Comparison of landmark position between conventional cephalometric radiography and CT scans projected to midsagittal plane

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Objective: The purpose of this study is to compare landmark position between cephalometric radiography and midsagittal plane projected images from 3 dimensional (3D) CT. **Methods:** Cephalometric radiographs and CT scans were taken from 20 patients for treatment of mandibular prognathism. After selection of landmarks, CT images were projected to the midsagittal plane and magnified to 110% according to the magnifying power of radiographs. These 2 images were superimposed with frontal and occipital bone. Common coordinate system was established on the base of FH plane. The coordinate value of each landmark was compared by paired *t* test and mean and standard deviation of difference was calculated. **Results:** The difference was from −0.14 ± 0.65 to −2.12 ± 2.89 mm in X axis, from 0.34 ± 0.78 to −2.36 ± 2.55 mm (6.79 ± 3.04 mm) in Y axis. There was no significant difference only 9 in X axis, and 7 in Y axis out of 20 landmarks. This might be caused by error from the difference of head positioning, by masking the subtle end structures, identification error from the superimposition and error from the different definition. **Conclusions:** This study revealed innate shortcomings of radiography. For the development of 3D cephalometry, more study was needed. **(Korean J Orthod 2008;38(6):427-436)**

Key words: Landmark position, Cephalometric radiography, Projected images from 3D CT

INTRODUCTION

Ever since Broadbent[1] first introduced cephalometric radiography, it was widely accepted that there were 2 general classes of error in the position of cephalometic landmarks, one was error of projection and the other was error of identification. The errors of projection result from the fact that the head film is a 2 dimensional (2D) shadow of a 3 dimensional (3D) object. Since X-ray beams are nonparallel and originate from a very small source, head films are always enlarged, according to the distances between the focus, the object, and the film.[2] Ahlqvist et al.[3] concluded that the projection errors in linear measurements were not a serious problem in cephalometry from a theoretical point of view.

The errors of identification are the errors of identifying specific landmarks on the headfilm. Midtgard et al.[4] suggested that the differences in measurement have the most part depended on the errors of identification. Tng et al.[5] insisted that each landmark has its own characteristic envelope of error. Henceforth, the landmarks estimated on the cephalometric radiographs differed from the true anatomical landmarks. The sources

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Received April 16, 2008; Last Revision July 26, 2008; Accepted August 3, 2008.
DOI:10.4041/kjod.2008.38.6.427

of error might result from the quality of the radiographic image, the precision of landmark definition, the subjectiveness of the reader, machine errors in point location, and errors in the registration procedures. However, these limitations could not disregard the diagnostic value of the cephalometric radiograph. Houston et al.[6] showed that the radiographic errors could be kept to an acceptably low level for most purposes with careful control. Henceforth, orthodontists have routinely used an array of 2D static imaging techniques to record the 3D anatomy of the craniofacial region.

Some pioneers tried to perform 3D analysis of the craniofacial structure with multiple radiographs. Broadbent[1] made the first attempt with his original design of the cephalostat. Grayson et al.[7] proposed a 3D multiplane cephalometric analysis for craniofacial asymmetry, but it was only a study of structures in various coronal and transverse planes. Baumrind et al.[8] sought a mechanical solution to improve landmark identification in 3 dimensions. Grayson et al.[9] followed the same technique as that of the Broadbent "Orientator", and tried to derive certain analyses in 3D form. Kusnoto et al.[10] investigated the reliability of linear and angular measurements produced by the biplanar cephalometric radiographs. They suggested that the biplanar projection provides not only greater accuracy but also clinical practicality for both linear and angular measurements compared with direct or CT measurements. Rousset et al.[11] developed a new method to correct for geometrical errors in the calculation of the 3D coordinates of a landmark viewed on 2 cephalometric radiographs, and suggested that the new corrected computed method reduces the geometrical errors so that they are not greater than the measurement errors.

With the advent of CT in the late 1970s, it was thought that CT could replace conventional radiography. Although CT technologies have an enormously important role in medicine, orthodontic applications have been impractical because of the high radiation dose, high cost and poor spatial resolution. The advancement of imaging technologies made it possible to develop new devices called cone beam CT.[12] By overcoming the limitations of conventional CT, cone beam CT might be an alternative tool to the conventional radiograph, which can provide 3D reconstruction of the entire craniofacial skeleton for use in orthodontics.

For the application of CT scans to the field of orthodontics, many authors tried to investigate the reliability of the CT measurements and also tried to compare it with that of conventional cephalometry. Christiansen et al.[13] suggested that linear measurements from CT have an observer error and accuracy within acceptable limits whether they are done in vitro or in situ on normal TMJ components. Hildebolt et al.[14] tried to quantify the morphology of the skull based on surface features that can be found in CT scans and 3D reconstructions. They concluded that 3D CT measurements are superior to those in which measurements were obtained directly from the original CT slices. Matteson et al.[15] found that measurements taken from CT scan were much more accurate than those obtained from cephalometric films and that the interobserver variability of the CT measurements was only 0.10 to 0.66 mm. Kragskov et al.[16] compared the reliability of anatomic cephalometric points from conventional radiography and 3D CT and concluded that the benefit of 3D CT is indicated for severe asymmetric patients. Adams et al.[17] compared the 3D imaging system and traditional cephalometry for accuracy in recording the anatomic structures as defined by physical measurements with a caliper. They concluded that the 3D method is more precise and accurate than the 2D approach.

Many authors stood by 3D measurements from the viewpoint of reliability. However, there were little methods for 3D measurements to be applied in clinical use. This might be due to lack of investigation about the correlation between cephalometric radiography and 3D CT. This study was performed to investigate the difference in the landmark positions from conventional cephalometric radiography to the projected images from CT scans.

MATERIAL AND METHODS

Sample selection

The sample was comprised of 20 adult patients who had received mandibular setback surgery to correct mandibular prognathism (ODI; 53.1 ± 5.1, APDI; 99.2 ± 5.8). Severe asymmetry cases were excluded. Half of them were male, and the others were female. The range of patient age was from 18 years 8 months to 33 years 3 months (average was 23 years 6 months).

CT data acquisition was performed using a Somatom Plus 4 (Siemens, Erlangen, Germany) with a 1.5 mm section interval, a 1 mm slice thickness in spiral mode, and a 512 × 512 matrix. The resultant 2D image data was stored in Digital Imaging and Communications in Medicine (DICOM) format.

Lateral cephalometric radiographs were taken with CX90SP (Ashahi, Tokyo, Japan). The target film distance was 15 cm, the focus target distance was 150 cm, and the magnification ratio was 110%. All the radiographs were traced by one orthodontist.

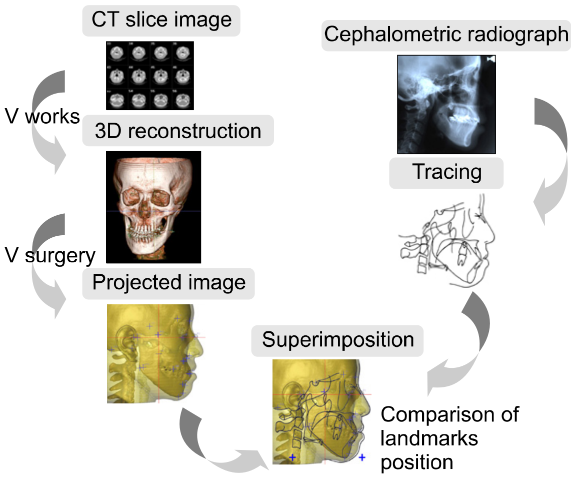

Fig 1. Overall procedure.

3D data processing; V works 4.0 and V surgery

Fig 1 shows the overall procedure. 3D image was reconstructed from the CT slice image using V-works 4.0 (Cybermed, Seoul, Korea). The bony parts were segmented out from each slice image using a threshold value of 176 HU (12 bit depth). The soft tissue parts were segmented out using a threshold value of -285 HU (Fig 2, *A*). The reconstructed image was positioned in 3D coordinate system. Park et al.[18] suggested a 3D coordinate system as follows. The horizontal reference plane was the FH plane composed with both Porion (Po) and left Orbitale (Or). The midsagittal plane was constructed perpendicular to the FH plane, and included the neck of crista galli (Nc) and midpoint of Foramen Spinosum simultaneously. The coronal reference plane was selected as the plane simultaneously perpendicular to the horizontal and midsagittal plane, including the PNS. The repositioned skull and skin models were exported to V surgery (Cybermed, Seoul,

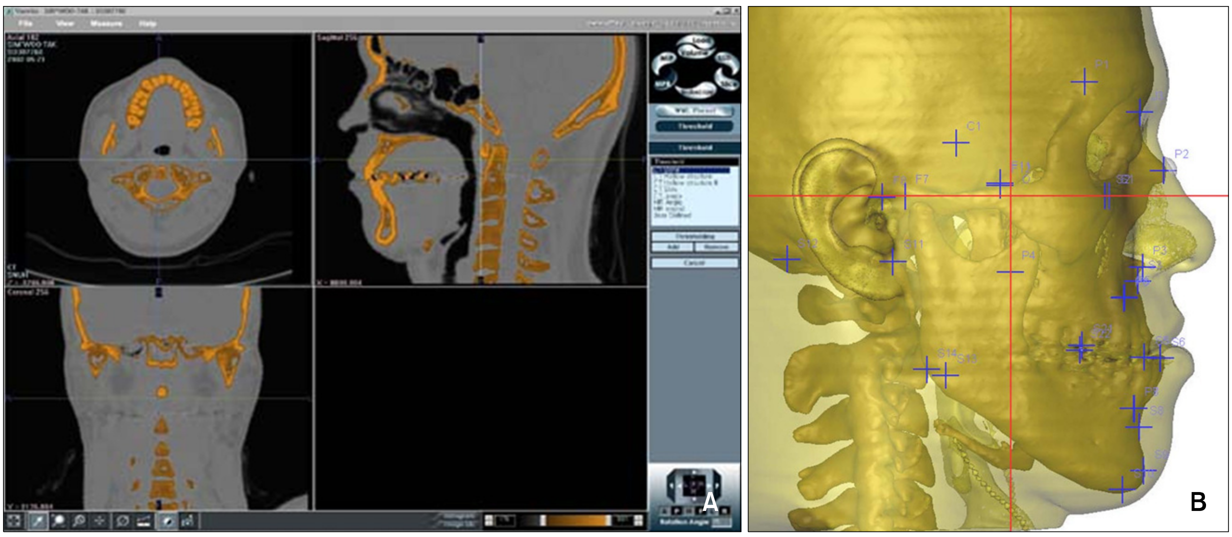

Fig 2. Acquirement of projected images from CT data. **A**, Segmentation of skull and skin part using V works; **B**, projected image to midsagittal plane. By reducing the transparency of the skin part, the projected image looks more like a cephalometric radiograph.

Table 1. Definition of selected landmark

Landmark	Definition
Na	The junction of the nasal and frontal bones as seen on the profile of the cephalometric radiograph; point in the midline of both the nasal root and the nasofrontal suture
Or	The lowest point on the lower margin of each orbit
A	The deepest midline point on the premaxilla between anterior nasal spine and prosthion
Is	The mid-point of the incisal edge of the maxillary central incisor
Ba	The most inferior posterior point in the sagittal plane on the anterior rim of foramen magnum
U6Cr	The mesiobuccal cusp tip of the maxillary 1st molar
Po	The highest point on the upper margin of porus acusticus externus
Ptm	The most posterior point on the outline of the pterygopalatine fossa: The geometric center of foramen rotundum which can be found in the most anterior coronal section
Rh	The most anterior inferior point on the tips of the nasal bones
ANS	The most anterior point of the nasal floor; tip of premaxilla
PNS	The most posterior point on the hard palate
U1apex	The root tip of the maxillary central incisor
S	The center of sella turcica
Ii	The mid-point of the incisal edge of the mandibular central incisor
B	The most posterior point of the bony curvature of the mandible below infradental and above pogonion
Pog	The most anterior point on the symphysis of the mandible
Me	The lowest point of the contour of the mandibular symphysis: The lowest median landmark on the lower border of the mandible- concave surface under the mentum in the mid-sagittal plane
Me'	The lowest most point of the contour of the mandibular symphysis: defined only in the projected image
Go	The point on the bony contour of the gonial angle determined by bisecting the tangent angle
L1apex	The root tip of the mandibular central incisor

Korea) after selection of the landmarks. Table 1 shows the selected landmarks. Projected images from the 3D model were obtained by reducing the transparency of the skin part. Projected images were saved as a pdf file format, and magnified to 110% using photoshop 6.0 (Fig 2, *B*).

Superimposition of projected images with cephalometric tracings

Because of the positional difference of the mandible according to body posture, the projected images had to be superimposed with cephalometric tracing in two ways. For overall superimposition, projected image to midsagittal plane was generated by reducing the transparency of the skin part. This made such an effect that the projected image looked like a cephalometric radiograph. Two reference points were arbitrarily selected along the FH plane in the lower area of the projected image (Fig 3, *A*). Cephalometric radiograph was traced (Fig 3, *B*). Two images were superimposed by overlapping the structures such as the anterior margin of frontal bone, dorsum of nose, and inferior margin of occipital bone between the two images. And then, the two reference points were copied to the tracing (Fig 3, *C*).

To compare the landmark position, a common Cartesian coordinates was established from the two reference points. Horizontal reference line (X axis) was

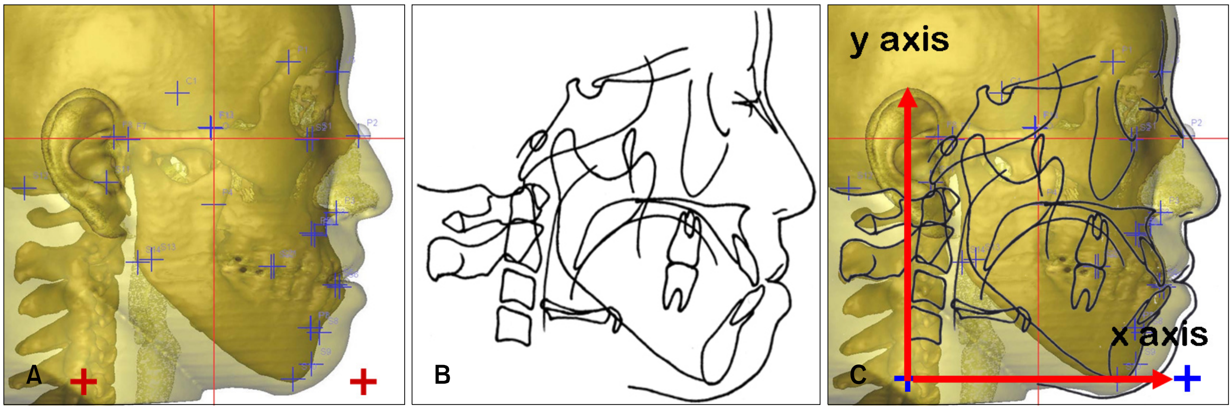

Fig 3. Superimposition of projected images with cephalometric tracings and establishment of common Cartesian coordinates. **A**, Two reference points were created parallel to the FH plane in the projected images; **B**, cephalometric radiograph was traced; **C**, projected image and tracing were superimposed on to frontal bone and occipital bone, and then the two reference points were copied to the tracing for reprinting of a common coordinate system.

generated by connecting the two points, which was parallel to the FH plane of the projected image. Another line for Cartesian coordinates (Y axis) could be made perpendicular to the FH plane, including a left sided reference point. After superimposition, a common Cartesian coordinates was reprinted from the duplicated two reference points.

For mandibular superimposition, all the steps were the same as the overall superimposition. The only difference was the structures to be superimposed. The anterior margin of the symphysis was used for superimposion.

Landmark selection

Table 1 shows the definition of landmarks used in this study. Midpoint was used when the landmark was located in the left and right side. Me' was newly defined in the projected images as the lowest point of the mandibular symphysis. The definition of Me' in cephalometry was the same as that of Me. The positional difference between Me and Me' was also calculated.

Comparison of the landmark position between projected images and tracing

To compare the positional difference of landmarks, paired *t*-test was performed with the X and Y coordinate values of landmarks obtained from projected images and tracings. The X and Y coordinate values from tracings were subtracted from the values from projected images to calculate the coordinate value difference. Mean and standard deviation (SD) of coordinate value difference were calculated.

All the landmarks were selected twice by one orthodontist with a lapse of four weeks, and the standard error (SE) was calculated to investigate the intraobserver repeatability.

RESULTS

Intraobserver repeatability is shown in Table 2. For cephalometric radiography, the error range was from 0.41 to 0.87 mm in the X axis, and from 0.37 to 0.73 mm in the Y axis. In 3D CT, the error range was from 0.37 to 0.95 mm in the X axis, from 0.49 to 1.37 mm in the Y axis.

Table 3 shows the mean, SD, and result of paired *t* test. The difference was from -0.14 ± 0.65 to -2.12 to 2.89 mm in the X axis, and from 0.34 ± 0.78 to 6.79 ± 3.04 mm in the Y axis. In the X axis, Pog showed the smallest standard error and Po showed the largest. In the Y axis, Me' showed the smallest error and Po showed the largest error and Ptm showed an extraordinary large error. Except for Ptm, the error range in the Y axis was from 0.34 ± 0.78 to -2.36 ± 2.55 mm.

Table 2. Intraobserver repeatability for landmark selection in cephalometric radiography and 3D CT (unit: mm)

	Cephalometric radiography		3D CT	
	X axis	Y axis	X axis	Y axis
Nasion	0.87	0.48	0.71	1.81
Orbitale	0.49	0.45	0.70	0.76
A point	0.55	0.49	0.37	0.91
Incision superius	0.44	0.45	0.40	0.90
Basion	0.44	0.53	0.75	0.70
U6Cr	0.41	0.48	0.63	0.41
Porion	0.50	0.63	0.56	0.73
Pterygomaxillary fissure	0.61	0.46	0.73	1.37
Rhinion	0.59	0.62	0.75	0.92
Anterior nasal spine	0.56	0.37	0.42	1.00
Posterior nasal spine	0.51	0.37	0.48	0.42
U1apex	0.47	0.40	0.57	0.67
Sella	0.59	0.39	0.69	0.49
Incision inferius	0.49	0.54	0.30	0.51
B point	0.50	0.52	0.44	1.18
Pogonion	0.47	0.52	0.61	1.05
Menton	0.48	0.53	0.78	0.96
Gonion	0.42	0.73	0.95	1.31
L1apex	0.50	0.40	0.40	0.84

U6Cr, The mesiobuccal cusp tip of the maxillary 1st molar; U1apex, the root tip of the maxillary central incisor; L1apex, the root tip of the mandibular central incisor.

There were significant differences in 11 out of 20 landmarks in the X axis, 13 out of 20 in the Y axis. Only 4 out of 20 landmarks showed no significant differences as a result. All the landmarks in the mandible showed significant differences in the Y axis except for only one landmark, the apex of the lower incisor.

Fig 4 shows the difference in landmark positions. The arrow head shows the landmark position in the radiograph and base of the arrow is the position in the projected image. The size of the arrow corresponds to the amount of error.

DISCUSSION

The error ranges from this study were similar to the previous study for the landmark identification. Richardson[19] investigated the interobserver and intraobserver differences for the cephalometric landmarks, and concluded that the error ranges were below 2 mm. Midtgard et al.[4] showed an intraobserver error range from 0.50 ± 0.13 to 2.44 ± 0.46 mm and all of the 15 landmarks showed significant differences in each identification. Liu et al.[20] compared the errors for automatic and manual landmark identification, and concluded that the accuracy of computerized automatic identification was acceptable for certain landmarks only. Nine out of 14 landmarks showed significant differences in his study. In manual identification, horizontal errors ranged from 0.38 ± 0.21 to 1.83 ± 0.79 mm, vertical errors ranged from 0.47 ± 0.22 to 1.70 ± 1.31 mm. In automatic identification, horizontal errors ranged from 0.57 ± 0.42 to 3.04 ± 2.86 mm, and vertical errors from 0.65 ± 0.52 to 4.30 ± 3.58 mm.

There were significant differences in 16 out of 20 landmarks in the x and/or y direction. This might mean that the position of cephalometric landmarks did not

Table 3. Mean and standard deviation (SD) of coordinate value difference between cephalometric radiography and 3D CT (unit: mm)

Landmark	X-axis		Y-axis	
	Mean ± SD	*p*-value	Mean ± SD	*p*-value
Nasion	1.01 ± 1.02	0.00*	0.47 ± 2.60	0.43
Orbitale	0.58 ± 1.50	0.10	0.34 ± 0.78	0.07
A point	2.97 ± 1.56	0.00*	−1.44 ± 1.41	0.00*
Incision superius	−0.60 ± 0.92	0.01*	−0.71 ± 0.97	0.00*
Basion	−0.30 ± 1.86	0.47	−0.06 ± 1.48	0.86
U6Cr	0.13 ± 1.23	0.65	−0.25 ± 1.16	0.35
Porion	−2.12 ± 2.89	0.00*	−2.36 ± 2.55	0.00*
Pterygomaxillary fissure	−0.44 ± 1.71	0.26	6.79 ± 3.04	0.00*
Rhinion	−0.81 ± 1.41	0.02*	1.04 ± 1.31	0.00*
Anterior nasal spine	1.58 ± 1.63	0.00*	−1.07 ± 0.86	0.00*
Posterior nasal spine	−1.78 ± 2.32	0.00*	−0.36 ± 1.26	0.21
U1apex	−0.46 ± 1.79	0.27	0.42 ± 2.10	0.38
Sella	0.23 ± 0.92	0.28	1.15 ± 1.04	0.00*
Incision inferius	−1.07 ± 1.08	0.00*	1.04 ± 0.84	0.00*
B point	−0.43 ± 0.62	0.01*	−2.73 ± 2.00	0.00*
Pogonion	−0.14 ± 0.65	0.33	1.24 ± 1.70	0.00*
Menton	0.28 ± 1.46	0.39	0.93 ± 0.97	0.00*
Menton’	−0.02 ± 1.38	0.96	−0.48 ± 0.63	0.00*
Gonion	−1.45 ± 1.30	0.00*	2.41 ± 1.62	0.00*
L1apex	−0.87 ± 1.17	0.00*	−0.84 ± 1.80	0.05

U6Cr, The mesiobuccal cusp tip of the maxillary 1st molar; U1apex, the root tip of the maxillary central incisor; L1apex, the root tip of the mandibular central incisor. *$p < 0.05$, paired *t*-test.

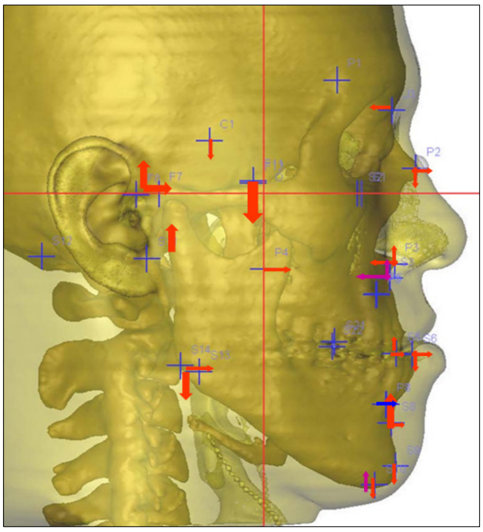

Fig 4. Difference of landmark position; arrow head is the position in the radiograph, base of arrow is the position in the projected image, and the size of arrow corresponds to the amount of error.

coincide with that of projected 3D landmarks. This was anticipated from the fact that there were two types of errors in the cephalometric radiograph errors of projection and errors of identification.[2] Moreover, the methods of making 2D images were slightly different between cephalometric radiographs and projected 3D images. Cephalometric radiographs were produced as the central ray was radially projected onto the midsagittal plane. In projected 3D images the central ray was projected perpendicular to the midsagittal plane. In addition, the midsagittal plane on cephalometric radiograph might not be identical to that in the projected 3D image. In spite of these imperfections, there might be other sources of error to be categorized between cephalometric radiographs and projected 3D images in this study.

Errors from the difference of body posture (Fig 5): body posture could affect the mandibular resting position. Radiographs were taken in the upright position with a cephalostat, and CT scans were taken in the supine position. To avoid the errors from positional difference, projected images were superimposed with the cephalometric tracing in two ways; overall superimposition and mandibular superimposition.

Errors from the discrepancy of midsagittal plane selected between x ray taking and projected images (Fig 6): these errors might arise from the discrepancy of the midsagittal plane between that defined for the x ray taking and that selected from the CT images. These kinds of errors also could occur in the landmarks which were defined in the midsagittal plane conceptually. The landmarks corresponding to this kind of errors were Na, Is, Ii, B, and vertical postion of Pog.

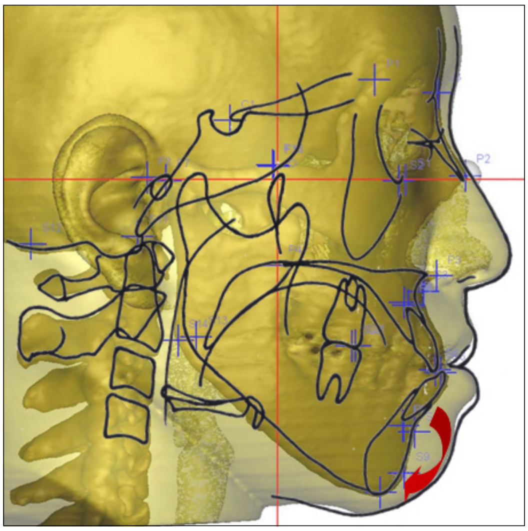

Fig 5. Errors from differences in body posture. Projected image showed backward downward movement of the mandible.

Errors from masking of bony end projections (Fig 7): the end of bony projections was so thin that radiographic images could not sharply demarcate its structure. Its image was obscured by adjacent structures so that the position of landmark was selected posterior to the real position on radiograph. Rh, ANS, A, and the horizontal position of PNS were the landmarks correspondent to this kind of error.

Errors from the superimposition of adjacent structures: in some anatomic structures, shapes in the cross sectioned image were different from the shapes in stacked images. Po is a good example: meandering auditory meatus might not only obscure the exact landmark position, but also change the position itself. The vertical position of S was another example: since pituitary gland is consisted of two lobes, the center of the base is somewhat elevated than the adjacent area, which brings the S position down.

Errors from the positional differences defined in the radiograph and CT scans (Fig 8): Me was the representative point of this example. Cephalometric definition of Me is the lowest point of the contour of the

Fig 6. Errors from the discrepancy of midsagittal plane selected between x-ray taking and projected images. Anterior contour of radiograph was changed with increase in projection angle. **A**, Projected line was perpendicular to the midsagittal plane; **B**, projected line was tilted to the midsagittal plane.

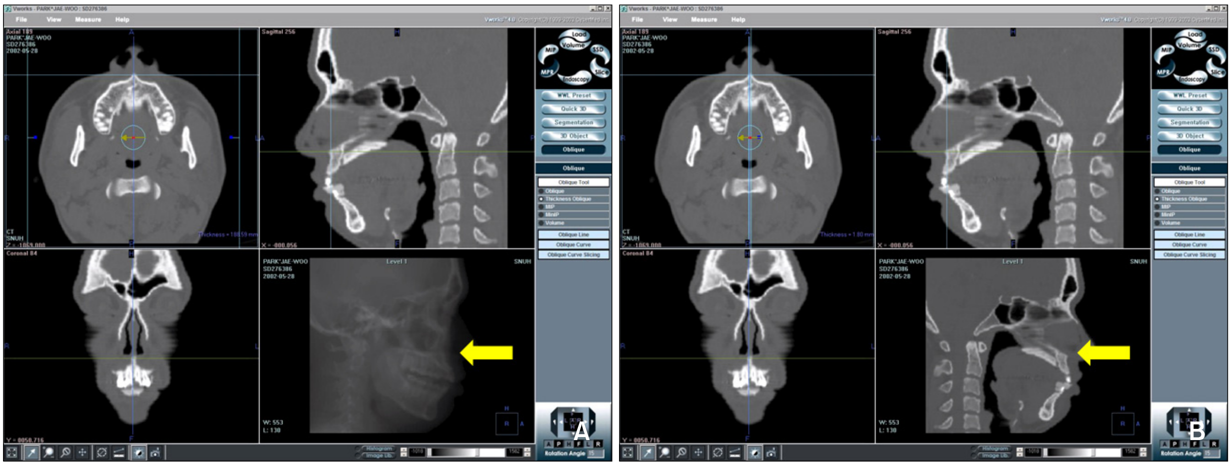

Fig 7. Errors from the masking of bony projection. **A**, Ray sum images of the entire head made the position of ANS appear more backward; **B**, ray sum image around point ANS revealed its original position.

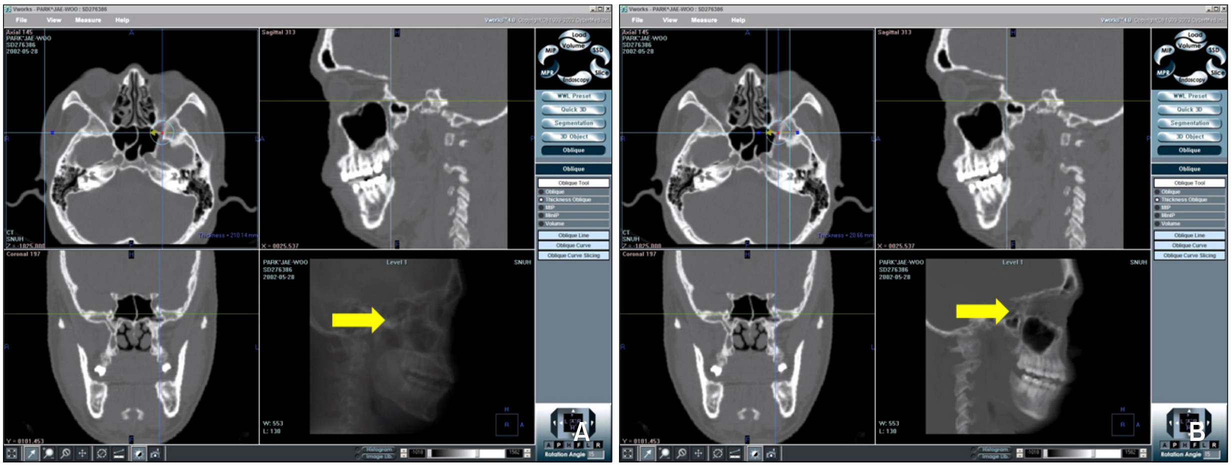

Fig 8. Errors from the positional differences defined in the radiograph and CT scans. **A**, Ray sum image of entire head made the position of Ptm appear more downward and backward; **B**, ray sum image around point Ptm revealed its original position.

mandibular symphysis, but Me in CT images is the lowest median landmark positioned on the concave surface at the lower border of the mandible. The difference of definition makes an error in the vertical position of Me. Ptm was another example: cephalometric definition is the most posterior point on the outline of the pterygopalatine fossa, which is usually located in the 11 o'clock direction. However, this is the geometric center of foramen rotundum which can be found most anteriorly in coronal sections in CT images. The extraordinary high error in the vertical position of Ptm can be explained by the difference in definition.

The errors of projection and the errors of identification might play a role in the positional differences of landmarks between two images, but it was certain that there were some sources of error from the limitation of the radiograph itself. Further studies would be needed to minimize or compensate for these errors.

CONCLUSION

Several landmarks showed significant positional differences between cephalometric radiography and CT images projected to midsagittal plane. This might be originated from the innate shortcommings of radiography. For the clinical use of 3D cephalometry, further study was needed to investigate the positional relation of landmarks between cephalometric radiography and CT scans.

- 국문초록 -

3차원 CT자료에서 선정된 계측점을
정중시상면으로 투사한 영상과
두부계측방사선사진상의 계측점의 위치 비교

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본 연구는 두부계측방사선사진에서 선정한 계측점과, 3차원 CT영상에서 계측점을 선정하고 이를 정중시상면으로 투영하였을때 두 계측점 사이의 위치적 연관성에 대해 알아보고자 시행하였다. III급 부정교합을 주소로 서울대학교 치과병원에 내원한 환자 20명을 대상으로 술 전에 CT와 두부방사선사진을 촬영하였다. CT자료에서 계측점을 선정하고, 정중시상면을 기준으로 투사영상을 얻은 후에 이것을 110%로 확대하였다. 전두면과 후두골의 외연을 기준으로 두부방사선사진 투사도와 CT자료의 정중시상면 투사영상을 중첩하고, FH평면을 기준으로 공통 좌표계를 설정하였다. 이 좌표계를 기준으로 얻은 계측점 좌표값 차이의 평균과 표준편차를 구하고 paired *t* test를 시행하였다. X축은 −0.14 ± 0.65에서 −2.12 ± 2.89 mm, Y축은 0.34 ± 0.78에서 −2.36 ± 2.55 mm (6.79 ± 3.04 mm)의 범위를 보였으며, 20개의 계측점 중 X축은 9개에서, Y축은 7개에서 통계적으로 유의한 차이가 없는 것으로 나타났다. 이러한 오차는 촬영자세에 따라 악골의 위치가 변화한 경우, 골단부에 위치함으로써 주변구조물에 가려진 경우, 해부학적 구조물의 중첩에 따른 식별오차, 계측점의 정의가 다른 경우 발생할 수 있다.

주요 단어: 계측점 위치, 두부계측방사선사진, 3D CT에서 투사된 영상

REFERENCES

1. Broadbent BH. A new x-ray technique and its application to orthodontia. Angle Orthod 1931;1:45-66.
2. Baumrind S, Frantz RC. The reliability of head film measurements. 1. Landmark identification. Am J Orthod 1971;60:111-27.
3. Ahlqvist J, Eliasson S, Welander U. The effect of projection errors on cephalometric length measurements. Eur J Orthod 1986;8:141-8.
4. Midtgard J, Bjork G, Linder-Aronson S. Reproducibility of cephalometric landmarks and errors of measurements of cephalometric cranial distances. Angle Orthod 1974;44:56-61.
5. Tng TT, Chan TC, Hägg U, Cooke MS. Validity of cephalometric landmarks. An experimental study on human skulls. Eur J Orthod 1994;16:110-20.
6. Houston WJ, Maher RE, McElroy D, Sherriff M. Sources of error in measurements from cephalometric radiographs. Eur J Orthod 1986;8:149-51.
7. Grayson BH, McCarthy JG, Bookstein F. Analysis of craniofacial asymmetry by multiplane cephalometry. Am J Orthod 1983;84:217-24.
8. Baumrind S, Moffitt FH, Curry S. Three-dimensional x-ray stereometry from paired coplanar images: a progress report. Am J Orthod 1983;84:292-312.
9. Grayson B, Cutting C, Bookstein FL, Kim H, McCarthy JG. The three-dimensional cephalogram: theory, technique, and clinical application. Am J Orthod Dentofacial Orthop 1988; 94:327-37.
10. Kusnoto B, Evans CA, BeGole EA, de Rijk W. Assessment of 3-dimensional computer-generated cephalometric measurement. Am J Orthod Dentofacial Orthop 1999;116:390-9.
11. Rousset MM, Simonek F, Dubus JP. A method for correction of radiographic errors in serial three-dimensional cephalometry. Dentomaxillofac Radiol 2003;32:50-9.
12. Mozzo P, Procacci C, Tacconi A, Martini PT, Andreis IA. A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. Eur Radiol 1998;8: 1558-64.
13. Christiansen EL, Thompson JR, Kopp S. Intra- and inter-observer variability and accuracy in the determination of linear and angular measurements in computed tomography. An in vitro and in situ study of human mandibles. Acta Odontol Scand 1986;44:221-9.
14. Hildebolt CF, Vannier MW, Knapp RH. Validation study of skull three-dimensional computerized tomography measurements. Am J Phys Anthropol 1990;82:283-94.
15. Matteson SR, Bechtold W, Phillips C, Staab EV. A method for three-dimensional image reformation for quantitative cephalometric analysis. J Oral Maxillofac Surg 1989;47:1053-61.
16. Kragskov J, Bosch C, Gyldensted C, Sindet-Pedersen S. Comparison of the reliability of craniofacial anatomic landmarks based on cephalometric radiographs and three-dimensional CT scans. Cleft Palate Craniofac J 1997;34:111-6.
17. Adams GL, Gansky SA, Miller AJ, Harrell WE Jr, Hatcher DC. Comparison between traditional 2-dimensional cephalometry and a 3-dimensional approach on human dry skulls. Am J Orthod Dentofacial Orthop 2004;126:397-409.
18. Park JW, Kim NK, Chang YI. Formulation of a reference coordinate system of three-dimensional (3D) head and neck images: Part I. Reproducibility of 3D cephalometric landmarks. Korean J Orthod 2005;35:388-97.
19. Richardson A. An investigation into the reproducibility of some points, planes, and lines used in cephalometric analysis. Am J Orthod 1966;52:637-51.
20. Liu JK, Chen YT, Cheng KS. Accuracy of computerized automatic identification of cephalometric landmarks. Am J Orthod Dentofacial Orthop 2000;118:535-40.