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Three-Dimensional Cephalometry Using Helical Computer Tomography: Measurement Error Caused by Head Inclination

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ABSTRACT

We performed a study of three-dimensional (3-D) linear measurements in the maxillofacial region using helical computer tomography (CT). The high accuracy of the linear measurements showed errors of less than 5% from the actual measures. But, it is possible that the accuracy was influenced by inaccurate head positions. In this study, we evaluated the errors when the head positions were tilted using the 3-D measurement system. Helical CT was used to scan a dry skull, and the data were reconstructed into a 3-D image. A total of 18 points were plotted on the 3-D images, and the distance between two points was calculated when the points were expressed as coordinates. A dry skull was tilted by 10° from the reference position in the horizontal, sagittal, and frontal planes and was then tilted in a combination of directions. Scanning was performed with slice thicknesses of 1 mm, 3 mm, 5 mm, and 7 mm. The length between two points measured by 3-D cephalometry was compared with the actual length determined using an antenna meter and a caliper and expressed as percentage errors of the actual length. In all head positions, errors in all linear measurements on the images and the actual length measured on the skull were less than 5% when a slice thickness of 1 mm or 3 mm was used. But, on using a slice thickness of 5 mm or 7 mm, some linear measurements showed larger measurement errors. Therefore, a thickness of less than 3 mm was thought to be clinically appropriate because the accuracy of the measurements was not influenced by head rotation.

KEY WORDS: Helical CT, Three-dimensional cephalometry, Head position.

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INTRODUCTION Return to TOC

Cephalometric radiography has provided valuable information for evaluating craniofacial morphology to arrive at definite clinical diagnoses and treatment plans. But many investigators have suggested that conventional cephalograms have several shortcomings.[1,2] Inaccuracy in the reproducibility of cephalometric landmarks has been reported, and such problems may be a major obstacle in establishing an accurate diagnosis and treatment plan.[3,4]

The X-ray computed tomograph (CT) was developed by Hounsfield[5] and first put to practical use in 1972. In dentistry, CT imaging has great clinical significance in the evaluation of maxillofacial morphology and in treatment planning. In two-dimensional (2-D) conventional cephalometry, it is difficult to evaluate lengths and angles for assessment of treatment effects and for treatment planning because 2-D cephalograms have problems of enlargement and distortion.[6] A very important point for clinicians, however, is finding differences or changes from the preceding examinations and determining a surgical plan for treating the facial bone deformity. To solve these problems, several studies have been made on 3-D reconstructions using 2-D posteroanterior and lateral cephalograms.[7–12] But the reproducibility and precision of measurements in these investigations were insufficient to enable utilization.

Recently, the introduction of helical CT has improved conventional computed tomography both in reducing motion-related artifacts and in the rapidity with which thin-section images are generated.[13] Therefore, Kitaura et al considered that these characteristic features of helical CT might improve the accuracy of measurements on reconstructed3-D images of the facial bones.[14] This study revealed that the values measured by CT using a slice thickness less than 3 mm showed almost no errors compared with the actually measured values.

In 2-D cephalometry, head rotation is one of the factors causing magnification or distortion.[6] Therefore, it was possible that head rotations also caused inaccuracy in measurements in 3-D cephalometry using helical CT. In this article, we investigated errors caused by head rotation when 3-D images using helical CT are reconstructed.

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Measurement points of 3-D cephalometry

We scanned a dry skull using the HiSpeed Advantage SG CT imaging system (General Electric Medical Systems, Milwaukee, Wis). Scanning of facial bones from the level of the upper margin of the frontal bone to the lower margin of the mandible was performed at collimation of 1 mm, 3 mm, 5 mm, and 7 mm, pitch of 1:1, 120 kVp, and 100 mA. The data obtained were sent to an Advantage Windows Workstation (General Electric Medical Systems) and a 3-D image reconstructed. The measurement points used with the radiographic cephalogram were plotted with this 3-D cephalometry. There were 18 points of reference located on the surface of the dry skull as shown in Figure 1. Details are shown in Table 1.

These points were confirmed and accurately plotted in axial, coronal, and sagittal images and also in the restructured 3-D cephalometry. Because these four images are projected at the same time on the cathode ray tube (CRT) monitor, the landmarks can be plotted accurately and easily.3-D vectoring shows these landmarks. The distance between two points can be obtained by the previously reported calculation.[14] The linear measurements on the observed cranial features are as shown in Table 2.

Head position

To evaluate the errors from the reference positions caused by head inclination, we first defined three references planes—the horizontal plane, the frontal plane, and the sagittal plane. The horizontal plane included right and left Porion and the right Orbitale. The frontal plane included right and left Porion and crossed perpendicular to the horizontal plane. The sagittal plane crossed squarely to the horizontal plane and through the center of Nasion and Basion.

Tapes were attached to the skull so that they could run along the horizontal, sagittal, and frontal planes (Figure 2). The positions where the beams emitted from the CT device overlapped with the tapes were determined to be the reference positions. Head position can be maintained in the reference position with a belt that is fixed to the chin and a belt fixed to the forehead. Next, the skull was tilted by 10° in the sagittal or frontal plane. The CT device itself was able to incline in the horizontal plane. The skull, inclined in combinations of two directions (eg, the horizontal and frontal planes or the horizontal and sagittal planes), was scanned.

A total of eighteen 3-D cephalometric points were plotted, and the distance between two points was calculated. The actual length was measured directly with an antenna meter and a caliper. The antenna meter is able to measure in 1/10 mm units, and the caliper is able to measure in 1/20 mm units. The antenna meter can be used to measure the insides of cranial bones that are difficult to measure with a caliper. In this study, we measured to 1/10 mm for accuracy. All measurement points (lengths) were measured three times, and the average value was considered the real length. The coefficient of variation was 0.15–1.03%, and the minimal linear measurement was G-Ba, whereas the maximal linear measurement was ANS-Pr.

2-D cephalometry

In clinical 2-D cephalometry, a slight rotation of the head position causes a distortion of the image and a crosswise difference. This can be important for treatment, and the error can be large.

In lateral cephalometry, we compared the head position that was parallel to the horizontal plane with the head position that was inclined to the frontal plane. In anteroposterior cephalometry, we compared the head position parallel to the horizontal plane with the head position after it was inclined.

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Errors of linear measurements in 3-D cephalometry caused by head inclination

The results of measurement error caused by head inclination are shown in Figure 3. When the head had a reference position that was defined by beams parallel to each plane that overlapped with tapes, the errors between values calculated using 3-D cephalometry and the errors actually measured on the skull by caliper were all less than 5% at slice thicknesses of 1 mm and 3 mm. When the slice thickness was 5 mm or 7 mm, the errors in ANS-Pr, Ol-PNS, and ANS-PNS were larger (Figure 3A).

When the head position was inclined in the sagittal, frontal, and horizontal planes, the errors of all measured values were less than 5% at 1 mm and 3 mm slice thicknesses. But on using a slice thickness of 5 mm or 7 mm, the errors of N-Pr, ANS-Pr, Pr-Gn, N-ANS, ANS-Gn, Ol-PNS, and ANS-PNS were more than 5% of the actual measured values (Figure 3B–F).

Errors of linear measurements in 2-D cephalometry caused by head inclination

When the skull was parallel to the horizontal plane, the relative error was about 0.4% to 10.4%, but when it was tilted 10° to the frontal plane, the error was about 2.7% to 25%. In particular, Go-Pog, Go-Gn, Cd-Pog, and Cd-Gn had large errors. When the skull was parallel to the horizontal plane, the relative error was about 3.2% to 10.3%, and when the skull was inclined to the horizontal plane, the relative error was about 7.9% to 19.4%. G-Gn, G-Pr, and Pr-Gn were larger, but Id-Gn was smaller than when the skull was parallel to the horizontal plane.

DISCUSSION Return to TOC

Ordinary 2-D cephalograms have problems of enlargement and distortion.[6] Enlargement is a result of the inherent property of X-rays to proceed in straight lines diverging from the source or anode, which is a very small area or point. The importance of enlargement compensation in both lateral and frontal cephalometric radiography arises from a variable enlargement of 4.6% to 7.2% in the lateral film using a 1.5-m distance from the anode to the midsagittal plane.[6]

Several techniques for stereolocation of certain cephalometric landmarks by combining point locations from the conventional lateral and posteroanterior cephalograms have been introduced. The results of these studies suggest that these techniques are able to compensate for or eliminate enlargement and distortion.[7–12,15] No techniques, however, have been satisfactorily employed for eliminating enlargement or distortion.

Ono et al[16] first applied helical CT for 3-D measurements of the facial bones. Kitaura et al extended their findings and obtained data confirming the value of helical CT for the development of 3-D cephalometry. The 3-D cephalometry they developed provided highly accurate measurements of lengths defined by landmarks directly placed on the surface of the facial bones and thus demonstrated that it could replace conventional 2-D cephalometry.

This method enables the measurement of actual lengths, which is not possible with conventional 2-D cephalometry. The special position of the landmarks was defined as a 3-D vector, and the distance between two landmarks could be calculated. The results of comparative measurements showed errors within 5% using a slice thickness of 1 mm or 3 mm in all head positions. But when the slice thickness was increased to 5 mm or 7 mm, measurement errors for some linear measurements increased considerably.

In the head position parallel to the horizontal plane, an increase in slice thickness increased measurement errors associated with ANS and PNS (ANS-Pr, Ol-PNS, ANS-PNS); the measurement errors were 18.6%, 19.3%, and 20.8%, respectively, with a slice thickness of 7 mm (Figure 3A). ANS and PNS are measurement points located on extremely thinned bones. With an increase in slice thickness, linear measurements containing such points are visualized as shorter than the actual values because of the partial volume effect. This may be because of the marked measurement errors.

In the head position tilted by 10° to the horizontal plane with a slice thickness of 7 mm, the measurement errors for ANS-Pr, Ol-PNS, and ANS-PNS decreased to 11.7%, 15.9%, and 11.3%, respectively (Figure 3B). This may be because X-rays began to be delivered to the points of reference such as ANS and PNS on thin bone that had been parallel to rays after tilting of the head position from the horizontal plane, thus creating an X-ray irradiation angle.

When the head position was tilted from the sagittal plane, the errors increased. The errors for ANS-Pr and ANS-PNS were 28.5% and 34.5%, respectively, with a slice thickness of 7 mm (Figure 3C). Because errors of the linear measurement containing ANS were marked, the influence of the head position on ANS and its association with the morphology of ANS could be considered.

When the head position was tilted from both the sagittal and horizontal planes, errors in the linear measurements containing ANS and PNS decreased compared with the head position being tilted from the sagittal plane only. This may also be because the creation of the X-ray irradiation angle allowed recognition of measurement points (Figure 3D). When the head position was tilted from the frontal plane, the errors for Ol-PNS and the ANS-PNS increased 69.2% and 67.0%, respectively (slice thickness, 7 mm) (Figure 3E).

Because errors of the linear measurements containing PNS increased, the influence of the head position on PNS was considered. The length measurements containing Pr also showed increased errors, which suggests their influence on Pr. The influence on PNS may be associated with the morphology of PNS, and that on Pr may be associated with a decrease in the incident angle. When this head position was also tilted from the horizontal plane, the measurement errors for Ol-PNS and ANS-NS decreased 12.0% and 20.8%, respectively (slice thickness, 7 mm) (Figure 3F). This may also be because the creation of the X-ray irradiation angle allowed recognition of measurement reference points.

The coefficient of variation about the measured real length was 0.15–1.03%, and the minimal linear measurement was G-Ba, whereas the maximal linear measurement was ANS-Pr. On the other hand, two observers assessed the precision of measured lengths between the landmarks in 3-D cephalometry on three occasions, and the averages were used as the linear measurements when a slice thickness of 3 mm was used. We expressed our results by calculating the coefficients of variation for the interobserver and intraobserver errors. The coefficient of variation for intraobserver variability was 0.023–1.70%, and the minimal linear measurement was Ba-Pr, whereas the maximal linear measurement was R-Ek-L-Ek. The value about one observer's coefficient of variation for interobserver variability was 0.236–2.91% (minimum, Go-Cd; maximum, ANS-Pr), whereas the value about the other was 0.144–2.85% (minimum, Ol-PNS; maximum, ANS-Pr).

In lateral 2-D cephalometry, the head was parallel to the horizontal plane and inclined to the frontal plane. Two observers traced and measured the lengths between landmarks three times, and the reproducibility of each landmark was investigated. The coefficient of variation for intraobserver variability was 0.18–4.72%. The values about one observer's coefficient of variation for interobserver variability nine were 0.61–3.14% (parallel to the horizontal plane) and 0.58–4.2% (inclined to the frontal plane). On the other hand, the values for the other observer were 0.578–4.58% (parallel to the horizontal plane) and 0.432–3.37% (inclined to the frontal plane).

When compared with 3-D cephalometry, the maximal values of 2-D cephalometry are higher in all cases. It was shown, however, that the reproducibility of 3-D cephalometry was better. This was because the axial, coronal, and sagittal images and the reconstructed 3-D cephalometry are projected at the same time in a CRT monitor so that the landmarks can be plotted accurately.

These results suggest that 3-D radiography with a slice thickness of 3 mm is appropriate in clinical practice regardless of head position. With a slice thickness of 5 mm or 7 mm, there are also points that can be measured irrespective of the head position. Changing in the slice thickness according to the purpose can reduce the exposure dose. With a slice thickness of 5 mm or 7 mm, measurement errors for items containing ANS and PNS increase in the head position parallel to the horizontal plane. Therefore, for accurate measurement of these lengths, radiography of the head position with a tilt to the horizontal plane may be appropriate.

CONCLUSIONS Return to TOC

It was revealed that with slice thickness of 1 mm and 3 mm, there were no problems in the measurements in all tilted head positions, and a slice thickness of 3 mm was thought to be clinically appropriate. With a slice thickness of 5 mm or 7 mm, accurate measurements were obtained in some cases in the skull in all tilted head positions. Therefore, it was suggested that changing the slice thickness according to the purpose of cephalometry could reduce the exposure dose.

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TABLE 1. Landmarks using 3-D Cephalometry

Symbols	Meanings	Characteristics
S	Sella turucica	Center of sella turcica
N	Nasion	Anterior limit of nasofrontal suture
Ba	Basion	Anterior midpoint on foramen magnum
Po	Porion	Most superior point on the outside edge of the external auditory foramen
Pr	Prosthion	Tip of maxillary alveolar bone between central incisors
Gn	Gnathion	Lowest point on mentum
ANS	Anterior nasal spine	Anterior nasal spine
Ek	Ectoconchion	Point where a line running parallel to upper orbital border cuts the lateral orbital margin
Fmt	Frontmalar temporale	Most laterally placed point on zygomatico-frontal suture
Fmo	Frontmalar orbitale	Point on lateral orbital margin where it is cut by zygomatico-frontal suture
Zy	Zygion	Point on top margin of zygomatic arch
Zm	Zygomaxillare	Lowest point on suture between zygomatic and maxillary bones
Ol	Orale	Midpoint between central incisors on a line perpendicular to their posterior surfaces
PNS	Posterior nasal spine	Posterior nasal spine
Go	Gonion	Most posterior inferior point of mandibular angle
Pog	Pogonion	Most prominent point of mentum
Cd	Condylion	Most superior point on mandibular condyle
Id	Infradentale	Tip of mandibular alveolar bone between central incisors

TABLE 2. Measurement Points of 3-D Cephalometry

No	Measurement Points
Cranial length	
1 Ba = Pr	Basion–prosthion length
Facial width	
2 R–Fmt = L–Fmt	Upper facial width
3 R–Fmo = L–Fmo	Frontal chord
4 R–Ek = L–Ek	Biorbital width
5 R–Zy = L–Zy	Bizygomatic width
6 R–Zm = L–Zm	Mid-facial width
Facial height	
7 ANS = Pr	Anterior maxillo–alveolar height
8 N = ANS	Upper anterior facial height
9 ANS = Gn	Lower anterior facial height
Maxillary or palatal length	
10 Ol = PNS	Palatal length
11 ANS = PNS	Anterior nasal spine–posterior nasal spine length
Mandibular length	
12 R–Go = L–Go	Bigonial width
13 Go = Pog	Length of mandibular corpus
14 Go = Gn	Length of mandibular corpus
15 Go = Cd	Rumus height
16 Cd = Pog	Length of mandibular base
17 Cd = Gn	Length of mandibular base
Cranial base dimensions	
18 N = Ba	Nasion–basion length

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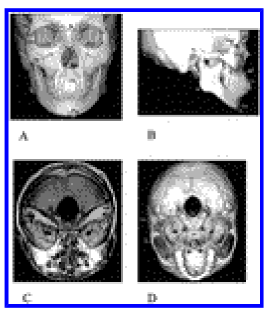

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FIGURE 1. Cephalometric landmarks shown on the surface of 3-D computer-reconstructed facial bones. The 3-D images show (A) the anterior and (B) the lateral views of the facial bones and (C) the inferior and (D) the superior aspects of the skull base. These landmarks and their characteristics are listed in Table 1

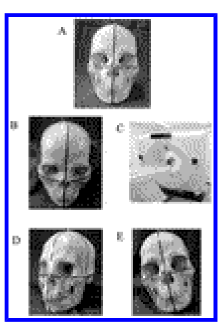

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FIGURE 2. The tapes along the horizontal plane, frontal plane, and sagittal plane were placed onto a skull. (A) A dry skull at the reference position. (B) Tilted by 10° in the horizontal plane. (C) CT device itself inclined in the horizontal plane. (D) A dry skull tilted by 10° in the frontal plane. (E) Tilted by 10° in the sagittal plane

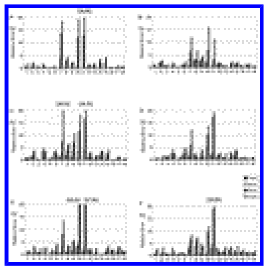

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FIGURE 3. The relative errors of 18 cephalometric measurements recording the lengths of the facial bones. The data acquisition was performed with 1 mm, 3 mm, 5 mm, and 7 mm collimation. The measurement points are listed in Table 2. (A) The reference head position. (B) The head position tilted by 10° in the horizontal plane. (C) Tilted by 10° in the frontal plane. (D) Tilted by 10° in the sagittal plane. (E) Tilted in the frontal and horizontal planes. (F) Tilted in the sagittal and horizontal planes from the reference head position.

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