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RESEARCH

Comparison of linear and angular measurements using two-dimensional conventional methods and three-dimensional cone beam CT images reconstructed from a volumetric rendering program *in vivo*

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Objective: The aim of this study was to compare the linear and angular measurements made on two-dimensional (2D) conventional cephalometric images and three-dimensional (3D) cone beam CT (CBCT) generated cephalograms derived from a 3D volumetric rendering program.
Methods: Pre-treatment cephalometric digital radiographs of 11 patients and their corresponding CBCT images were randomly selected. The digital cephalometric radiographs were traced using Vista Dent OC (GAC International, Inc Bohemia, NY) and by hand. CBCT and Maxilim® (Medicim, Sint-Niklass, Belgium) software were used to generate cephalograms from the CBCT data set that were then linked to the 3D hard-tissue surface representations. In total, 16 cephalometric landmarks were identified and 18 widely used measurements (11 linear and 7 angular) were performed by 2 independent observers. Intraobserver reliability was assessed by calculating intraclass correlation coefficients (ICC), interobserver reliability was assessed with Student *t*-test and analysis of variance (ANOVA). Mann–Whitney *U*-tests and Kruskal–Wallis H tests were also used to compare the three methods ($P < 0.05$).
Results: The results demonstrated no statistically significant difference between inter-observer analyses for CBCT-generated cephalograms ($P < 0.05$), except for Gonion-Menton (Go-Me) and Condylion-Gnathion (Co-Gn). Intraobserver examinations showed low ICCs, which was an indication of poor reproducibility for Go-Me and Sella-Nasion (S-N) in CBCT-generated cephalograms and poor reproducibility for Articulare-Gonion (Ar-Go) in the 2D hand tracing method ($P < 0.05$). No statistical significance was found for Vista Dent OC measurements ($P > 0.05$).
Conclusions: Measurements from *in vivo* CBCT-generated cephalograms from Maxilim® software were found to be similar to conventional images. Thus, owing to higher radiation exposure, CBCT examinations should only be used when the inherent 3D information could improve the outcome of treatment.
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Keywords: cone-beam computed tomography generated cephalograms; measurement; accuracy; volumetric rendering; orthodontics

Introduction

Since the advent of cephalometry by Broadbent[1] in the early twentieth century, this radiographic technique has become an important orthodontic clinical and research tool used to evaluate craniofacial growth and dentofacial deformities.[1–6] Using standardized radiographs, the orientation of various anatomical structures can be studied by means of angular and linear measurements.[2,7] However, cephalometric measurements have several drawbacks, including errors that are classified as either "errors of projection" or "errors of identification". Like all conventional radiographic techniques, lateral cephalometric radiographs collapse a three-dimensional (3D) structure onto a two-dimensional (2D) plane. The

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resulting superimposition of anatomical structures complicates image interpretation and landmark identification, and this distortion and magnification may lead to reduced measurement accuracy.[2,8–11] For example, the lower borders of the mandible often produce double images as a result of differences in magnification between the patient's left and right sides owing to differences in proximity to the image receptor.[5]

New technological advances in craniofacial imaging have been able to solve these problems and are becoming increasingly popular for use in orthodontic diagnosis and treatment assessment.[6] Superimposition and problems related to magnification are avoided with 3D CT as it is able to visualize craniofacial structures with more precision than 2D methods.[8–11] Initially, craniofacial imaging was performed using multidetector CT (MDCT), and although MDCT has been shown to yield accurate and reliable assessments for orthodontic and maxillofacial applications,[3,12–15] its effective dose is much higher than that of conventional cephalometric radiography, which renders its use for routine cephalometric analysis and growth assessment unjustifiable. Moreover, MDCT requires expensive equipment that is not readily accessible to dentists.[6,16,17]

Cone beam CT (CBCT) is a technique that has been proposed for maxillofacial imaging[4,18–24] during the last decade and was first reported on by Mozzo et al.[25] A CBCT scan uses a different type of acquisition than MDCT. Rather than capturing an image as separate slices like MDCT, CBCT produces a cone-shaped X-ray beam that makes it possible to capture the image in a single shot.[21,26,27] The resultant volume can be reformatted to provide multiple reconstructed "lateral cephalograms" with image perspectives such as sagittal, coronal and axial that are similar to traditional MDCT images.[5,6,10,18,19] CBCT thus offers the distinct advantage of a lower radiation dose than MDCT and the possibility of importing and exporting individualized, overlap-free reconstructions and digital imaging and communications in medicine (DICOM) data to and from other applications.[20,28] These possibilities and increasing access to CBCT imaging for orthodontics are enabling the movement from 2D cephalometric analysis to 3D analysis. Studies of CBCT applications in orthodontics have examined both CBCT-generated 2D cephalometric projections from CBCT data sets and 3D cephalometric analysis, which consists of a 3D radiographic representation of the patient's skull reconstructed from CBCT scans. In addition to these modalities, a number of software programs are dedicated to managing and analysing DICOM images derived from CT and CBCT images for orthodontic purposes. Evaluating the accuracy of measurements obtained with cephalometric images generated or reconstructed from 3D CT and CBCT data is important for orthodontists.

Several studies have been published on the accuracy of linear and 3D measurements using CBCT.[4–6] Most studies have indicated that both CBCT and CT techniques can be used reliably to obtain dimensionally accurate linear and angular measurements.[4–6,20–23] However, some investigators have noted that individual landmarks exhibit characteristic patterns of error that contribute to measurement inaccuracy.[29] Data on CBCT accuracy and reliability are still scarce and more clear insight is necessary. Despite various comparative studies[10,21,22,26,27] conducted mainly on human dry skulls, very few studies have compared the reliability of CBCT-generated cephalograms using rendering programs with conventional methods *in vivo*.[2,5,6,23,30] Much work is still needed to demonstrate the added value of CBCT in routine orthodontics, and it is still unclear whether data obtained from CBCT-generated cephalograms and 3D reconstructed skull models can be compared with existing databases and population norms derived from conventional cephalometric images.[10]

The aim of this study was to determine whether CBCT-generated cephalograms linked to 3D hard tissue skull representations using Maxilim® software version 2.3.0 (Medicim, Sint-Niklass, Belgium) provide the same linear and angular measurement accuracy and reliability on patient images as conventional cephalograms obtained from 2D direct digital cephalometric radiographs (Vista Dent OC, 4.2.44, GAC International Inc, Bohemia, NY) and hand tracing of printouts.

Materials and methods

Using retrospective data from our faculty, a power analysis (Power and Precision software, Biostat, Englewood, NJ) was conducted which indicated that detection of differences between 2D and 3D cephalometric measurements could be obtained with 11 patients at a power of 0.8 (alpha = 0.05). Thus, this study was conducted using 11 (6 female and 5 male) randomly selected, good quality, lateral cephalometric images and their corresponding CBCT images.

The study protocol was carried out according to the principles of the Helsinki Declaration, including all amendments and revisions. Collected data were only accessible to the researchers. Patients or their legal delegates gave their informed consent prior to radiography and the consent forms were reviewed and approved by the institutional review board of the Near East University, Faculty of Dentistry. Subjects with evidence of current orthodontic treatment, missing permanent incisors or first molars, erupted or supernumerary teeth overlying incisor apices, gross skeletal asymmetries or bone disease were excluded from the study.[5]

Landmark identification and measurement for 2D and 3D cephalometric analyses were performed by two independent and calibrated orthodontic consultants (UO, NA) who are experienced in the measurement of 2D and 3D images. In total, 16 cephalometric landmarks were identified and 18 widely used measurements (11 linear and 7 angular) were recorded (Table 1). In

Table 1 Landmarks and cephalometric measurements

Angular measurements	
SNA	Angle determined by points S, N and A
SNB	Angle determined by points S, N and B
ANB	Angle between SNA and SNB planes
SNGoGn	Angle formed between SN and GoGn lines
NSBa	Angle determined by points N, S and Ba
NSAr	Angle determined by points N, S and Ar
ArGoMe	Angle determined by points Ar, Go and Me
Linear measurements	
Co-Gn	Distance between points Co and Gn
Ar-Go	Distance between points Ar and Go
Go-Me	Distance between points Go and Me
S-N	Distance between points S and N
ANS-Me	Distance between points ANS and Me
N-ANS	Distance between points N and ANS
N-Me	Distance between points N and Me
S-Go	Distance between points S and Go
WIT'S	Wits appraisal
Overjet	Vertical distance between the tips of maxillary and mandibulary central incisor
Overbite	Horizontal distance between the tips of maxillary and mandibulary central incisor

S, Sella; N, Nasion; A, point A; B, point B; Go, Gonion; Gn, Gnathion; Ba, Basion; Ar, Articulare; Me, Menton; Co, Condylion; ANS, Anterior nasal spine

order to determine intraobserver variability, each observer performed the analysis twice with an interval of 2 weeks.

Digital cephalometric radiographs were obtained using a Planmeca PM 2002 cc Proline (Helsinki, Finland). In line with previous studies that indicate linear and angular measurements are likely to be affected by head rotation,[31,32] radiographs were acquired according to the Near East University, Oral, Teeth and Jaw Radiology clinic's strict standardized protocol, with the head in the natural position and stabilized by ear rods, a focus-to-median plane distance of 152 cm and a detector-to-mid-sagittal distance of 12 cm. Images were exposed at 73 kVp, 14 mA for 0.64 s each at a magnification of 1.25, as recommended by the manufacturer. Digital images were stored in a computer database within the manufacturer's own software (Dimaxis pro, version 4.0.5, Planmeca, Helsinki, Finland), corrected for magnification and imported to Vista Dent OC 4.2.44 (GAC International Inc, Bohemia, NY). Observers were permitted to adjust the image using the enhancement functions for brightness and contrast. Images were calibrated by digitalizing two points on the ruler within the digital image using the manufacturer's software. Following digitalization of landmarks, measurements were automatically generated by the Vista Dent program. For manual tracings, printouts of radiographs were obtained using a 14-bit greyscale Laser Dry printer (Konica 793 Drypro printer, Osaka, Japan) with 25 μm spatial resolution. Hard- and soft-tissue landmarks were traced on acetate overlays using a 0.3 mm diameter lead pencil.

CBCT scans were obtained using a Newtom 3G (Quantitative Radiology s.r.l., Verona, Italy). Despite recent studies indicating that small variations in head position do not influence accuracy of measurements from 3D CBCT,[33] all CBCT scans were obtained according to the strict standardized scanning protocol used in the Near East University, Oral, Teeth and Jaw Radiology clinic. Patients were placed in a horizontal position, checked to ensure that their mouths were closed in a normal, natural occlusive position and instructed to lie still throughout the length of the scan. Images were obtained using a 12 inch field of view (FOV) to ensure inclusion of the entire facial anatomy, with 0.3 mm-thick axial slices and isotropic voxels. Axial images were exported in a DICOM file format with a 512×512 matrix and were imported to Maxilim® version 2.3.0. All images were reconstructed on a 21.3 inch flat-panel colour active matrix TFT medical display (Nio Color 3MP, Barco, France) with a resolution of 76 Hz, 0.2115 mm pitch and 10-bit. The examiners were also permitted to use enhancements and orientation tools such as magnification, brightness and contrast to improve visualization of the landmarks.

In line with previous studies, reconstruction was performed in multiple stages in order to obtain images which were diagnostically suitable for landmark identification and 3D reconstruction.[12,20,23,24] First, bone and soft-tissue surfaces are segmented by applying a threshold on the acquired image volume of radiographic densities. An attempt was made to reduce noise without reducing actual osseous anatomy. To begin the analysis, the segmented hard- and soft-tissue surface representations of the skull are rendered in a virtual scene. Although natural head position has been described as ideal for lateral cephalogram acquisition, the extracranial references (mid-sagittal ruler and chain) of the natural head position are not included in CBCT volumes. For this reason, as described in a previous study by Ludlow et al,[23] we used intracranial reference planes to approximate the orientation of a patient in a conventional cephalometric image after data segmentation. Following this semi-automated virtual standardized positioning of the skull, high-quality virtual lateral and frontal cephalograms are computed as orthogonal projections from the CBCT data set and linked to the 3D hard-tissue surface representations (Figure 1).

Linear and angular measurements of CBCT-generated images were made using landmarks identified by a cursor-driven pointer. All of the landmarks were traced on the CBCT-generated cephalograms and then checked and corrected as necessary using 3DMaxilim® software (Medicim, Sint-Niklass, Belgium).

For 2D and 3D cephalometric analysis, 16 cephalometric landmarks were identified and 18 widely used measurements were recorded (Table 1). Each observer performed the analysis with an interval of 2 weeks.

Statistical methods

Statistical analysis was carried out using the SPSS 12.0.1 (SPSS, Chicago, IL) software program. Intraobserver reliability was assessed by calculating intraclass

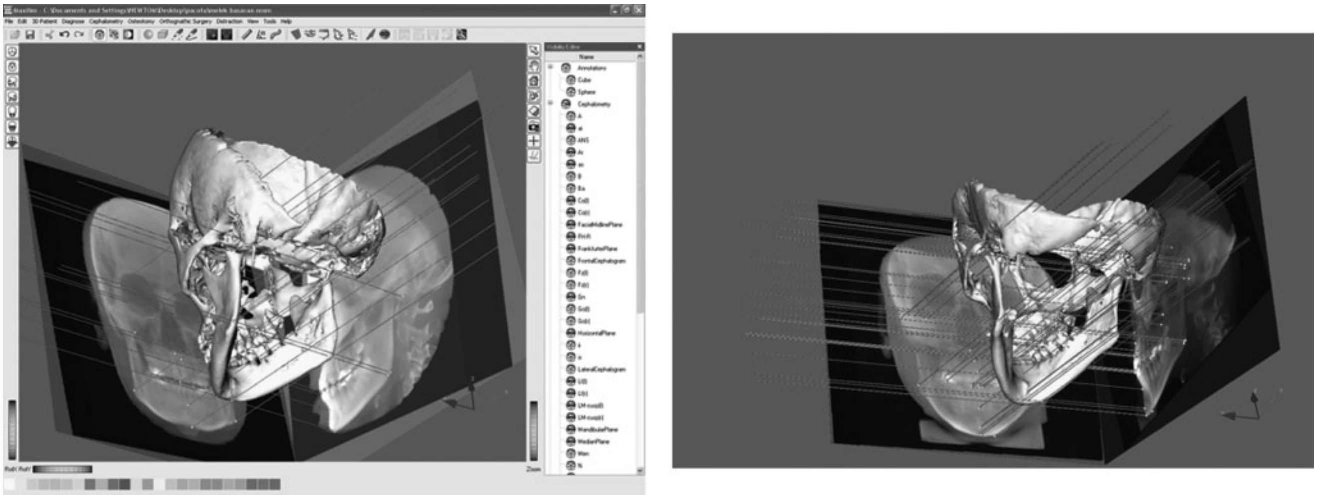

Figure 1 General layout of the Maxilim® software showing hard-tissue volume segmentation together with cone beam CT (CBCT)-generated cephalograms

correlation coefficients (ICC), interobserver reliability was assessed by Student *t*-test and analysis of variance (ANOVA), and Mann–Whitney *U* and Kruskall–Wallis H tests were used to compare the three methods. A *P*-value of ≤ 0.05 was considered statistically significant.

Results

Method error

Overall, intraobserver reproducibility using all 3 tracing methods was from 0.43 to 0.99 for Observer 1 and from 0.50 to 0.99 for Observer 2. Evaluated separately, ICCs for Observer 1 ranged from 0.67 to 0.99 for hand tracings, from 0.61 to 0.99 for Vista Dent OC tracings and from 0.43 to 0.99 for CBCT-generated cephalogram tracings, while ICCs for Observer 2 ranged from 0.50 to 0.99 for hand tracings, from 0.78 to 0.99 for Vista Dent OC tracings and from 0.57 to 0.98 for CBCT-generated cephalogram tracings.

Almost all measurements were found to be highly reproducible, with the exception of Gonion-Menton (Go-Me) and Sella-Nasion (S-N) CBCT-generated cephalogram measurements of both observers and Articulare-Gonion (Ar-Go) measurements of Observer 2 obtained by hand tracing. For both observers, Go-Me measurements of CBCT-generated cephalograms linked to 3D hard-tissue surface representations were significantly longer than both Vista Dent measurements and hand tracings. There was no significant intraobserver variability for Vista Dent OC measurements for either observer (Table 2).

Interobserver comparison of methods: hand-tracing, Vista Dent OC and CBCT-generated cephalograms

Differences in cephalometric measurements for all methods and observers are given in Table 3 and Figure 2. No statistical differences were found among 2D and 3D CBCT-generated cephalogram measurements, with the exception of Go-Me and Condylion-Gnathion (Co-Gn) linear measurements ($P < 0.05$). Mean Go-Me measurements for hand tracings were 67.07 and 67.0 for Observer 1 and 2, respectively, compared with 69.71 and 70.8 for Vista Dent OC images and 78.27 and 77.6 for CBCT-generated cephalograms. The differences in Go-Me measurements for hand tracing and Vista Dent OC were not significantly different; however, for both observers the Go-Me measurements from CBCT-generated cephalograms were significantly longer when compared with both hand tracing and Vista Dent OC ($P = 0.001$) (Figure 2).

The results also showed no statistical significance according to the mean difference values of both observers together among the three methods, with the exception of Go-Me and Co-Gn measurements. These were again significantly lower measurements for hand and Vista Dent OC tracings than CBCT-generated cephalograms ($P < 0.05$) (Table 3).

Discussion

Lateral and frontal cephalograms together with facial photographs are currently the main diagnostic imaging modalities used in the assessment of orthodontic problems.[10] However, the use of 2D views in the analysis of 3D objects can cause overlapping of structures and lead to landmark identification errors, which has in turn led to a search for new techniques.[2,5,30] CT and CBCT modalities that have come into use over the past decade have been found to overcome the limitations associated with traditional cephalometric analysis. Several studies have been conducted to assess the accuracy of cephalometric measurements using 3D CT images.[2,3,15,27,34–36] Although CT data were found to be accurate and

Table 2 Intraclass correlation coefficients

	1st observer			*2nd observer*		
	Hand	*VistaDent OC*	*CBCT-Maxilim*	*Hand*	*VistaDent OC*	*CBCT-Maxilim*
SNA	0.91	0.92	0.93	0.97	0.94	0.81
SNB	0.96	0.87	0.96	0.94	0.93	0.88
ANB	0.99	0.99	0.95	0.88	0.78	0.84
SNGoGn	0.97	0.97	0.98	0.98	0.99	0.90
NSBa	0.91	0.76	0.90	0.69	0.99	0.66
NSAr	0.92	0.88	0.96	0.89	0.93	0.70
ArGoMe	0.96	0.95	0.96	0.97	0.90	0.84
Co-Gn	0.67	0.90	0.94	0.88	0.91	0.90
Ar-Go	0.80	0.85	0.97	**0.50***	0.85	0.88
Go-Me	0.83	0.97	**0.47***	0.92	0.81	**0.57***
S-N	0.92	0.79	**0.43***	0.71	0.92	0.83
ANS-Me	0.97	0.93	0.95	0.99	0.98	0.98
N-ANS	0.82	0.61	0.92	0.73	0.94	0.86
N-Me	0.95	0.92	0.96	0.97	0.98	0.95
S-Go	0.65	0.81	0.93	0.73	0.85	0.84
WIT'S	0.96	0.96	0.99	0.94	0.98	0.97
Overjet	0.82	0.71	0.92	0.85	0.76	0.91
Overbite	0.94	0.97	0.91	0.89	0.87	0.91

*indicates statistical significance
S, Sella; N, Nasion; A, point A; B, point B; Go, Gonion; Gn, Gnathion; Ba, Basion; Ar, Articulare; Me, Menton; Co, Condylion; ANS, Anterior nasal spine

reproducible when used for cephalometric analysis, the high radiation dose to which patients are exposed led to questions regarding the necessity of CT examination.[23] With the advent of CBCT for dental practice, 3D imaging is being increasingly used in orthodontics for initial diagnoses and for assessing growth, treatment changes and stability with superimpositions.[37,38]

Many studies have assessed the accuracy and reliability of measurements on CBCT images, and in most cases, no statistically significant differences have been found between CBCT and gold standards (generally consisting of direct calliper measurements of dry skulls).[4,10,20,21,24,30,39–41] Although some studies have reported significant differences in the identification of specific points or small errors in study methodology,[2,5,10,20,22,23,26,42] according to a recent review by Grauer et al,[37] the overall reliability of measurement and landmark identification on CBCT images has been reported to be good to very good.

New 3D technology continues to increase in popularity and new segmentation software programs for the analysis of 3D data are rapidly being developed. A recent report by Van Vlijmen et al[21] has indicated the next step in cephalometry to be 3D cephalometric analysis, a process that entails the analysis of 3D radiographic representations of a patient's skull reconstructed from CT or CBCT DICOM data. Although several studies have been conducted on cephalometric landmark identification using 3D volumetric reconstructions of CT and CBCT data sets,[2,5,6,10,22,24,30,35,42] there is still a lack of data regarding the reliability and accuracy of linear measurements made from 3D volumetric renderings of CBCT data reconstructed using orthodontic software.[20]

While CBCT-generated images discard much of the 3D information embedded in CBCT volumes, 2D image simulation tools or certain cephalometric registration and superimposition may be used on 3D volumes during this period of technological transition in the field of radiology.[10] Limited information is available regarding the transposition of 2D-generated cephalograms to *in vivo* 3D reconstructed skull analysis using CBCT DICOM data.[3,5,6,23,30] Therefore, this study aimed to test the accuracy and reliability of data obtained from CBCT-generated cephalograms linked to 3D reconstructed skull analysis.

The current study found no statistical differences between the measurements obtained by conventional methods and those obtained from CBCT-generated cephalograms linked to 3D reconstructed skull analysis ($P > 0.05$), with the exception of Go-Me and Co-Gn linear measurements. Previous studies have demonstrated difficulties in locating the landmarks Go and Me using both manual and computerized tracing methods.[5,43–45] Moreover, while hand tracing may rely on the construction of multiple reference planes to assist in identifying the Co, Go, Porion (Po) and Me, this may not be possible with on-screen digitalization.[43]

In general, this study found a high level of reproducibility for all methods investigated, with the exception of Go-Me and S-N measurements obtained from CBCT-generated cephalograms (for both observers) and Ar-Go measurements obtained from 2D hand tracings (for Observer 2). ICCs for Go-Me and S-N were similarly low for both observers. Previous studies have also demonstrated low rates of reproducibility of measurements involving the points Go, Me and Po.[26] The low reproducibility of measurements involving points such as nasolabial angle, Go, Po and Orbitale may be associated with the fact that different reference planes may be constructed to identify the innermost point of a curve when using conventional 2D tracings.[5] In both this study and previous studies, the landmarks with the smallest errors in identification were those located on sharply

Table 3 Analysis of mean differences for both observers and all three methods

	Mean 2D error of hand tracing			*Mean 2D error of VistaDent OC*			*Mean 3D error of CBCT-Maxilim*			*Absolute differences*		
	Mean	*Absolute difference*	*SD*	*Mean*	*Absolute difference*	*SD*	*Mean*	*Absolute difference*	*SD*	*Hand-Vista OC*	*Hand-CBCT Maxilim*	*Vista OC-CBCT Maxilim*
SNA	80.46	0.165	0.12	80.96	0.705	0.50	80.1	0.76	0.54	−0.54	−0.595	−0.055
SNB	79.11	0.525	0.37	79.41	0.565	0.40	79.2	0.39	0.28	−0.04	0.135	0.175
ANB	1.503	−0.49	0.35	1.493	0.27	0.19	1.8	0.045	0.03	−0.76	−0.535	0.225
SNGoGn	28.6	−0.5	0.35	28.53	−0.025	0.02	27.0	−1.02	0.72	−0.475	0.52	0.995
NSBa	132.8	0.75	0.53	132.9	0.545	0.39	131.3	0.48	0.34	0.205	0.27	0.065
NSAr	123.5	1.05	0.74	124.4	1.425	1.01	117.5	5.525	3.91	−0.375	−4.475	−4.1
ArGoMe	124.2	1.52	1.07	121	1.335	0.94	119.0	1.545	1.09	0.185	−0.025	−0.21
Co-Gn	105.1	0.37	0.03	107.5	0.71	1.10	112.2	−1.8	3.46	−0.34	**2.17***	**2.51***
Ar-Go	45.69	2.255	1.59	48.38	0.575	0.41	48.5	−0.33	0.23	1.68	2.585	0.905
Go-Me	68.69	−0.97	0.69	71.33	−1.535	1.09	81.6	0.71	0.50	0.565	**−1.68***	**−2.245***
S-N	64.64	−0.805	0.57	65.83	0.185	0.13	65.3	−1.06	0.75	−0.99	0.255	1.245
ANS-Me	63.05	−0.285	0.20	63.52	0.49	0.35	63.0	0.665	0.47	−0.775	−0.95	−0.175
N-ANS	47.91	−0.28	0.20	49.27	0.21	0.15	49.2	0.675	0.48	−0.49	−0.955	−0.465
N-Me	110.7	0.35	0.25	112.2	0.675	0.48	112.6	0.5	0.35	−0.325	−0.15	0.175
S-Go	73.66	1.205	0.85	75.11	1.21	0.86	75.6	0.945	0.67	−0.005	0.26	0.265
WIT'S	−0.66	−0.22	0.16	−0.33	−0.33	0.23	−0.4	0.11	0.08	0.11	−0.33	−0.44
Overjet	2.511	0.305	0.22	2.404	0.355	0.25	2.7	0.205	0.14	−0.05	0.1	0.15
Overbite	1.673	0.31	0.22	1.736	0.125	0.09	1.8	0.225	0.16	0.185	0.085	−0.1

*indicates statistical significance

S, Sella; N, Nasion; A, point A; B, point B; Go, Gonion; Gn, Gnathion; Ba, Basion; Ar, Articulare; Me, Menton; Co, Condylion; ANS, Anterior nasal spine; 2D, two-dimensional; 3D, three-dimensional

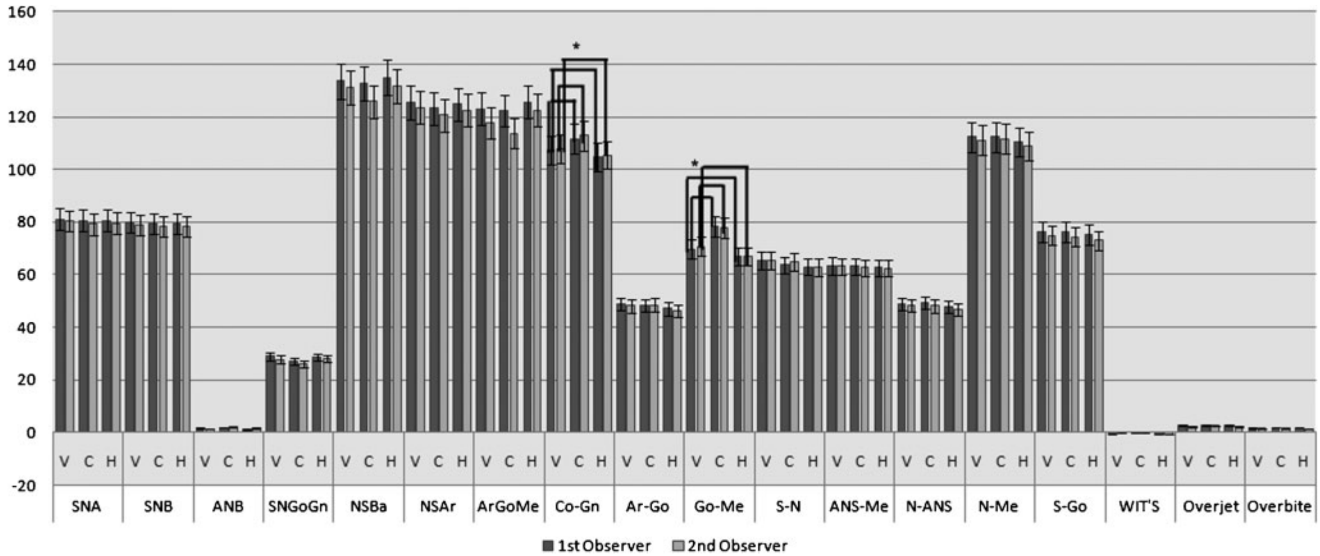

Figure 2 Differences between cephalometric measurements of both observers for the three methods. The standard deviations are also reported. *indicates statistical significance, V indicates Vista OC, C indicates cone beam CT (CBCT)-generated cephalograms, H indicates hand tracing

curved or pointed structures in areas with high-density contrast between adjacent structures.[23,24,30,37]

In our study, CBCT-generated cephalometric analysis resulted in the greatest margins of error in the identification of the landmarks Go, Me and Co. This result is consistent with several previous studies.[6,23] In a recent study, Chien et al[5] reported difficulty in identifying the *y*-axis of the gonion to be a common problem in 2D and 3D imaging modalities, with errors in 3D imaging related to operator use of shaded surface displays and segmentation. Similar to our study, Lascala et al[26] also reported measurements of Go-Me to be significantly longer using 3D imaging compared with 2D imaging.

Previous studies have shown that the use of three co-ordinates (*x*, *y* and *z*) to identify landmarks in 3D systems is quite a different process compared with the use of two co-ordinates (*x*, *y*) used in 2D systems. Specifically, the re-marking of landmarks medially and anteriorly on the *x* and *y* axes based on the subsequent identification of a *z* co-ordinate resulted in greater error in Go and Me measurements using 3D systems compared with 2D systems.[2,5,26] In this study, despite the use of 3D reconstructed skull images to identify the final positions of landmarks after initial identification using CBCT-generated cephalograms, observers still had difficulties measuring Go-Me and Co-Gn. This may be due to difficulties identifying landmarks on curved surfaces using CBCT-generated cephalograms, even when using 3D information obtained from the patients.[6,46]

While 3D analysis is able to analyse actual anatomical structures rather than their 2D projections, it cannot make use of certain non-existent constructed landmarks (*e.g.* Ar) that are used in conventional cephalometric analysis. Recently, Van Vlijmen et al[22] concluded that there is a need to develop and test new 3D cephalometric systems that use 3D representations of the skull as there is still no data available which can be used as reference values for 3D cephalometric measurements. In a very recent study, Jacquet et al[47] proposed the use of a new registration system called focus mutual information (FMI) with both CBCT and lateral cephalometric images. The authors found FMI to be a promising method for the semi-automatic alignment of lateral cephalometric images with minimum practitioner interaction. However, while making the transition from 2D to 3D cephalometry studies, the gap between these modalities needs to be examined[10] with further detailed comparative studies.

Designing *in vivo* studies to compare conventional and 3D methods presents a number of difficulties. The most important difficulty is the positioning of the patient. Most of the studies on these investigations were conducted as *ex vivo* dry skull studies. However, the positioning and the movement of the patient should be considered in CBCT examinations. In conventional cephalometry, the patient is fixed by the ear rods; however, in CBCT devices there are no ear rods to fix the position of the patient. Extra care must be taken when positioning the patient in order to prevent the occurrence of distortion when 2D images are reconstructed from a 3D data set.[21]

The Maxilim® software used in this study is one of a number of 3D orthodontic software programs available for generating and measuring cephalograms. Although our study found low ICCs for some cephalometric measurements from *in vivo* 3D volumetric renderings generated using Maxilim®, most of the angular and linear measurements of CBCT-generated cephalograms linked to 3D reconstructed images of patients' skulls were highly reproducible.

The main disadvantages of CBCT are the high radiation dose and costs, which limit the use of this specific application.[2,4,5,23] According to the International

Commission on Radiological Protection (ICRP),[45] standard diagnostic imaging for orthodontic purposes, *i.e.* panoramic, lateral cephalometric and PA cephalometric radiography, involves a radiation dose of between 25 μSv and 35 μSv, whereas CBCT imaging for orthodontic purposes involves a dose ranging from 68 μSv to 1073 μSv. The excess risk is equivalent to between a few days and several weeks of the average per capita background dose.[23] Given the risks associated with radiation, CBCT should not be recommended unless the additional diagnostic information is likely to improve treatment results.[2,23,37,48]

Conclusions

In general, measurements from conventional 2D digital radiographs and CBCT-generated cephalograms linked to 3D reconstructions of patients' skulls created by a rendering software program yielded similar results with good reproducibility. However, the identification and measurement of landmarks located on the curved surfaces of the skull (such as Go and Co) from CBCT-generated cephalograms are still prone to error, even with the use of 3D information obtained from the patient *in vivo*. Considering that conventional images deliver the lowest radiation doses to patients, the use of CBCT for orthodontic purposes should be limited to situations in which the inherent 3D information can be expected to improve treatment outcome. If the technology can be improved to reduce radiation exposure as well as costs, 3D cephalometric analysis may eventually replace conventional imaging methods used in orthodontic practice.

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