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CBCT versus MSCT-Based Models on Assessing Condylar Morphology

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Abstract

Objective—To quantitatively compare condylar morphology using CBCT and MSCT virtual 3D surface models.

Study Design—The sample consisted of secondary data analysis of CBCT and MSCT scans obtained for clinical purposes from 74 patients treated with condylar resection and prosthetic joint replacement. 3D surface models of 146 condyles were constructed from each scan modality. Across-subject models were approximated and voxel-based registration was performed between homologous CBCT and MSCT images, making it possible to create an average CBCT and MSCT-based condylar models. SPHARM-PDM provided matching points on each correspondent model. ShapeAnalysisMANCOVA assessed statistical significant differences between observers and imaging modalities. One-sample t-test evaluated the null hypothesis that the mean differences between each CBCT and MSCT-based model were not clinically significant (<0.5mm). Tests were conducted at a significance level of P<0.05.

Results—ShapeAnalysisMANCOVA showed no statistically significant difference between the average CBCT and MSCT-based models (*P*>0.68). During pairwise comparison, the mean difference observed was 0.406mm, SD 0.173. One sample t-test showed that mean differences between each paired CBCT and MSCT-based models were not clinically significant (P=0.411).

Conclusion—3D surface models constructed from CBCT images are comparable to those derived from MSCT scans and may be considered reliable tools for assessing condylar morphology.

Keywords

Cone-beam computed tomography; Mandibular Condyle; Multislice spiral computed tomography

INTRODUCTION

Since the introduction of the cone-beam computed tomography (CBCT) imaging modality into dentistry in 1998,[1] this exam has undergone rapid evolution and has become an increasingly important source of three-dimensional (3D) volumetric information for defining normal and abnormal anatomy of craniofacial structures.[2] CBCT images have assumed a prominent role in the diagnosis of temporomandibular joint (TMJ) dysfunction, particularly for assessment of morphological changes in mandibular condyles presenting with osteoarthritis (OA).[3] CBCT has been shown to render high-resolution images providing a clear visualization of the hard tissues of the TMJ,[3–5] and markedly reduces radiation and cost compared to multislice spiral computed tomography (MSCT).[1, 4, 6–8]

CBCT scans provide isotropic voxels (i.e., equal dimension in height, width, and depth) which easily allow a multiplanar reconstruction without loss of spatial resolution.[9–12] Voxel sizes in CBCT imaging range from 0.076 mm to 0.4 mm, depending on the protocol being used.[9, 13] Although some authors have stated that high-resolution images (voxel size smaller than 0.2 mm) provide significantly more accurate diagnosis,[14–20] others did not find differences among voxel sizes ranging from 0.125 to 0.4 mm for most clinical purposes.[21–28] It has been shown that a 0.3 mm voxel size associates good diagnostic performance with lower X-ray exposure.[29–31] However, further clinical studies are needed to better understand specific protocols for different diagnostic tasks.[32, 33]

New technologies, such as the use of CBCT-based surface models, allow for comprehensive qualitative and quantitative evaluations of the overall TMJ morphological alterations.[2] 3D shape correspondence analysis (SPHARM-PDM) has been described as a method to precisely locate and quantify morphological changes between healthy and pathological structures.[34] This innovative method for diagnosing TMJ osteoarthritis potentially minimizes the importance of examiner's experience, reducing intra- and inter-rater related errors, standardizes findings, and contributes to the development of new imaging markers for risk factors.[5]

While CBCT has been shown to provide novel 3D research data and clinically relevant diagnostic and treatment planning information,[2, 5] its validity as a reliable tool compared to MSCT data is still questionable. Surgeons have often preferred MSCT data in order to produce anatomically accurate sterolitographic models of the jaws and joints through rapid prototyping technology systems.[35–40] This study tested the diagnostic hypothesis that CBCT-based 3D condylar surface models are reliably comparable to MSCT. Therefore, we quantitatively compared assessments of mandibular condyle morphology using CBCT and MSCT virtual 3D surface models.

MATERIALS AND METHODS

This study is a secondary data analysis of available CBCT and MSCT scans obtained for clinical purposes from 74 patients (146 mandibular condyles) diagnosed with chronic TMJ osteoarthritis (OA) (Figure 1). Two condyles were excluded from the study due to the presence of unilateral TMJ prostheses. CBCT scans were taken as a diagnostic clinical record for detecting TMJ morphological changes in patients with clinical symptoms of TMJ OA using diagnostic criteria for temporomandibular disorders (DC/TMD).[41] A 17 × 23cm extended field of view image acquisition protocol was used during a 8.9s scan, with an isotropic 0.3 mm voxel size (i-Cat® CBCT, 120 kV, 5 mA, Imaging Sciences, Hatfield, PA). The treatment plan for the patients included in this study involved condylar resection and prosthetic joint replacement of at least one of the TMJs. The precise custom-fitted fabrication of a total TMJ joint prosthesis required a MSCT scan (LightSpeed16® MultiSlice CT Scanner, 120 kV, 180 mA, 1.0 pitch, 512.512 matrix size, 0.625 mm slice thickness, pixel size of 0.390, resolution of 2.564 pixels per mm, GE Medical Systems, Milwaukee, WI). Each device was made using computer aided design/computer aided manufacturing (CAD/CAM) technology to construct a 3D stereolithographic model of the TMJ and associated bony structures. The secondary data analysis of de-identified CBCT and

MSCT scans in this study was approved by the university institutional review board and is in compliance with the Helsinki Declaration.

A total of 292 three-dimensional surface models of the condyles were constructed from each CBCT (146 condyles) and MSCT scans (146 condyles). The cortical boundaries of the condylar region visible in the cross-sections of volumetric datasets were outlined using a semi-automatic segmentation procedure. Thus, after selecting the region of interest, the program automatically segmented the mandibular condyle and part of the ramus region. The operator was then able to check out slice-by-slice the effectiveness of the automatic segmentation and perform manual editing in the three planes of space. Such an approach combined the efficiency and repeatability of automatic segmentation with the sound judgment of human expertise (ITK-SNAP software v.2.4, www.itksnap.org) (Figure 2A–H). [42, 43]

After generation of the 3D surface models, left condyles were mirrored in the sagittal plane to form right condyles to facilitate comparisons (Figure 3A). All CBCT-based models were consistently approximated to a chosen reference condyle in order to establish a common co-ordinate system within the three-dimensional space (Figure 3B) and make it possible to create average CBCT and MSCT-based condylar models. For a paired comparison, the homologous CBCT and MSCT images were also registered relative to each other using regional voxel-based registration, and the anisotropic voxels of the MSCT scans were automatically reformatted to 0.3 mm isotropic voxels. Thus, the grey level intensity of each voxel in the MSCT was registered to the CBCT images.

After registration, all models were simultaneously cropped to obtain the condylar region of interest. Shape Correspondence analysis (SPHARM-PDM software, http://www.nitrc.org/projects/spharm-pdm)[44] was used to generate a mesh approximation from the volumes, establishing correspondence between each of the 4002 points in the condylar surface models across all subjects from both image modalities (Figure 3C). An average 3D condylar shape was then generated for the CBCT and the MSCT groups (Linux MeshMath script, http://www.nitrc.org/projects/spharm-pdm).[44]

The linux MeshMath script was then used to calculate 3D point-wise subtractions between each homologous CBCT and MSCT correspondent condylar surface models, and also between the group average condylar surface models. Semi-transparent overlays between the average models were used to visually compare the two groups in the 3D Slicer software.[45] The computed 4002 vector differences were displayed as corresponding signed surface distances on each comparable condylar surface (Figure 2I,J).

Intra and inter-observer errors in segmentation of the mandibular condyles were tested by two calibrated observers, using a randomly selected sample of 10 CBCTs and 10 MSCTs volumetric datasets. Systematic differences between the observers were assessed using a Hotelling T^2 test in a multivariate analysis of covariance software (ShapeAnalysisMANCOVA).

The statistical framework for testing pairwise and group differences between CBCT and MSCT-based condylar models also inlcuded ShapeAnalysisMANCOVA.[46] Results were analysed by using corresponding absolute distances, i.e., the magnitude of the differences between the models in each surface point. Statistical significance is graphically displayed in the average surface model using color-coded maps: highly significant differences ($p < 0.01$) would be color-coded in red, intermediately significant differences would vary from yellow to green ($0.01 > p > 0.05$) and non-significant differences would be color-coded in blue ($p > 0.05$). Descriptive statistics of mean, standard deviation, median, 75th and 95th percentiles, maximum and minimum differences were also calculated for each pairwise comparison. A one sample t-test was conducted to evaluate if the absolute mean differences between each CBCT and MSCT-based models were statistically significantly different than 0.5 mm. In order to exclude possible outliers, this test considered the 95^{th} percentile data. All the tests were conducted with 5% significance level.

RESULTS

The largest intra and inter-observer differences were 0.15mm (mean 0.07mm, SD 0.02) and 0.19mm (mean 0.10mm, SD 0.03) respectively. These differences were found between the average models derived from each observer's condyle segmentations of both CBCT and MSCT scans. The significance maps showed no statistically significant differences for any of the 4002 points in study during both intra ($P > 0.88$) and inter-observer reproducibility ($P > 0.73$) (Figure 4).

Descriptive statistics of the absolute differences observed between paired CBCT and MSCT-based models are summarized in Table 1 and Figure 5. For each one of the 146 pairs of condyles in this study, the mean differences observed between the 4002 correspondent points on the surface of CBCT and MSCT-based models ranged from 0.15mm to 1.12mm (mean 0.41 mm, SD 0.17, 95% CI, 0.38 to 0.44). Considering all the differences between each correspondent 4002 points in 146 condylar surface models, a total of 584.292 comparisons, the largest difference observed was 2.55 mm. The 95^{th} percentile showed that at 95% of the condylar surface the differences observed were below 0.52mm (SD 0.25, 95% CI, 0.48 to 0.56).

Figures 6A and 6B show respectively the semi-transparencies and the absolute distances color-coded map obtained from the comparison between the average CBCT and MSCT-based models. The distances observed in the color-coded map were determined by subtracting each one of 4002 correspondent surface points on average CBCT from the average MSCT condyle. ShapeAnalysisMANCOVA showed no statistically significant difference between the groups ($P > 0.68$). A 3D visualization of the absence of statistically significant differences is presented in Figure 6C, where non-significant differences are color-coded in blue ($P > 0.05$).

The one sample t-test showed that the 95% of the absolute mean differences between each paired CBCT and MSCT-based models were not statistically significantly greater than 0.5 mm ($P = 0.411$, mean difference of 0.02mm, 95% CI, −0.02 to 0.06, as shown in Table 2).

DISCUSSION

This study compared quantitative assessments of 3D mandibular condyle morphology using CBCT and MSCT scans taken for clinical purposes. CBCT has revolutionized diagnosis and treatment planning in the field of craniofacial disorders, particularly in the assessment of TMJ bony alterations. The lower radiation dose and cost compared to MSCT, provide clinicians and researchers with a valuable diagnostic tool for identifying specific changes in the morphology of the mandibular condyles with osteoarthritis.[1, 4, 6–8] However, for planning surgical interventions with stereolithographic technology, a MSCT is still often acquired.[35–40, 47]

Previous studies have compared CBCT and MSCT images for different medical and dental applications. Those studies utilized linear measurements obtained from axial, coronal and sagittal slices, 2D measurements based on 3D rendering, or volume differences.[48–53] Other investigations specifically comparing CBCT and MSCT images of the TMJ condyles were also limited to assessment of the 2D multiplanar cross-sections or to subjective evaluations.[19, 33, 54–57] The current paper is the first clinical study to quantitatively compare whole 3D mandibular condyle surfaces constructed from CBCT and MSCT scans. The 3D surface models provide additional diagnostic information on size, shape, and exact location of the bone abnormality on the affected joint.[2, 5, 6, 34, 58]

This study did not utilize an absolute geometric ground-truth to evaluate the quality of CBCT imaging, and instead used the MSCT scans as a clinically established method of reference.[54, 59–63] Therefore, the mandibular condyle models generated from CBCT scans were compared to MSCT-based models of the same structures, which were considered as the gold standard. In the present study, the models were constructed through a semi-automatic discrimination procedure, by examiners previously calibrated with other scans not included in this study. Our results showed excellent intra and inter-observer reliability of the segmentation procedures, which corroborates other authors' findings.[5, 64–66] These images were analyzed at a 0.3mm isotropic voxel size, which has been considered as an appropriate resolution for most clinical purposes.[29] Moreover, the anatomical correspondence between 4002 points in each homologous CBCT and MSCT models were automatically established by voxel-based registration and quantified by SPHARM-PDM, which are observer independent tools. Thus, our results were not confounded by examiner subjectivity.

The image analysis procedures in this study utilized voxel-wise rigid registration and shape correspondence to quantify the differences between 3D surface models constructed from CBCT and MSCT. The fully automated superimposition using voxel-wise rigid registration between CBCT and MSCT scans in this study does not depend on landmarks or planes and, rather, compared the selected reference structures voxel by voxel, achieving the least grey scale density difference between the two images. Previous studies have shown that this method provides high accuracy in 3D registration.[58, 67, 68] Likewise, the surface parametrization method employed in this study, the SPHARM-PDM shape analysis toolbox, [69] has been shown to provide a unique and symmetric point-to-point correspondence across all measured surfaces. In the current study, shape differences were calculated between each correspondent point on CBCT and MSCT-based models and statistical shape analysis allowed for a localized analysis of shape, via multivariate analysis of covariance (MANCOVA). After correspondence establishment using SPHARM-PDM,[69, 70] alignment and scaling normalization in a shape population, the traditional statistical analysis approach consisted in testing for differences between groups at every surface location.[71] This method has been validated as an accurate tool for localizing and quantifying the degree of morphological mandibular condylar changes.[34]

This study results showed that the mean differences between paired-comparisons of CBCT and MSCT-based models were at a sub-millimeter level, except for 3 condyles that showed mean differences greater than 1mm and smaller than 1.12mm. Taking into account all the 584.292 differences between corresponding points in this study, only 1 condyle presented with maximum point difference of 2.55mm (Figure 5). While the overall mean difference for all condyles was 0.41mm, the 95th percentile was only slightly larger, 0.52 mm (Table 1, Figure 5). Nine condyles that presented with severe condylar changes showed 95th percentile differences ranging from 1mm to 1.43mm. These morphological abnormalities possibly made the segmentation procedure more challenging and prone to larger errors.

The use of 0.3mm isotropic voxel size CBCT scans in this study has been previously justified in the literature, even though not specifically for assessments of 3D condylar dysmorphology. Patel et al. observed that the agreement between CBCT and physical truth measurements are not significantly different with the use of 0.2mm or 0.4mm voxel size[31] and, Primo et al. reported no significant differences between maxillofacial prototypes produced from CBCT data with 0.25mm and 0.4mm voxel sizes, and MSCT data with 0.3 mm pixel size.[28] Other specific assessments of erosive condylar changes[19] have reported only findings at the 2D multiplanar views, where cross-sectional slices of CBCT images acquired using a 6-in FOV at a voxel size of 0.2 mm presented significantly better image quality than CBCT scans acquired using a 12-in FOV with a voxel size of 0.4 mm. However, those findings referred to the quality of the grey level images and not the 3D condylar surface models constructed from the scans and assessed in this study.

The accuracy of CBCT scans in detecting TMJ osteoarthritic changes has been previously tested using dry skulls with simulated bone defects or phantoms, which do not fully reproduce clinical conditions.[19, 33, 54–56] The current study revealed that the mean differences between CBCT and MSCT-based models were found to be around 0.5mm, which has been considered adequate precision for most clinical applications.[31, 34, 67, 72, 73] This study assessed 3D morphological changes that occur in the mandibular condyle surface, such as erosion, flattening, and osteophytosis; however, it did not evaluate internal bony alterations of degenerative arthritis, such as increased sclerosis, or the presence of subchondral cysts. Further studies are required to investigate the detection of clinically relevant subchondral changes in CBCT and MSCT.

CONCLUSION

The present findings indicate that CBCT-based models are comparable to those derived from MSCT scans in identifying some of the changes associated with OA in the mandibular condyle. 3D virtual surface models constructed from CBCT scans may be considered as reliable tools for assessment of condylar morphology.

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Clinical Relevance

CBCT-based condylar models are reliably comparable to MSCT. The CBCT images lower radiation dose and cost provide clinicians and researchers with a valuable diagnostic tool for identifying specific osteoarthritic changes in the mandibular condyles such as erosion, flattening, and osteophytosis.

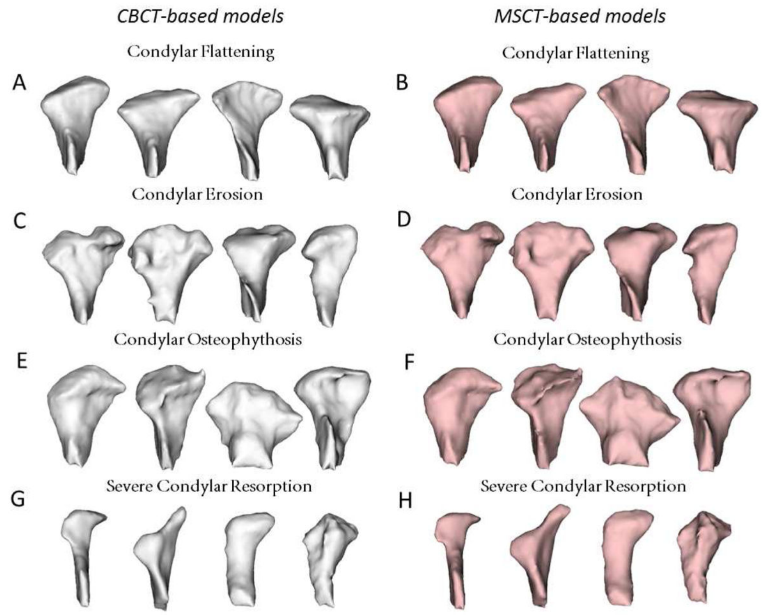

Fig. 1.

CBCT and MSCT-based models of condyles diagnosed with chronic TMJ osteoarthritis (OA). Osteoarthritic surface changes in study included condylar flattening (A, B), erosion (C, D), osteophythosis (E, F) and severe condylar resorption (G,H).

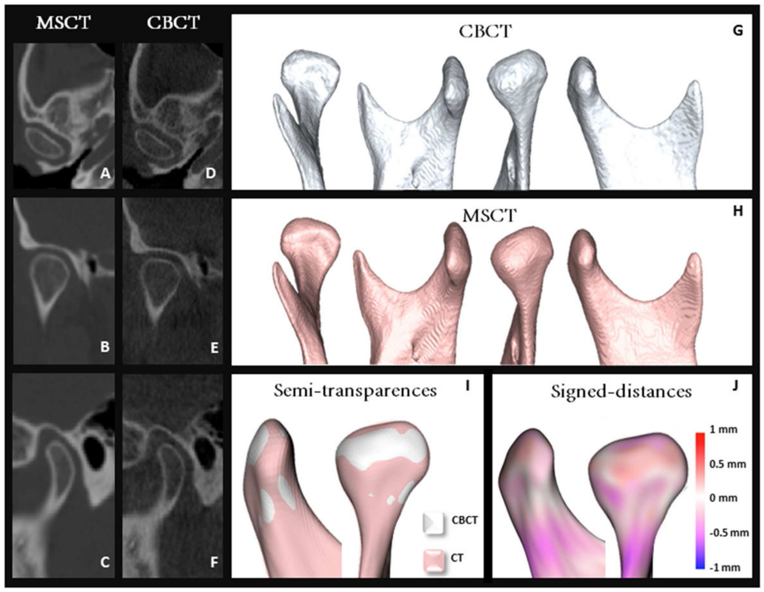

Fig. 2.
Construction of 3D surface models of the right condyle from CBCT and MSCT grey level images of a patient. A, B and C show MSCT multiplanar images: axial (A), coronal (B) and sagittal (C) views; D, E and F show CBCT multiplanar images: axial (D), coronal (E) and sagittal (F) views; G and H show frontal, medial, posterior and lateral views of the right condyles rendered respectively from the CBCT and MSCT grey level images; I, Semi-transparent overlays of the registered surface models; J, Color-coded maps displaying the computed differences between 4002 corresponding points in the condylar surface constructed from MSCT – CBCT models. For this condyle, the maximum difference observed was 0.48mm and the 50th, 75th, and 95th percentiles were respectively 0.21mm, 0.29mm and 0.29mm.

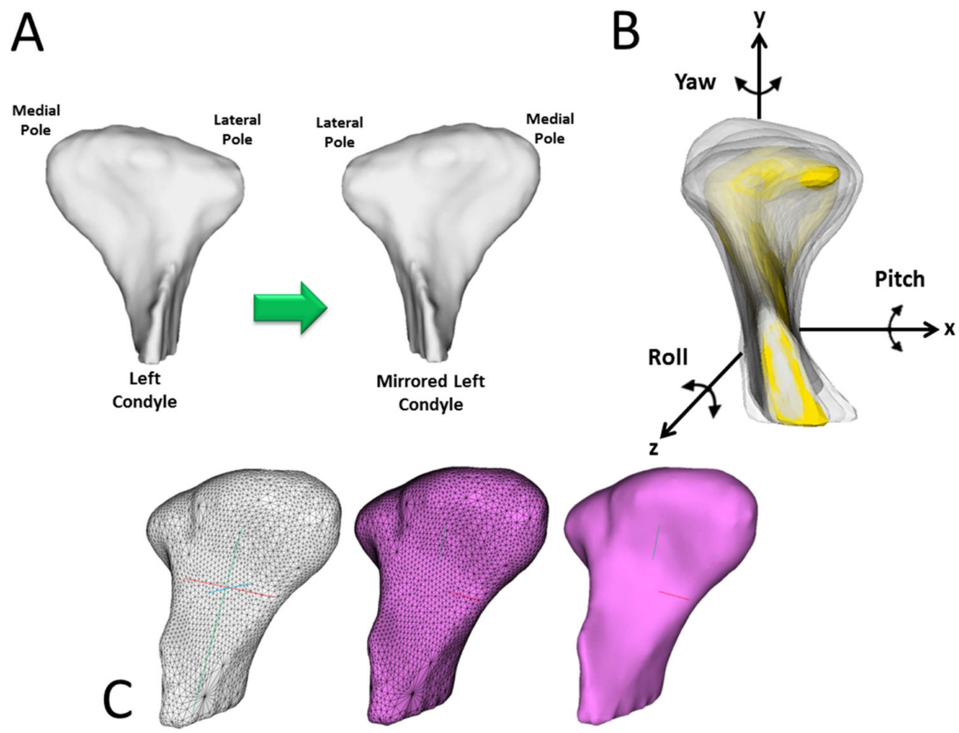

Fig. 3.

A, All left condyles were mirrored as right condyles making it possible the superimposition and construction of the average condylar morphology for both CBCT and MSCT-based models. B, Reference condylar model (yellow) with the overlay of multiple condyles approximated in the same coordinate system. C, Parameterization of 4002 correspondent surface mesh points for statistical comparisons and detailed morphological characterization.

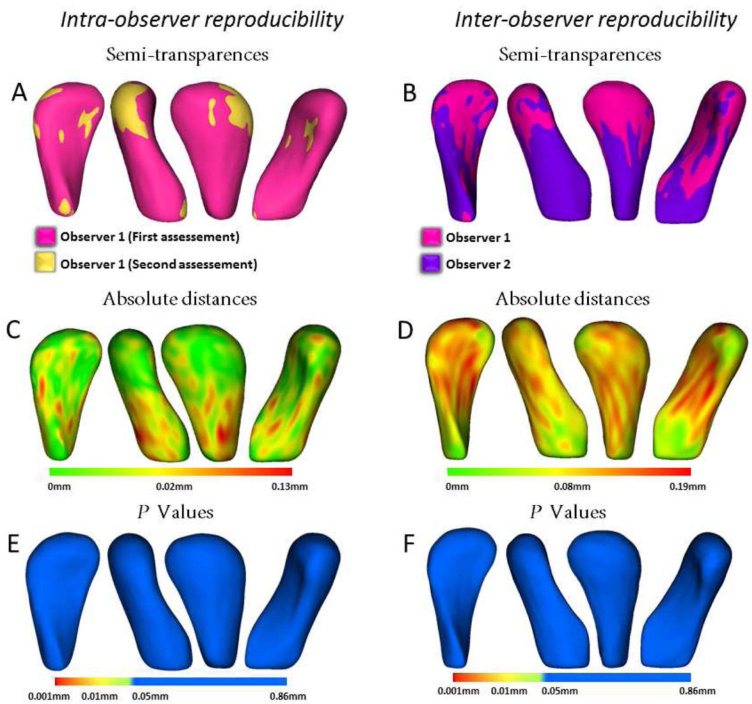

Fig. 4.

Intra and Inter-observer reproducibility results. A, B Overlay of the average models constructed by the observers for 10 CBCT and 10 MSCT images randomly selected. C, D Absolute distances map obtained after subtracting the average models constructed from the segmentations of two independent observers. E, F Significance map shows $P > 0.05$ for the whole condylar surface considering both intra and inter-observer reproducibility.

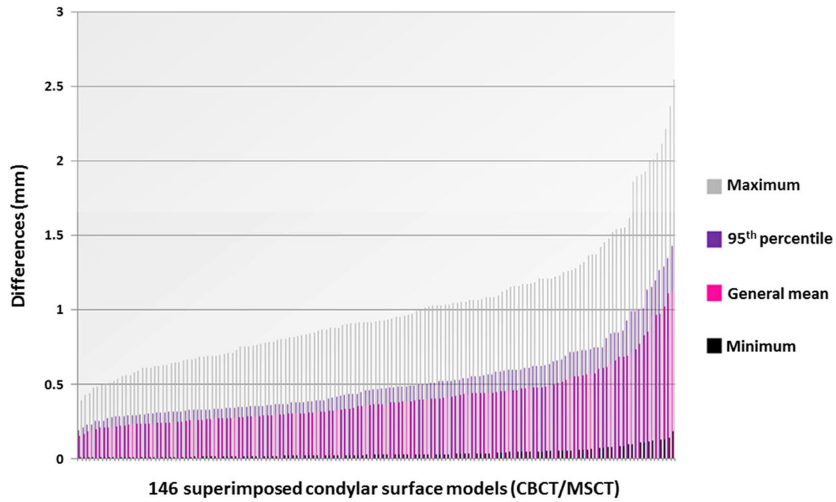

Fig. 5.
Differences observed between CBCT and MSCT-based models.

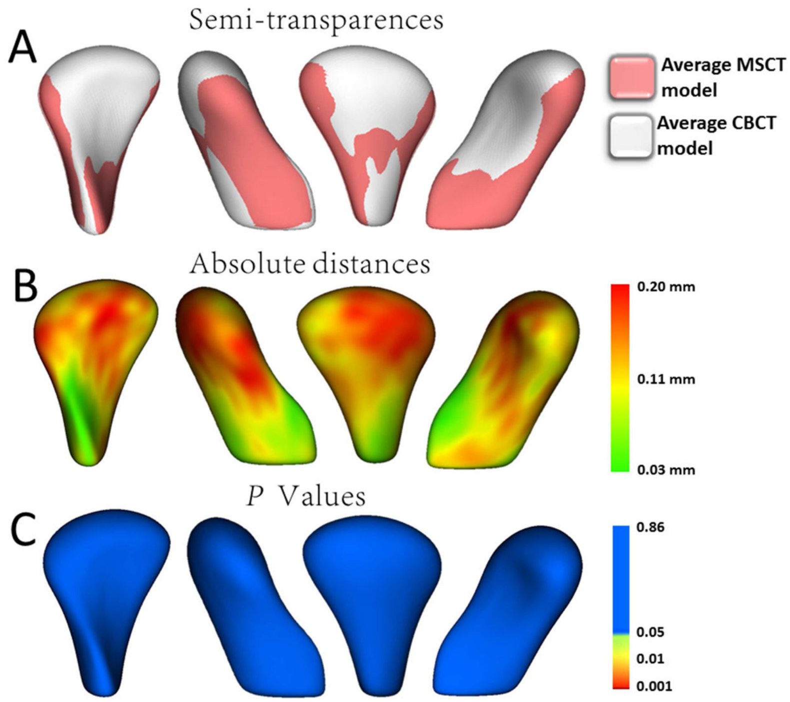

Fig. 6.

A, Semi-transparences showing the superimposition of the average CBCT and MSCT-based models. B, Absolute distances obtained after subtracting the average models. C, Significance map shows $P > 0.05$ for the whole condylar surface.

Table I

Descriptive statistics of the differences between CBCT and MSCT-based models

N	Mean[a]	SD[a]	Min[a]	Max[a]	Percentile[a]			Sig.[c]
					50th (Median)	75th	95th	
146	0.41 Range: 0.15 – 1.12	0.17 Range: 0.07 – 0.48	0.03 Range: 0.00[b] – 0.19	1.01 Range: 0.39 – 2.55[b]	0.39 Range: 0.14 – 1.13	0.52 Range: 0.19 – 1.43	0.52 Range: 0.19 – 1.43	P > 0.68

[a]Values obtained from the mean differences observed for each of the 146 condyles (4.002 points)

[b]Values refer to the minimum and maximum differences observed considering each one of the points in the surface models for all patients in this study (584.292 correspondent points)

[c]Value obtained from the comparison between the average CBCT and MSCT-based models

Table II

One-sample t test for the null hypothesis that the differences observed between CBCT and MSCT-based models were 0.5mm

N	Mean	SD	Test value = 0.5					
			t	df	Sig.	Mean Difference	95% Confidence Interval of the Difference	
							Lower	Upper
146	0.52	0.24	0.82	145	0.41	0.02	−0.02	0.06