Using Superimposition of 3-Dimensional Cone-Beam Computed Tomography Images with Surface-Based Registration in Growing Patients

Kiyoshi Tai * / Jae Hyun Park ** / Katsuaki Mishima *** / Hitoshi Hotokezaka ****

Objective: *The purpose of this research was to evaluate a new method of superimposing detailed cone-beam computed tomography (CBCT) images.* ***Materials and Methods:*** *This study used 5 different software programs to transform the digital imaging and communication in medicine (DICOM) data from CBCT image into polygon data. The data conversion errors from different software programs were verified by the polyacetal ball test and the dry skull test. The iterative closest point (ICP) method was used for precise superimposition. To evaluate changes related to growth, three different domains were superimposed in order to investigate appropriate areas for evaluation by the ICP method.* ***Results:*** *The ICP method in the cranial base (excluding the peripheral zone) was indicated as the most reliable surface in this research. There were no measurement errors in converting the image data between software programs.* ***Conclusion:*** *The ICP method in the cranial base (excluding the peripheral zone) is one of the most accurate methods for superimposition when the mandibular rotation or displacement has not occurred during growth or treatment. This 3-dimensional (3D) superimposition technique can be used for a valid and reproducible assessment of treatment outcomes for growing subjects. This method is considered to be of clinical value because of the manageability and 3D accuracy of the data comparison with multi planar reconstruction (MPR) images.*
Keywords: *Three-dimensional (3D) CBCT, superimposition, iterative closest point (ICP) method*
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* Kiyoshi Tai, DDS, Visiting Adjunct Assistant Professor, Postgraduate Orthodontic Program, Arizona School of Dentistry & Oral Health, A. T. Still University, Mesa, AZ, and PhD Student, Okayama Department of Oral and Maxillofacial Reconstructive Surgery, Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, and Private Practice of Orthodontics, Okayama, Japan.
** Jae Hyun Park, DMD, MSD, MS, PhD, Associate Professor and Chair, Postgraduate Orthodontic Program, Arizona School of Dentistry & Oral Health, A. T. Still University, Mesa, AZ and International Scholar, the Graduate School of Dentistry, Kyung Hee University, Seoul, Korea.
*** Katsuaki Mishima, DDS, PhD, Senior Assistant Professor, Okayama Department of Oral and Maxillofacial Reconstructive Surgery, Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, Okayama, Japan.
**** Hitoshi Hotokezaka, DDS, PhD, Senior Assistant Professor, Department of Orthodontics and Dentofacial Orthopedics, Nagasaki University Graduate School of Biomedical Sciences, Nagasaki, Japan.

Send all correspondence to: Dr. Jae Hyun Park, Postgraduate Orthodontic Program, Arizona School of Dentistry & Oral Health, A.T. Still University, 5855 East Still Circle, Mesa, AZ 85206.

Tel: 480.248.8165
Fax: 480.248.8180

Email: JPark@atsu.edu

INTRODUCTION

Various techniques for the reconstruction of 3-dimensional (3D) cone-beam computed tomography (CBCT) images have been used in diagnosis, treatment planning, and simulation.[1-4] However, image superimposition for the assessment of changes with treatment or growth poses many challenges. There have been several reports about the superimposition of the CBCT.[5-7] These reports evaluated the 3D images as 3D data.[6,7] 3D diagnosis should be evaluated using the coordinate system.[8] However, the superimposition of lateral cephalograms is the standard method to quantify changes from treatment and growth.[1-4] Even if technology progresses, it will take time for many clinicians to become familiar with a 3D analysis because most clinicians were trained to use conventional 2-dimensional (2D) analysis of cephalometric radiographs. The current study used 3D data for precise superimposition and then converted it into MPR images that could be evaluated by conventional superimposition. Most clinicians would find this method to be quite acceptable. The purpose of the study was to determine the reproducibility of 3D superimposition for analysis with MPR images.

MATERIALS AND METHODS

The initial data was recorded in a private orthodontic office, and the 14 patients (six males and eight females) were randomly selected. The subjects were diagnosed as having well

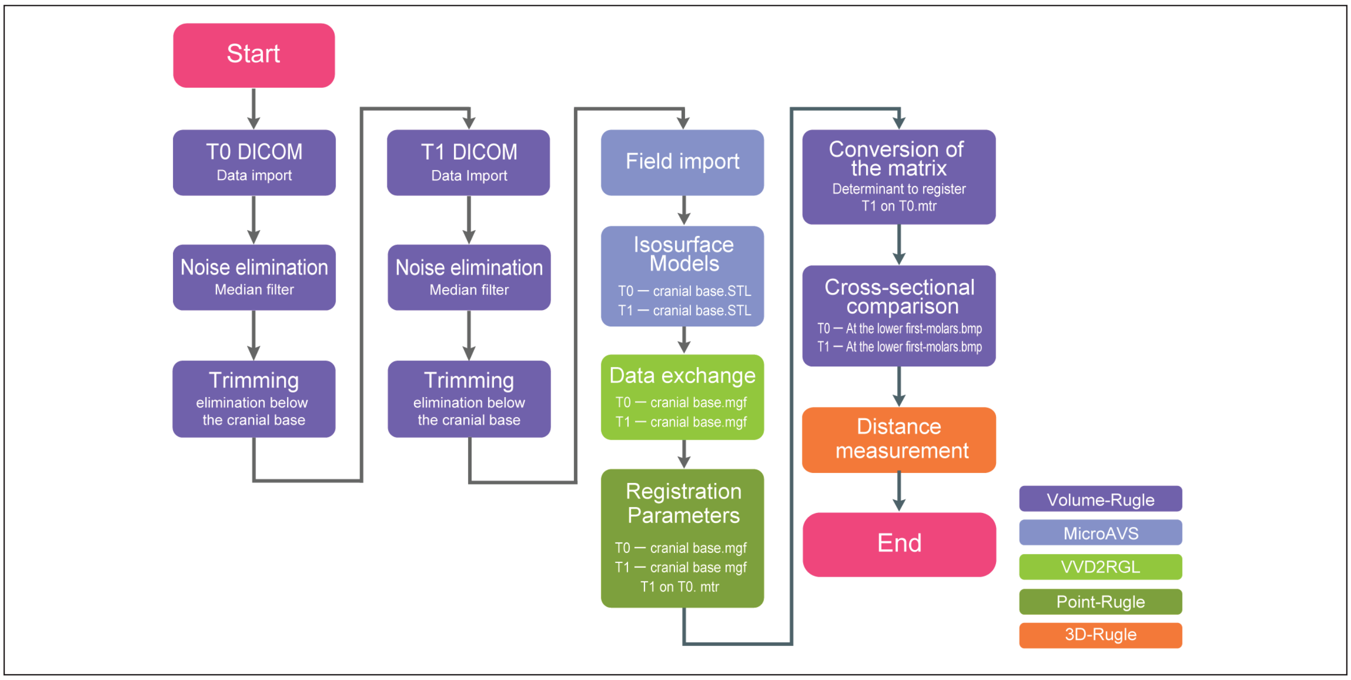

Figure 1. A flow chart illustrating the methods used to convert the CBCT-derived DICOM data into polygon data. The polygon data was used for registration and then the target distances were measured.

balanced facial profiles with competent lips. Intraoral examination indicated Angle Class I malocclusions with minor crowding and normal vertical dimensions with no posterior crossbites. The first CBCT (T0) was taken at an average age of 8 years 0 months, and the second CBCT (T1) was taken at an average age of 9 years 8 months.

The natural head position[9] was obtained by orienting the Frankfurt plane parallel to the floor at a seated position, and an image was taken at the intercuspal position using a CB MercuRay (Hitachi Medical Corporation, Tokyo, Japan).

Five different software programs, Volume-Rugle (Medic Engineering, Kyoto, Japan), MicroAVS (KGT, Tokyo, Japan), VVD2RGL, Point-Rugle, 3D-Rugle (Medic Engineering, Kyoto, Japan) were used to transform the digital imaging and communication in medicine (DICOM) data from CBCT images into polygon data (Figure 1). The iterative closest point (ICP) method[10,11] is able to superimpose images very precisely with repeatability because numerous corresponding points are utilized to compare with point-based registration.[12,13] The ICP method was used to superimpose two 3D images at T0 and T1. These methods make an accurate superimposition of two separate 2D multi-

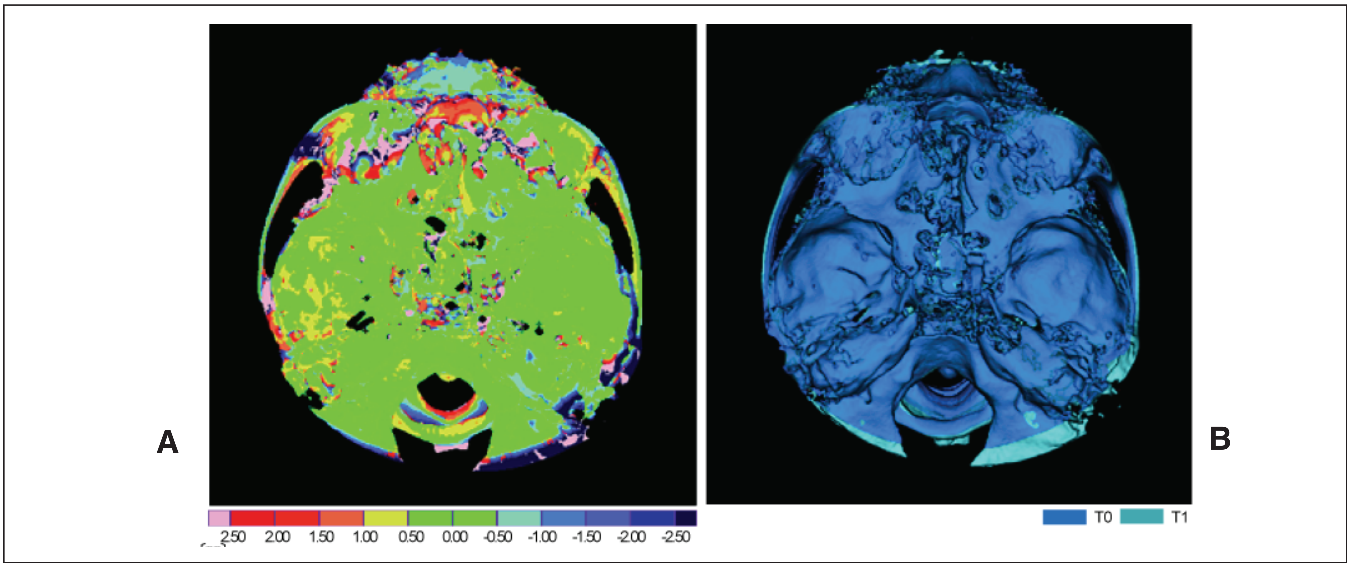

Figure 2. The ICP method at the cranial base: A. Superimposition was performed in all areas of the cranial base excluding the peripheral zone that experienced growth. The green area shows that superposition (or registration) was performed within ± 0.50 mm. The yellow area shows it to range from +0.50 mm to +1.00 mm. The light blue area shows it to range from -0.50 mm to -1.00 mm; B. 3D image demonstrates the superimposition of T1 on T0 at cranial base. In this method to increase the accuracy of the superimposition combining manual and automatic registrations are possible. Blue and light blue colors indicate T0 and T1 respectively.

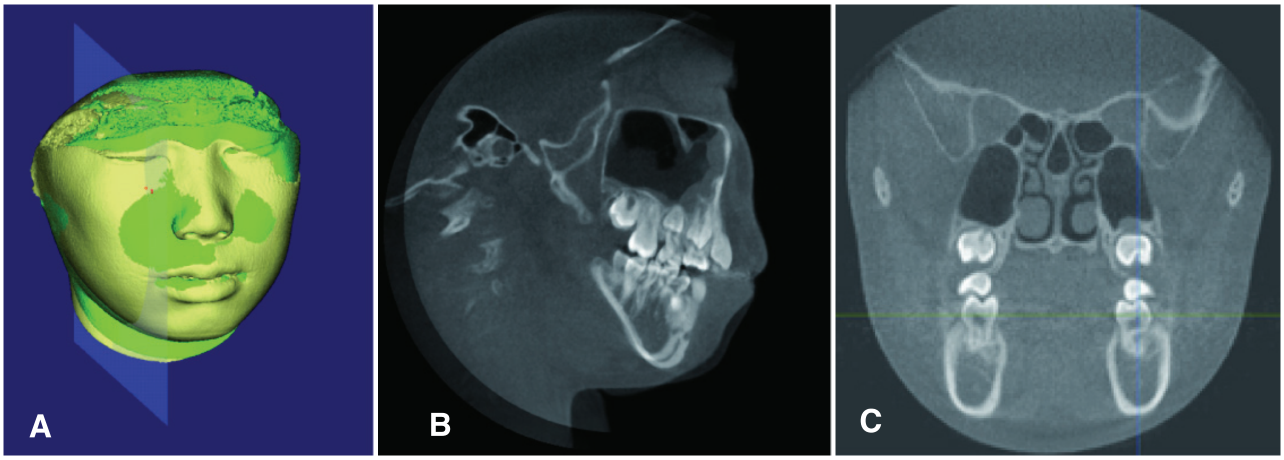

Figure 3. The registered 3D images and derived MPR images. Green and yellow color indicates T0 and T1 respectively (A). To facilitate measurement, the T0 and T1 MPR images were overlapped (B). The MPR image of the mandibular first molars that was obtained by the cutting down an arbitrary plane we designed (C).

planar reconstruction (MPR) images possible. Furthermore, specific points of the cranial base were used as the reference points for registration (superimposition) to enhance the accuracy of the ICP method, because the cranial base is not greatly influenced by growth (Figure 2).[14-16]

The combined images were cut down an arbitrary plane and made into two units. The DICOM data was converted into MPR images along the cross-sectional surface and a comparison examination was accurately performed. The MPR images, which display excellent dimensional accuracy,[17] were used to compare the T0 and T1 data (Figure 3).

Validity verification

The polyacetal ball tests and dry skull tests were employed for both the examination of the accuracy of CBCT and the examination of the error margin because different software packages are used as the measuring methods. The tests were used to prove whether there were measurement errors in the data conversion of the images as shown in the flow chart (Figure 1). In other words, these tests were used to validate the superimposition technique and analysis of the MPR images after superimposing the 3D images.

Verification of measurement error using the polyacetal balls

The accuracy of the measurement device was checked using two polyacetal balls (Sato-tekkou, Toyama, Japan). Two different sizes of balls, 25.20 mm and 49.70 mm, were used to examine how they affect the validity of the measurements during the data conversion from different software programs. Three dimensional coordinates of position were set on the arbitrary space so that the width, depth and height were measured (Figure 4). According to the manufacturer's information, the diameters measured were 25.20 mm and 49.70 mm and the size error was ± 0.02 mm. The CBCT was performed 10 times. The first image was taken when the two different sizes of balls were positioned in the center of the image domain to see whether any significant measurement differences existed according to the position of balls. The different sized balls were positioned at the border area of the image domain for the second image. The diameters of the balls were measured using 3D-Rugle software. The same examiner (KT) performed ten measurements with 3D-Rugle, and the average, standard deviation, measurement error margin, and average error margin rate were thus obtained.

Verification of measurement error using a dry skull

The procedures for measuring the distance between landmarks must contain measurement errors. The distance between the right and left mandibular antegonial notches and the distance between the right and left condylar heads (Figure 5) were measured to increase the validity and repeatability of measurements using the 3D-Rugle software program (A). Another CBCT image was taken and measured using the 3D-Rugle software program by placing lead markers

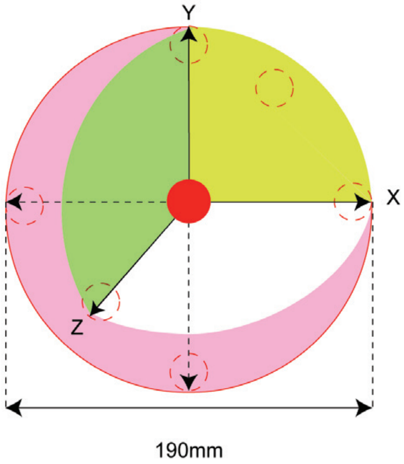

Figure 4. Three dimensional coordinates of position were set on the arbitrary space so that the width, depth and height were measured.

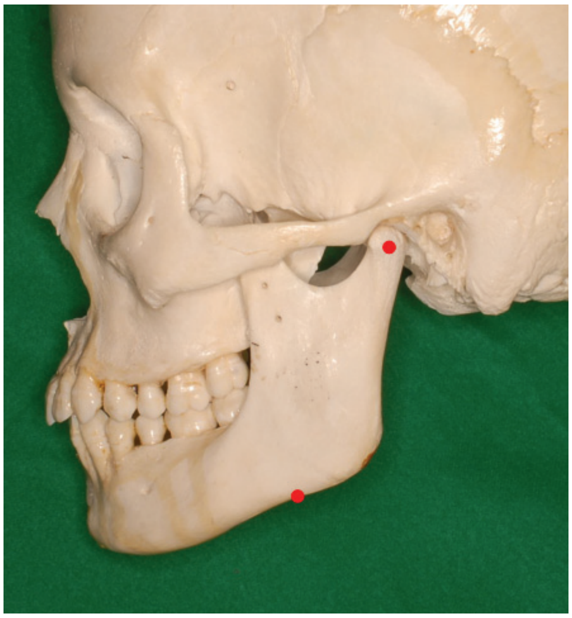

Figure 5. Verification of measurement error using a dry skull. The outermost parts of the condylar heads and the mandibular antegonial notches were used for measuring the distance between landmarks.

with diameters of 0.5 mm to the outermost parts of the condylar heads and the mandibular antegonial notches (B).

The same distances on the dry skull with lead markers were measured manually using a digital caliper (NTD 12-15PMX, Mitsutoyo, Kanagawa, Japan), which is accurate to 0.01 mm (C). These three measurements were collected 10 times, and their average and standard deviation were calculated, followed by an analysis of the significance.

Verification of superimposing domain of the ICP method

The cranial base,[14-16] infraorbital margin[18,19] and the corpus axis (Xi-Pm line)[20-23] were used as domains of superimposing in the ICP method of T0 and T1 (Figures 6–8). In order to evaluate the morphological growth changes, the ICP superimposition error was compared using different domains. The purpose and the evaluation of the change of the form, will dictate the appropriate ICP method.[6,7,18-21] A slice plane perpendicular to the occlusal plane, passing through both sides of the mesial buccal cusp tips of the mandibular first molars, was prepared for the measurements. On the plane, each the buccolingual width of the right and left lower first molar were measured ten times, and the mean value and standard deviation were obtained respectively, because the first molars were constant from T0 to T1. In any three ICP, the value of the first molar of T0 was assumed to be a true value, the difference with the value of T1 was judged to be superimposing error margin. Margin of error and rate of average error were obtained.

RESULTS

The polyacetal ball test

The measurement errors within the CBCT apparatus, including the data conversion of the software, were determined using polyacetal balls. The margin of error and average error rates of the polyacetal balls ranged from ± 0.03 - 0.07 mm and 0.12 - 0.16%, respectively, when the polyacetal balls were placed at the center or edge of the image domain. No significant differences were observed between the balls with a diameter 25.20 mm and 49.70 mm. The error was not influenced by either the difference in size or the position of the ball when the polyacetal ball was placed in the photography area. Therefore, the measurements of distance in this study were mechanically satisfactory.

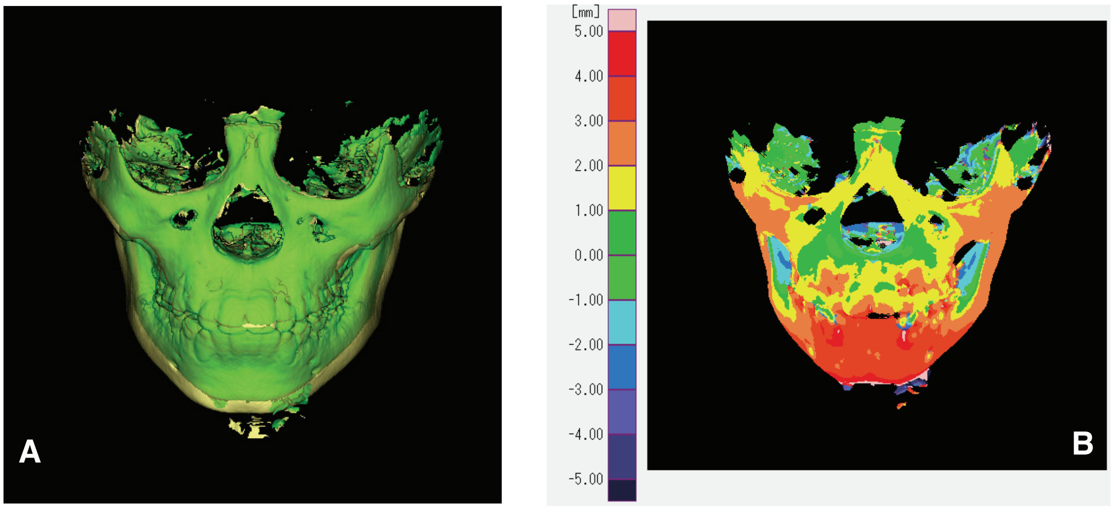

Figure 6. 3D images demonstrate the superimposition of T1 on T0 by the ICP method at the cranial base. Green and yellow colors indicate T0 and T1 respectively (A). The green area shows that superposition (or registration) was performed within ±1.00 mm. The yellow area shows it to range from +1.00 mm to +2.00 mm. The light blue area shows it to range from -1.00 mm to -2.00 mm (B).

Table 1. The verification of a measurement error using a dry skull

	Margin of error		Rate of average error	
	A-B	B-C	A-B	B-C
Distance b/w antegonial notches	±0.17 mm	±0.11 mm	0.18%	0.12%
Distance b/w condylar heads	±0.16 mm	±0.11 mm	0.13%	0.09%

A: the distance between the right and left mandibular antegonial notches and the distance between the right and left condylar heads measured using the 3D-Rugle software program,
B: the same distances on the dry skull with lead markers using the 3D-Rugle software program,
C: the same distances with lead markers measured manually using a digital caliper.

The dry skull test

A dry skull was used to estimate the measurement error. The measurement error and the average were obtained by measuring the lengths of A-B, B-C, the inter-mandibular antegonial notches, and the inter-condylar heads (Table 1).

Table 2. The verification of a superimposing error by the ICP method

	Left M1		Right M1	
	ME	RAE	ME	RAE
Cranial base	±0.02 mm	0.15%	±0.01 mm	0.12%
Infraorbital margin	±0.04 mm	0.35%	±0.04 mm	0.38%
Corpus axis (Xi-Pm line)	±0.06 mm	0.56%	±0.05 mm	0.52%

M1 indicates the mandibular first molar; ME, margin of error; RAE, rate of average error.

The error of the A-B length may be derived mainly from an error of point setting on the mandibular antegonial notches and condylar heads in the CBCT image.

The error of the B-C length was attributed to a person's technical error of measurement because the point of measurement was a stationary lead ball. The average error of A-B was larger than that of B-C, although no significant difference was observed (P = .141). This result indicates that the measurement in a CBCT image is sufficiently accurate.

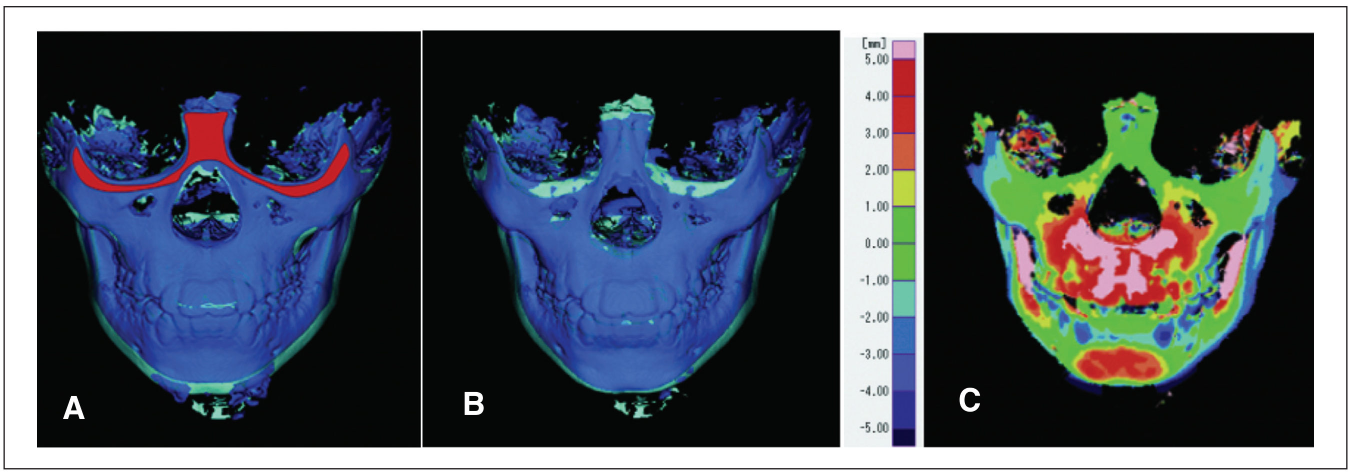

Figure 7. The infraorbital margin (red area) was used as domains of superimposing in the ICP method of T0 and T1 (A). The 3D image demonstrates the superimposition of T1 on T0 at cranial base. Blue and light blue colors indicate T0 and T1 respectively (B). The proportions of colors that represent the matching levels (C) are similar to Fig 6(B).

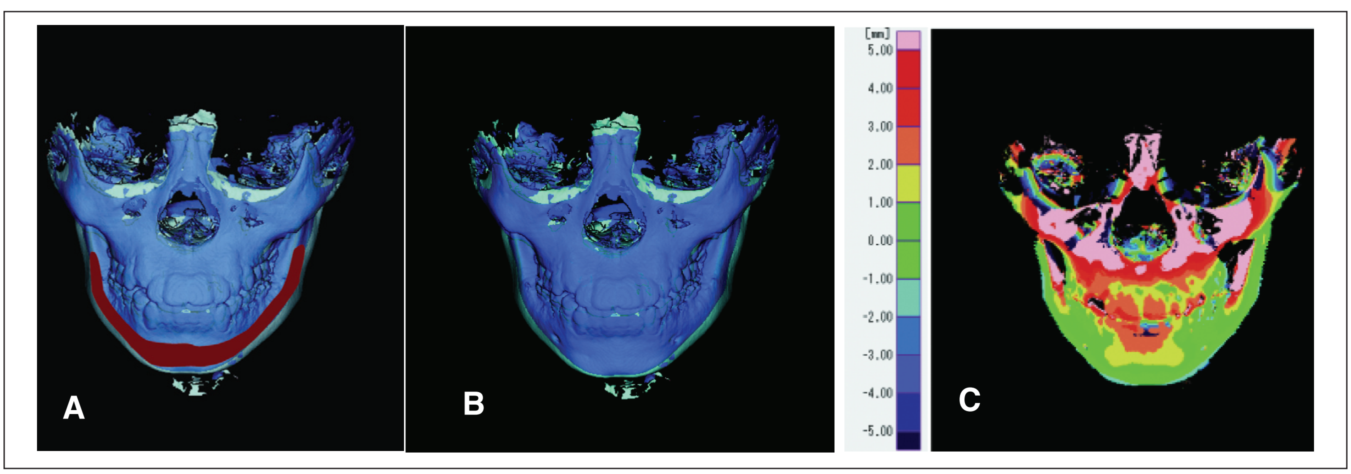

Figure 8. The corpus axis (red area) was used as domains of superimposing in the ICP method of T0 and T1 (A). The 3D image demonstrates the superimposition of T1 on T0 at cranial base. Blue and light blue colors indicate T0 and T1 respectively (B). The proportions of colors that represent the matching levels (C) are similar to Fig 6(B).

Verification of superimposing domain of the ICP method

The cranial base, the infraorbital margin, and the corpus axis (surface on the Xi-Pm line) were used as domains of superimposing in the ICP method of T0 and T1 (Table 2). The measurements of the cranial base had a margin of error of ±0.03 mm with a 0.13% average error rate. The margin of error and average error rate of the infraorbital margin and the corpus axis were ±0.06 mm and 0.54% and ±0.04 mm and 0.37%, respectively.

DISCUSSION

Three-dimensional superimposition to compare a growing subject with the passage of time is much more complicated than 2D superimposition. Surface-based registration with the least-squares method was used to superimpose two 3D images. The ICP method was selected for this research since the cranial base is stable in form through growth. The ICP method can superimpose extremely precisely with repeatability because a lot of corresponding points are utilized to compare with point-based registration. The 3D data at T0 and T1 were superimposed at the cranial base utilizing the ICP method. This fusion data can then be cut with an arbitrary plane. The 3D data is converted into MPR images again along the cross-sectional surface so a comparison examination can be performed.

The cranial base is not affected by the influence of the growth change. The ICP method in the cranial base which excludes the peripheral zone is one of the most recommended ways for superimposition. This ICP method can be automatically performed. Furthermore, it is possible to confirm every step, and change it into the manual operation if needed. This new method shows excellent validity.

In our study, there were not significant changes in the mandible during normal growth. Therefore, ICP method was employed using the cranial base. However, it is very difficult to evaluate the mandibular change by using the cranial base ICP method when the mandibular rotation or displacement has occurred during treatment. In this case, other superimposing domains such as the corpus axis (surface on the Xi-Pm line) should be considered.[20,21]

If the ICP method is carried out in the area near to the measurement, it improves the accuracy of the measurement. For example, there are possibilities that the maxilla and mandible are not superimposed precisely if we use the ICP method using the cranial base. An effective way for the measurement of midface is the ICP method utilizing the infraorbital margin part and the nasal bone.[18,19] However, depending on the selection of the superimposing area, there is a possible measurement error and this might cause validity and reproducibility problem. In order to solve these problems, ICP methods are repeated many times which can be a labor intensive and time-consuming process. Pfuger et al[24] reported that sometimes manual registration is more precise than automatic registration. Confirmation by the investigators' observation of the image registration is important for this method. As a result, combining manual and automatic operations is expected to increase the accuracy of this modality in the future. However, in case the time interval between two images is extended or the growth change is outstanding the procedure of ICP has to be performed more carefully.

Because of the development of 3D imaging technology, the field of orthodontics is moving from traditional 2D images to new 3D imaging techniques. Future studies will include the validity of other superimposing domains or the possibility to utilize 3D superimposition for various analyses on the MPR images. The present study was more focused on evaluating the reproducibility of 3-dimensional superimposition for MPR image analysis.

CONCLUSIONS

1. CBCT images can show precise changes in internal structures, including tooth roots and external structures like soft tissues.
2. The ICP method in the cranial base (excluding the peripheral zone) is one of the most reliable ways for superimposition when the mandibular rotation or displacement has not occurred during growth or treatment.
3. The technique used in this study provides a valid and reproducible 3D assessment of growing patients. The MPR image analysis derived from new 3D superimposition method will allow a more comprehensive description of treatment or growth outcomes.

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