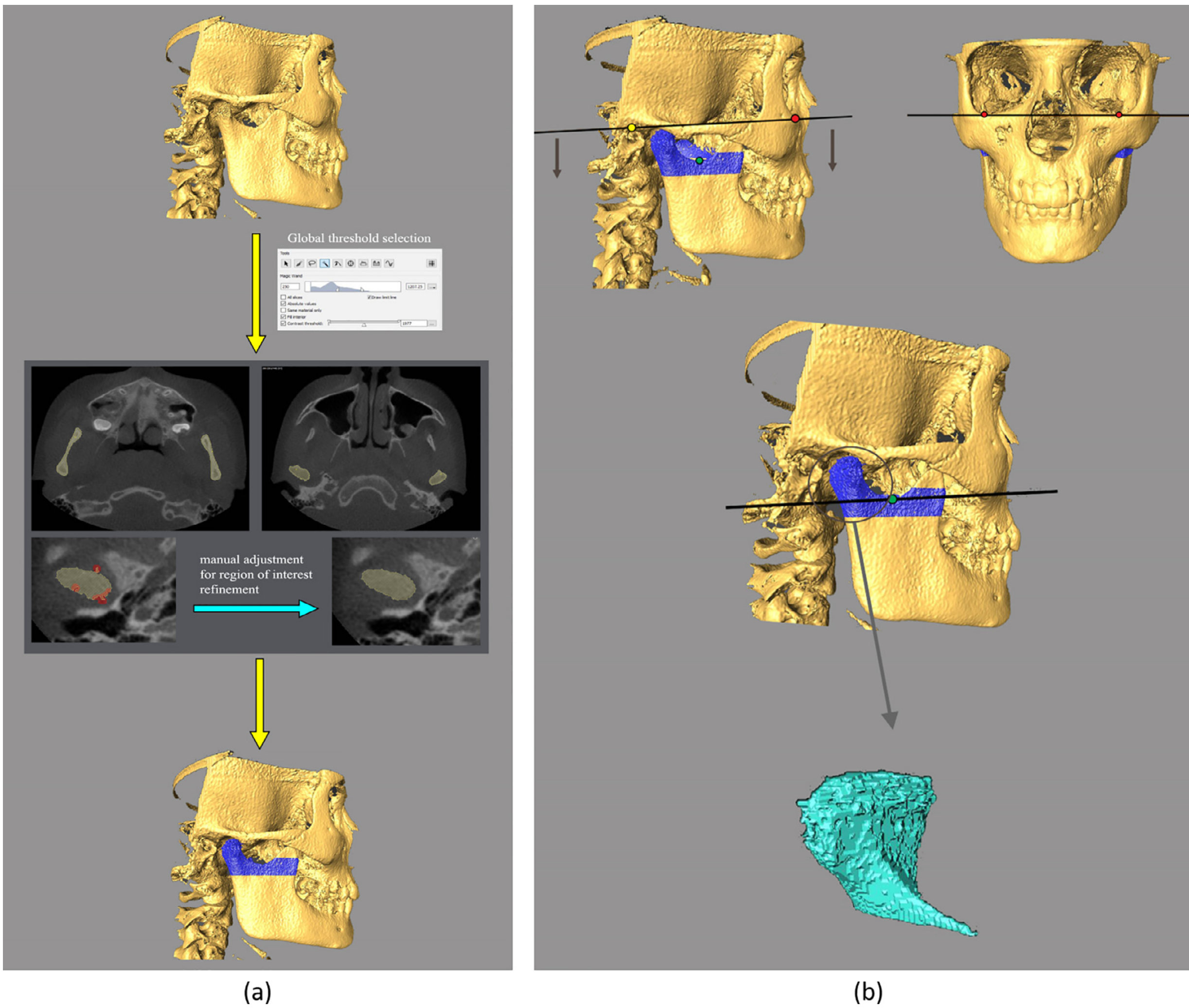

Fig. 2. **A,** Schematics showing steps for semiautomatic segmentation of the mandibular condyle, including bulk threshold selection for cone beam computed tomography (CBCT) and manual adjustment of individual slices to clearly identify the mandibular region of interest for further segmentation. **B,** Identification of the Frankfurt horizontal (FH) 3-dimensional (3-D) plane *(top)*; translation of the FH plane inferiorly to the inferior most point of the sigmoid notch *(middle)*; and segmented condylar volume after determining the volume of interest (VOI) *(bottom)*.

slice through the condylar VOI. When an obvious addition of surrounding structures outside the VOI or omission of condylar structure occurred as a result of diminished contrast in gray value, the threshold range was manually adjusted, or a limiting line was used to correct the selected area of interest. A new surface model from the segmented volume was constructed with zero surface smoothing.

VOI determination in CBCT

A 3-D FH plane, which passed through the lowest point of the inferior orbital margins (orbitale) and the most superior point of external auditory meatus (porion), was constructed by using 3 landmarks from the craniofacial structure (Figure 2B): left and right infraorbitale and porion. The porion that was used in generating the FH plane depended on the condyle of interest. If the right or left condylar volume was to be measured, the right or left porion was used, respectively, for generating the FH plane. The condylar VOI was determined by translating the FH plane inferiorly until it reached the most inferior point of the sigmoid notch, and the resulting condylar volume superior to this plane comprised the VOI. This process of CBCT condylar segmentation and VOI determination was repeated by the same operator 3 times, a week apart each for the 6 condyles, in random order each time.

Comparison of CBCT and physical condylar VOI

The inferior plane marking the condylar VOI was transferred to the 3-D-printed mandibular model using 12 linear distance measurements on each condyle constructed

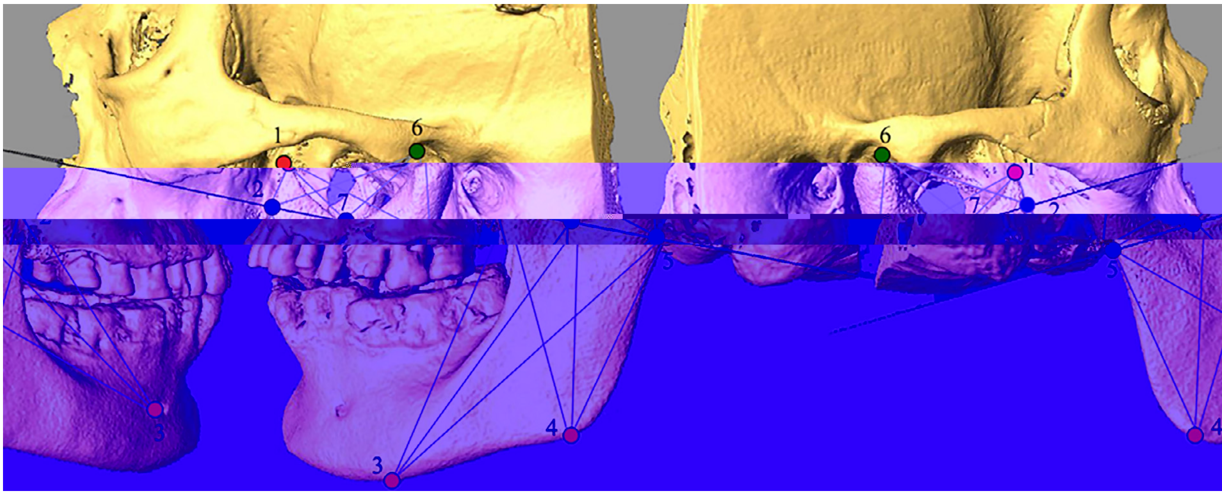

Fig. 3. Reference markers including 6 radiopaque markers *(red)* and 2 anatomic landmarks: superior most point of the right and left condyles in the calibrated mandibular orientation *(green)*; 3 points along the inferior border of the VOI *(blue)*; 12 linear measurements between reference markers and the 3 points defining the inferior border of VOI *(gray lines)*, with all points numbered for identifying measurements.

through radiopaque markers and landmarks (Figure 3). The reference points were represented by 6 radiopaque markers (red circles in Figure 3) and the most superior point on the condylar heads (green circles) for each mandibular model. Small pieces of gutta percha were embedded into putty pressed onto the mandible before CBCT imaging such that they would be located in scans and could be physically measured. To locate the superior most point of the condylar head, 3 radiopaque markers along the inferior border of the physical model were used to calibrate the orientation of the mandible by using CBCT reconstructions. The 3 inferior points, as shown in Figure 3, were located through the natural resting locations of the physical mandibular models on a flat surface. Subsequently, the most superior point of the condyles was identified in the CBCT volume and in the physical models with the consistent mandibular orientation. Because 2 of the resting points resided on the left side of the mandible, an additional inferior point was necessary on the right side for adequate verification of physical landmarks. As such, the right mental foramen was used.

Three points were identified along the inferior border of the VOI on CBCT reconstructions: 1 in the anterior aspect of the coronoid process, 1 at the most inferior point of the sigmoid notch, and 1 in the posterior aspect of the condylar neck (blue circles in Figure 3). The linear distances from each of the 4 reference markers to each of the 3 points along the inferior border of the VOI were measured in the CBCT volume, totaling 12 linear measurements per condyle. Using the reference markers on the physical model and the linear measurements from the CBCT volume, 3 points along the inferior border of the VOI were identified and marked initially on the physical models by using a digital caliper. Linear measurements between the identified points and reference markers on all 6 physical condyles were validated by using a FARO Arm coordinate measurement machine (FARO, Lake Mary, FL), which has a linear accuracy of 0.025 mm,[14] and comparing them with those obtained from the CBCT images.

By using the validated marked points, the inferior border of the VOI was marked and scribed on the physical models with 0.5 mm depth indentation using a high-speed metal disk. Three impressions of each of the physical condyles were obtained by using laboratory putty (Coltene/Whaledent Inc., Cuyahoga Falls, OH), and any excess material beyond the scribed plane was removed. Each impression was measured on an analytic balance (sensitivity = 0.1 mg) before and after being filled with distilled water at 23°C (density = 0.9982 g/cm^3). The final volume of the physical model of the condyle was calculated by using the mass difference and the known density of water.

Measurement sensitivity in determining the condylar VOI

To assess the effect of potential operator errors in determining the inferior plane of the VOI on the final volume of the condyle through errors in landmark placement, the FH plane was rotated in intervals of 1 degree up to 3 degrees in both clockwise and counterclockwise directions. Each plane was then translated until it intersected the inferior most point of the sigmoid notch, and the final condylar volume was calculated for each interval. Furthermore, the inferior plane was translated up to 0.9 mm by using intervals of 0.3 mm (representing the linear voxel size) superiorly and inferiorly, and the resulting condylar volumes were calculated. This process was repeated for all 6 condyles.

Statistical analysis

Statistical analysis was performed by using the SPSS software version 23.0 for Mac (SPSS Inc., Chicago, IL) with a significance level of α = 0.05. Intraclass correlation coefficients (ICCs) were used to compare the linear measurements obtained from the CBCT images with those obtained from the 3-D printed mandible by using the FARO Arm . Assessment of intrarater reliability and accuracy of condylar volume measurements, by using the semiautomatic segmentation compared with the physical volume, was performed by using ICC. Interpretation of ICC values was done according to the guidelines outlined by Koo and Li.[15] Repeated-measures analysis of variance (ANOVA) was used to compare the CBCT and physical volume measurements of the condyle.

RESULTS

A comparison of the linear measurements obtained from CBCT images with those obtained from the 3-D printed models by using the FARO Arm , with percentage error for each measurement, is summarized in Table I. The mean difference of the linear distances between the 2 measurement modalities was −0.51 ± 0.94 mm. The ICC result of 0.998 (95% confidence interval [CI] 0.997− 0.999; $P < .001$) showed an excellent agreement between the 2 modalities.

ICC values of the 3 sets of volume measurements from the physical condylar models and the CBCT images, with use of the semiautomatic segmentation technique from the same observer for intrarater reliability, are shown in Table II. In terms of the intrarater reliability for both the physical and the CBCT methods, the average error differences and standard deviations among the 3 sets of measurements were calculated to be −0.89 ± 25.42 mm^3 for the physical volume and 4.56 ± 17.17 mm^3 for the CBCT volume. The mean difference between the physical volume and the CBCT image volume was 4.83 ± 11.89 mm^3. The percentage difference ranged from 0.18% to 0.78%, and the mean percentage difference was 0.54%. The ICC value demonstrating the agreement between the resulting condylar volumes from the CBCT images using the semiautomatic segmentation technique and those obtained from the physical condylar models was 0.988 (95% CI 1 0.918−0.998) (see Table II). Repeated-measures ANOVA of CBCT and physical volume measurements showed no statistically significant difference ($P = .365$).

Sensitivity analysis (Table III) demonstrated the change in resultant condylar volume in percentage difference and absolute difference values when the segmentation plane was translated along a superoinferior axis and rotated within the sagittal plane . The mean of absolute difference change in condylar volume per 0.3 mm translation was 25.49 ± 6.92 mm^3 when

Table I. Linear distance measurements obtained from cone beam computed tomography (CBCT) images and from the 3-dimensional (3-D)−printed mandibular models by using the FARO Arm (FARO, Lake Mary, FL) with differences in percentage. Points are as referred to in Fig, 2 with the side of the mandible in parentheses.

Points	*CBCT (mm)*	*FARO Arm (mm)*	*%error*
Mandible 1			
2-1 (R)	9.42	9.77	3.57%
2-4 (R)	17.61	17.42	1.08%
2-6 (R)	34.94	36.53	4.35%
5-1 (R)	33.16	34.79	4.68%
5-4 (R)	21.50	20.69	3.89%
5-6 (R)	19.74	20.82	5.19%
7-1 (R)	63.08	62.74	0.55%
7-4 (R)	67.73	69.79	2.95%
7-6 (R)	76.25	77.81	2.01%
2-1 (L)	9.48	9.84	3.66%
2-4 (L)	16.44	16.51	0.44%
2-6 (L)	33.79	36.63	7.76%
5-1 (L)	33.98	33.34	1.92%
5-4 (L)	23.32	20.30	14.86%
5-6 (L)	20.80	21.04	1.13%
7-1 (L)	49.20	48.46	1.52%
7-4 (L)	46.43	46.95	1.12%
7-6 (L)	47.46	46.85	1.31%
Mandible 2			
1-2 (L)	9.20	9.43	2.39%
1-5 (L)	34.49	35.78	3.59%
1-7 (L)	17.91	17.92	0.07%
4-2 (L)	49.78	49.78	0.00%
4-5 (L)	47.04	48.73	3.46%
4-7 (L)	45.71	46.14	0.93%
6-2 (L)	32.95	33.88	2.73%
6-5 (L)	17.94	18.06	0.64%
6-7 (L)	19.68	19.40	1.47%
8-9 (R)	7.85	8.21	4.37%
8-12 (R)	33.66	35.03	3.90%
8-14 (R)	17.34	17.33	0.09%
11-9 (R)	49.37	50.53	2.29%
11-12 (R)	47.39	48.94	3.17%
11-14 (R)	46.56	47.14	1.24%
13-9 (R)	31.83	32.34	1.58%
13-12 (R)	18.30	19.08	4.09%
13-14 (R)	18.90	19.17	1.43%
Mandible 3			
1-2 (L)	8.72	8.80	0.90%
1-5 (L)	34.51	36.04	4.25%
1-7 (L)	16.96	17.09	0.75%
4-2 (L)	49.31	49.94	1.26%
4-5 (L)	44.58	45.15	1.27%
4-7 (L)	44.75	45.45	1.53%
6-2 (L)	32.93	33.90	2.86%
6-5 (L)	19.00	19.78	3.94%
6-7 (L)	20.50	20.63	0.61%
8-9 (R)	8.04	8.44	4.78%
8-12 (R)	15.09	15.86	4.82%
8-14 (R)	32.85	34.50	4.77%
11-9 (R)	50.31	50.39	0.16%
11-12 (R)	44.93	44.28	1.47%
11-14 (R)	43.65	45.87	4.85%
13-9 (R)	31.05	31.39	1.07%
13-12 (R)	19.62	20.48	4.21%
13-14 (R)	21.18	20.47	3.48%

Table II. Intraclass correlation coefficient values for the physical condylar models' volume determination and semiautomatic condylar segmentation technique from CBCT images

	Intraclass correlation coefficient	*95% Confidence interval*	
		Lower-bound	*Upper-bound*
Physical	0.932	0.748	0.989
CBCT	0.990	0.959	0.999
Physical−CBCT	0.988	0.918	0.998

CBCT, cone beam computed radiography.

shifted in the inferior direction and −29.86 ± 10.81 mm^3 when shifted in the superior direction. Regarding rotation, the volume changed an average of 13.86 ± 9.92 mm^3 when the plane was rotated counterclockwise by 1 degree and −12.67 ± 3.08 mm^3 when rotated clockwise by 1 degree.

DISCUSSION

Although there are various methods of segmenting mandibular condyles with CBCT imaging, the semiautomatic segmentation technique has shown promise as an effective method of segmenting and analyzing condyles while still being attractive with regard to clinical efficiency and usability.[11,12] The results from this study demonstrated excellent intrarater reliability (ICC = 0.990) when the same condylar volume was calculated 3 times by the same rater, each a week apart, using the condylar volume determination technique described above. Additionally, there was excellent agreement between the condylar volume results obtained from the physical models (the gold standard) and those obtained from CBCT images by using the developed semiautomatic segmentation technique (ICC = 0.988). This supports the high reproducibility of this segmentation technique, which has been presented previously,[12,16] and excellent accuracy in assessing condylar volume compared with reference values. Despite the use of this approach in previous studies, its accuracy compared with an appropriate reference model had not been demonstrated in those studies. Such evidence is paramount in understanding the validity of the method and its inherent limitations. The intrarater reliability of physical volume determination (ICC = 0.932) had a wider CI (0.748−0.989) compared with that of the CBCT method. This is explained by possible errors introduced by the dimensional stability of the impression material and possible human error in physically cutting along the segmentation line.[17]

CBCT 3-D imaging and analysis techniques have the advantage of allowing the operator to conveniently select and move different planes through specified anatomic landmarks.[18] The ICC value of 0.998 indicated excellent agreement between the linear distances measured from CBCT images by using the Avizo software and those measured by using the FARO Arm , given that the mean difference found (−0.51 ± 0.943 mm) was slightly lower than the size of 2 voxels. This suggests that the method described to transfer the segmentation plane defined in the CBCT volume to the 3-D-printed mandibular model is highly correlated, with minimal mean difference. For this particular application, the magnitude of the difference is likely to be clinically irrelevant.

Accurate volume analysis of the results of therapeutic interventions requires accurate and repeatable establishment of a VOI.[10] In terms of mandibular condylar volume analysis, the reproducibility of the inferior plane segmenting the mandibular condyle had a substantial impact on the resultant condylar volume. The method presented in this study is based on reliable determination of the skeletal FH plane by using 3 landmarks: left and right orbitale and left or right porion corresponding to the condyle of interest. Although the skeletal FH plane has been used as a reference plane for analysis from CBCT image volumes,[11-13,19] the sensitivity of the corresponding measures resulting from the selection of this plane had not been previously considered. First, the predetermined inferior plane of the VOI was translated by 1 voxel size interval (0.3 mm), and the difference (25.49 ± 6.92 mm^3) was considerably larger than the difference detected when the plane was rotated counterclockwise by 1 degree (13.86 ± 9.92 mm^3). Pure translational error is less likely to occur because once the FH plane is determined, locating and moving the plane to the inferior most point within the sigmoid notch is generally reproducible. It is considerably more probable that the human errors associated with determining the FH plane would surpass those arising from translating it to the sigmoid notch. Mohsen et al. described the reproducibility of landmarks constituting the FH plane, and their study revealed that the porion z-axis coordinate, in the superoinferior direction, exhibited the lowest interobserver and intraobserver reliability relative to other axes of porion coordinates and all axes of orbitale coordinates.[20] This is further supported by the results reported by Hofmann et al.[21] This relatively low reproducibility in the superoinferior axis coordinate of porion caused changes in the rotation of the FH plane within the sagittal plane, thereby affecting overall condylar VOI. When the inferior segmentation plane was rotated by 1 degree, the mean difference in the resultant condylar volume was approximately half of the change observed by 1-voxel translation, and with less than 1.51% volume discrepancy. This 1-degree rotation of the inferior segmentation plane would result from approximately

Table III. Changes in the condylar volume resulting from translation and rotation of the inferior plane of the VOI in percentage difference and absolute values

Translational change	*Translation (%)*	*Translation (mm^3)*	*Rotational change*	*Rotation (%)*	*Rotation (mm^3)*
Condyle 1 R					
−0.9 mm	2.76%	56.71	−3 deg	1.57%	32.19
−0.6 mm	1.72%	35.30	−2 deg	0.74%	15.30
−0.3 mm	0.88%	18.03	−1 deg	0.22%	4.51
0	0.00%	0.00	0	0.00%	0.00
+0.3 mm	−1.65%	−33.98	+1 deg	−0.52%	−10.64
+0.6 mm	−3.64%	−74.82	+2 deg	−1.25%	−25.75
+0.9 mm	−4.56%	−93.67	+3 deg	−1.72%	−35.32
Condyle 1 L					
−0.9 mm	5.19%	99.63	−3 deg	3.73%	71.70
−0.6 mm	3.59%	68.87	−2 deg	2.66%	51.16
−0.3 mm	1.77%	33.96	−1 deg	1.51%	28.97
0	0.00%	0.00	0	0.00%	0.00
+0.3 mm	−1.06%	−20.43	+1 deg	−0.49%	−9.44
+0.6 mm	−2.35%	−45.04	+2 deg	−1.04%	−20.02
+0.9 mm	−3.59%	−68.94	+3 deg	−1.60%	−30.73
Condyle 2 R					
−0.9 mm	2.81%	57.78	−3 deg	1.80%	36.90
−0.6 mm	1.90%	39.09	−2 deg	0.93%	19.19
−0.3 mm	0.89%	18.34	−1 deg	0.15%	3.07
0	0.00%	0.00	0	0.00%	0.00
+0.3 mm	−2.08%	−42.79	+1 deg	−0.56%	−11.47
+0.6 mm	−3.72%	−76.54	+2 deg	−1.16%	−23.72
+0.9 mm	−4.85%	−99.85	+3 deg	−1.72%	−35.28
Condyle 2 L					
−0.9 mm	4.85%	93.98	−3 deg	2.71%	52.46
−0.6 mm	3.21%	62.18	−2 deg	1.94%	37.51
−0.3 mm	1.47%	28.53	−1 deg	1.10%	21.23
0	0.00%	0.00	0	0.00%	0.00
+0.3 mm	−1.06%	−20.50	+1 deg	−0.59%	−11.38
+0.6 mm	−2.21%	−42.72	+2 deg	−1.79%	−34.62
+0.9 mm	−3.98%	−77.08	+3 deg	−1.92%	−37.19
Condyle 3 R					
−0.9 mm	3.30%	67.54	−3 deg	1.86%	38.16
−0.6 mm	2.02%	41.50	−2 deg	1.02%	20.92
−0.3 mm	1.08%	22.19	−1 deg	0.67%	13.78
0	0.00%	0.00	0	0.00%	0.00
+0.3 mm	−2.01%	−41.25	+1 deg	−0.81%	−16.58
+0.6 mm	−3.59%	−73.63	+2 deg	−1.70%	−34.79
+0.9 mm	−4.56%	−93.48	+3 deg	−2.91%	−59.69
Condyle 3 L					
−0.9 mm	4.18%	81.57	−3 deg	2.08%	40.70
−0.6 mm	2.91%	56.87	−2 deg	1.20%	23.35
−0.3 mm	1.63%	31.89	−1 deg	0.59%	11.61
0	0.00%	0.00	0	0.00%	0.00
+0.3 mm	−1.03%	−20.20	+1 deg	−0.84%	−16.49
+0.6 mm	−2.77%	−54.15	+2 deg	−1.83%	−35.71
+0.9 mm	−3.97%	−77.43	+3 deg	−2.89%	−56.37

Deg, degrees; *L,* left; *R,* right; *VOI,* volume of interest.

1.5 mm of vertical change in the porion point landmark of the FH plane on a normal human cranium. This is well above the inferosuperior consistency of the porion landmarks of 0.59 ± 0.42 mm assessed by 9 different assessors on CBCT volumes as demonstrated by Schlicher et al.[22] The same study also suggested that porion should be used for analysis of vertical and sagittal measurements but not for analysis consisting of the transverse dimension because of relatively high inconsistency in transverse dimension in locating the porion. The results from this study suggested that possible human error in locating porion, potentially a less reliable landmark when establishing the FH plane, had a minimal impact on the resultant condylar volume.

Multiple different condylar segmentation techniques have been proposed and studied.[9,10,12,23] The semiautomatic segmentation offers a potential advantage of minimizing operator subjectivity and potentially saving time by relegating much of the manual work to the software algorithm. Although the reliability of this method had been well established in previous studies,[10,11] there was a lack of any comparisons with a validated reference model to demonstrate accuracy. Accuracy of the collected data is crucial when assessing condylar volumetric changes to ensure that the methods used are valid and understand the quantitative limits when considering the desired measures. The results of the present investigation will facilitate understanding of condylar volumetric changes with regard to both pathologic and physiologic alterations within the TMJ. This will help quantify both condylar resorption and growth and may be useful in the analysis of various TMJ treatments involving mandibular condyles. This study demonstrated that the semiautomatic condylar segmentation technique is both highly reliable and accurate and helped determine the sensitivity of the desired measures in response to potential deviations of the FH plane from the desired orientation, which had not been examined previously.

This study had a number of limitations that need to be considered when interpreting the presented data. The most significant factor may be the use of CBCT scans of the 3-D-printed model to perform semiautomatic segmentation. CBCT scans of 3-D-printed materials have a different gray-scale value compared with that of human mandibular condyles measured in clinical settings, and this can influence the segmentation process carried out by the software algorithm. Although this was done to prevent the irreversible damage on physical specimens that is necessary to accurately measure the physical condylar volume, it is important to note that this study design can potentially result in a meaningful difference when segmentation is performed in vivo. However, this is unlikely to have had any significant influence on our findings with regard to the effect of VOI changes in condylar volume. Only one mandibular geometry was considered in this study to account for possible variations in production, cutting, and measurement compared with the segmented volume measurements from CBCT scans. This allowed us to rigorously investigate the accuracy of a known and fixed geometry. The ability of this method to accurately measure a range of condylar shapes and sizes was not explored, but it would be an interesting topic of future investigations to overcome the potential limitations of the presented methods.

CONCLUSIONS

The semiautomatic segmentation technique developed by us to segment the mandibular condyle from CBCT images proved to be highly reliable. Condylar volume measurements computed from the described segmentation technique were highly accurate compared with the physical condylar volume measurements. Observer variability in locating landmarks constituting the FH plane, which was used to determine condylar VOI, yielded minimal impact on the resultant condylar volume. Overall, this clinically relevant and useful tool for determining condylar volume may be valuable in a range of scenarios to study pathologic and physiologic changes associated with the condyle.

REFERENCES

1. Shukla S, Chug A, Afrashtehfar KI. Role of cone beam computed tomography in diagnosis and treatment planning in dentistry: an update. *J Int Soc Prev Community Dent*. 2017;7:S125-S136.
2. Damstra J, Fourie Z, Huddleston S, James JR, Ren Y. Accuracy of linear measurements from cone-beam computed tomography-derived surface models of different voxel sizes. *Am J Orthod Dentofacial Orthop*. 2010;137. 16.e1-e7.
3. Saccucci M, Cipriani F, Carderi S, et al. Gender assessment through three-dimensional analysis of maxillary sinuses by means of cone beam computed tomography. *Eur Rev Med Pharmacol Sci*. 2015;19:185-193.
4. Caruso S, Storti E, Nota A, Ehsani S, Gatto R. Temporomandibular joint anatomy assessed by CBCT images. *Biomed Res Int*. 2017;2017:2916953.
5. Rehan OM, Saleh HAK, Raffat HA, Abu-Taleb NS. Osseous changes in the temporomandibular joint in rheumatoid arthritis: a cone-beam computed tomography study. *Imaging Sci Dent*. 2018;48:1-9.
6. Fourie Z, Damstra J, Schepers RH, Gerrits PO, Ren Y. Segmentation process significantly influences the accuracy of 3 D surface models derived from cone beam computed tomography. *Eur J Radiol*. 2012;81:e524-e530.
7. Engelbrecht WP, Fourie Z, Damstra J, Gerrits PO, Ren Y. The influence of the segmentation process on 3 D measurements from cone beam computed tomography-derived surface models. *Clin Oral Investig*. 2013;17:1919-1927.
8. Schlueter B, Kim KB, Oliver D, Sortiropoulos G. Cone beam computed tomography 3 D reconstruction of the mandibular condyle. *Angle Orthod*. 2008;78:880-888.
9. Bayram M, Kayipmaz S, Sezgin OS, Küçük M. Volumetric analysis of the mandibular condyle using cone beam computed tomography. *Eur J Radiol*. 2012;81:1812-1816.
10. Nicolielo LFP, Dessel JV, Shaheen E, et al. Validation of a novel imaging approach using multi-slice CT and cone-beam CT to follow-up on condylar remodeling after bimaxillary surgery. *Int J Oral Sci*. 2017;9:139-144.
11. Xi T, van Loon B, Fudalej P, Bergé S, Swennen G, Maal T. Validation of a novel semi-automated method for three-dimensional surface rendering of condyles using cone beam computed tomography data. *Int J Oral Maxillofac Surg*. 2013;42:1023-1029.
12. Xi T, Schreurs R, Heerink WJ, Bergé SJ, Maal TJJ. A novel region-growing based semi-automatic segmentation protocol for three-dimensional condylar reconstruction using cone beam computed tomography (CBCT). *PLoS One*. 2014;9:e111126.
13. Xi T, Schreurs R, van Loon B, et al. 3 D analysis of condylar remodelling and skeletal relapse following bilateral sagittal split advancement osteotomies. *J Craniomaxillofac Surg*. 2015;43:462-468.
14. Vu AF, Chundury RV, Perry JD. Comparison of the FaroArm laser scanner with the microscribe digitizer using basicranial measurements. *J Craniofac Surg*. 2017;28:e460-e463.
15. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med*. 2016;15:155-163.

16. Tecco S, Saccucci M, Nucera R. et al. Condylar volume and surface in Caucasian young adult subjects. *BMC Med. Imaging*. 2010;10:28.
17. Rodriguez JM, Bartlett DW. The dimensional stability of impression materials and its effect on in vitro tooth wear studies. *Dent Mater*. 2011;27:253-258.
18. Scarfe W, Azevedo B, Toghyani S, Farman A. Cone beam computed tomographic imaging in orthodontics. *Aus Dent J*. 2017;62:33-50.
19. Shibata M, Nawa H, Kise Y, et al. Reproducibility of three-dimensional coordinate systems based on craniofacial landmarks: a tentative evaluation of four systems created on images obtained by cone-beam computed tomography with a large field of view. *Angle Orthod*. 2012;82:776-784.
20. Mohsen NA, Radwanelbeialy RA, El-Din HS, Zeid SA. Reliability of different Frankfurt reference planes for three-dimensional cephalometric analysis: an observational study. *IOSR J Dent Med Sci*. 2018;17:41-52.
21. Hofmann E, Fimmers R, Schmid M, Hirschfelder U, Detterbeck A, Hertrich K. Landmarks of the Frankfort horizontal plane: reliability in a three-dimensional Cartesian coordinate system. *J Orofac Orthop*. 2016;77:373-383.
22. Schlicher W, Nielsen I, Huang JC, Maki K, Hatcher DC, Miller AC. Consistency and precision of landmark identification in three-dimensional cone beam computed tomography scans. *Eur J Orthod*. 2012;34:263-275.
23. Wallner J, Hochegger K, Chen X, et al. Clinical evaluation of semi-automatic opensource algorithmic software segmentation of the mandibular bone: practical feasibility and assessment of a new course of action. *PLoS One*. 2018;13:e0196378.

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