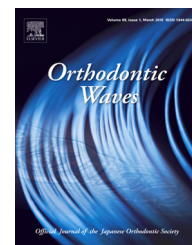


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## Original article

# Qualitative and quantitative evaluation of central incisor movement by integration of three-dimensional images of dental cast and cephalogram

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## ABSTRACT

**Purpose:** The present study aimed to establish a method for qualitatively and quantitatively determining tooth movement by integrating three-dimensional (3D) model analysis and cephalometric analysis.

**Materials and methods:** Superimposition of 3D images of dental casts before and after orthodontic treatment was performed in two steps. First, initial and final 3D images of dental casts were superimposed at the central incisor and then the reference axis of the incisor was constructed. Second, another superimposition was carried out at the medial points of the third palatal rugae and the palatal vault. The changes in the inclination of the central incisor were measured using an established method of 3D model analysis and cephalometric analysis. The error of measurement in 3D model analysis was compared with that in cephalometric analysis. **Results:** There was no significant difference in the degree of incisor tipping between times (Time 1 and Time 2) for cephalometric analysis and 3D model analysis, and between the averaged (Time 1 and Time 2) measurements from cephalogram and the 3D model. The error of measurement for 3D model analysis was 0.58°, and the 95% confidence interval (CI) was [−0.62, 0.62]. Corresponding values for cephalometric analysis were 2.02° and [−1.49, 2.73], respectively. **Conclusion:** The 3D model superimposition method established in the present study was found to be reliable enough to determine the degree of tipping and the location of the center of rotation of the incisor before and after orthodontic treatment.

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## 1. Introduction

Proper evaluation of the outcome of orthodontic treatment is important for further improvement of therapeutic efficiency

in treatment mechanics. Cephalometric superimposition has been widely used to assess orthodontic tooth movement. However, conventional two-dimensional (2D) cephalometric measurements have several shortcomings, including the difficulty of identifying landmarks due to overlapping

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anatomical structures and the consequent low contrast, and enlargement and distortion due to divergent X-ray beams [1,2]. Moreover, rotation of the patient's head when taking serial cephalograms induces errors of projection [2,3]. For these reasons, the reproducibility of cephalometric measurements is considered to be low [4]. Another disadvantage is that the patient is exposed to radiation.

As an alternative method to cephalometric analysis, three-dimensional (3D) analysis of orthodontic tooth movement using serial dental casts has been performed since the 3D surface scanning system was developed [5-7]. Although many studies have been conducted in order to establish a method for qualitatively and quantitatively evaluating tooth movement based on 3D images of serial dental casts [8,9], most measurements were limited to only determination of 3D displacement of an arbitrary point on the crown and/or amount of tipping and rotation [10,11], which is insufficient for understanding the movement pattern of each tooth. Hayashi et al. [12,13] successfully established a sophisticated method for analyzing 3D tooth movement that is presented as rotation about and translation along the finite helical axis. However, the complexity of descriptions makes it somewhat difficult for clinicians to intuitively understand the tooth movement patterns in the course of treatment.

A lack of positional information about root apices of teeth in dental cast analysis can be a major obstacle preventing the accurate analysis of tooth movement. Such information can be complemented by the integration and registration of the images of dental casts and cephalograms. Therefore, the present study was conducted with the following aims: (1) to establish a method for qualitatively and quantitatively

determining tooth movement by integrating 3D images of dental casts and cephalograms; and (2) to compare the errors of measurements in cephalometric analysis with those in 3D model analysis.

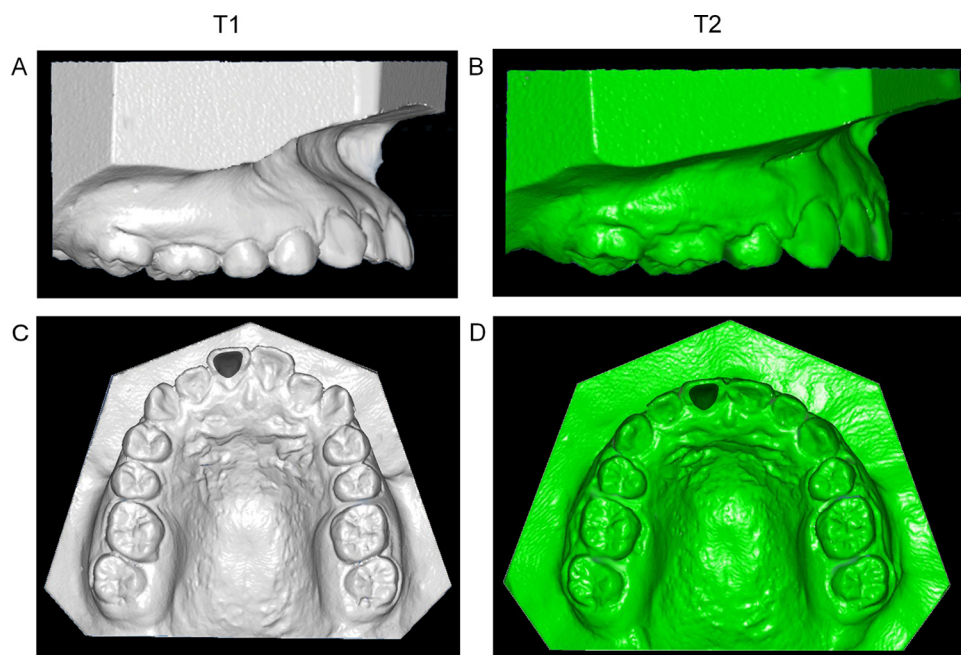
## 2. Materials and methods

### 2.1. Sample

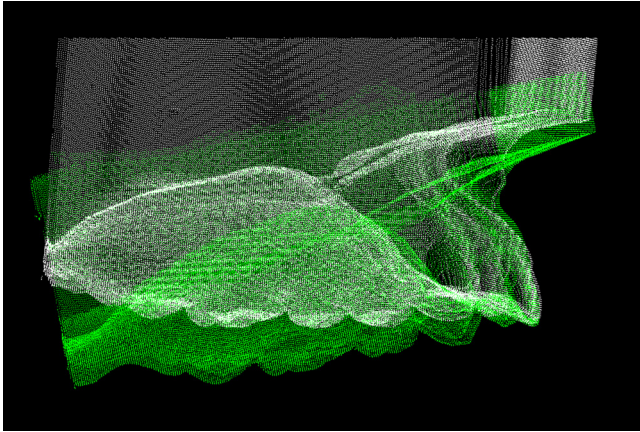
The initial (T1) and final (T2) lateral cephalograms and dental casts obtained from 10 patients (4 males and 6 females) who were undergoing orthodontic treatment after a diagnosis of maxillary protrusion and extraction of bilateral maxillary first premolars at the Department of Orthodontics, Nagasaki University Hospital. The patients' ages ranged from 17 years 3 months to 24 years 9 months (mean age: 22 years 6 months).

### 2.2. Measurements using cephalometric and 3D model analyses

The changes in the inclination of the central incisor were measured using the lateral cephalograms and dental casts before and after orthodontic treatment. For the radiograph, the conventional cephalometric superimposition method was employed. That is, initial and final lateral cephalograms were superimposed on SN plane at S, and the change of U1 to SN angle was measured. For the model analysis, impressions for maxillary dental casts were taken using alginate impression material (Aroma Fine Plus, GC Corp., Tokyo, Japan), and



**Fig. 1** – Reconstructed 3D laser-scanned images of dental casts. Lateral view before (A) and after treatment (B). Occlusal view before (C) and after treatment (D). The reference area for first superimposition is blackened on the lingual surface of the central incisor.



**Fig. 2 – Lateral view of the first superimposition of 3D images of the initial and final dental casts registered on the central incisor.**

then dental casts were made with extra hard dental die stone (New Fujirock, GC Corp., Tokyo, Japan). 3D dental cast superimposition method was utilized to evaluate the degree of the incisor tipping.

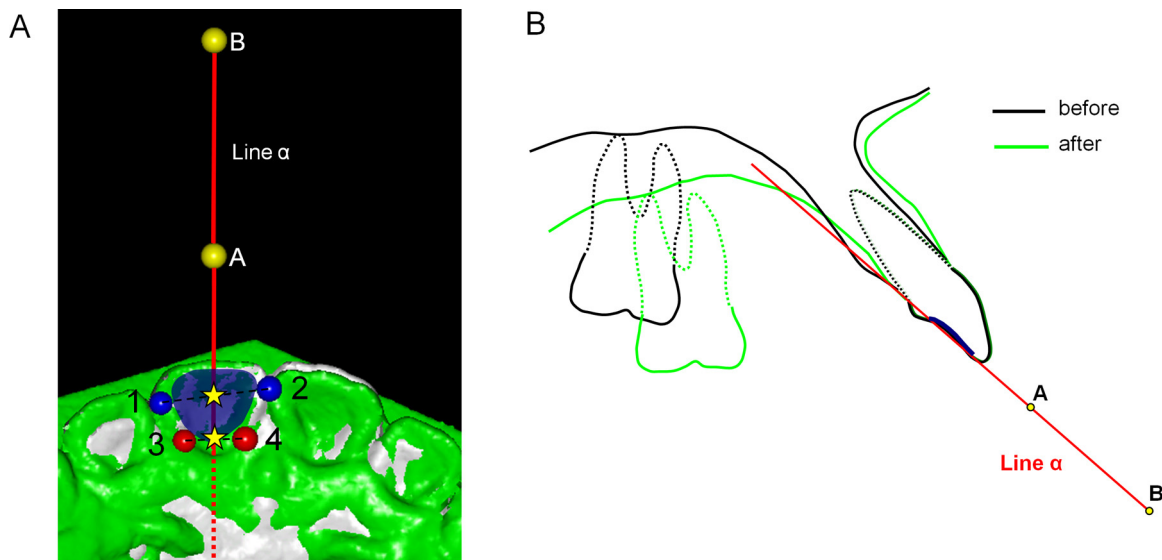
Dental casts were scanned using a laser surface scanning system (VMD-25, UNISN, Osaka, Japan) that measured pitch in the x and y directions to within 0.25 mm and with a range of resolution in the Z direction of  $\pm 0.05$  mm. Based on scanned data, reconstruction and analysis of 3D images were performed using commercial software (Imageware 9, UGS

PLM Solutions, Plano, TX, USA). Reconstructed 3D laser-scanned images of dental casts before and after orthodontic treatment are shown in Fig. 1.

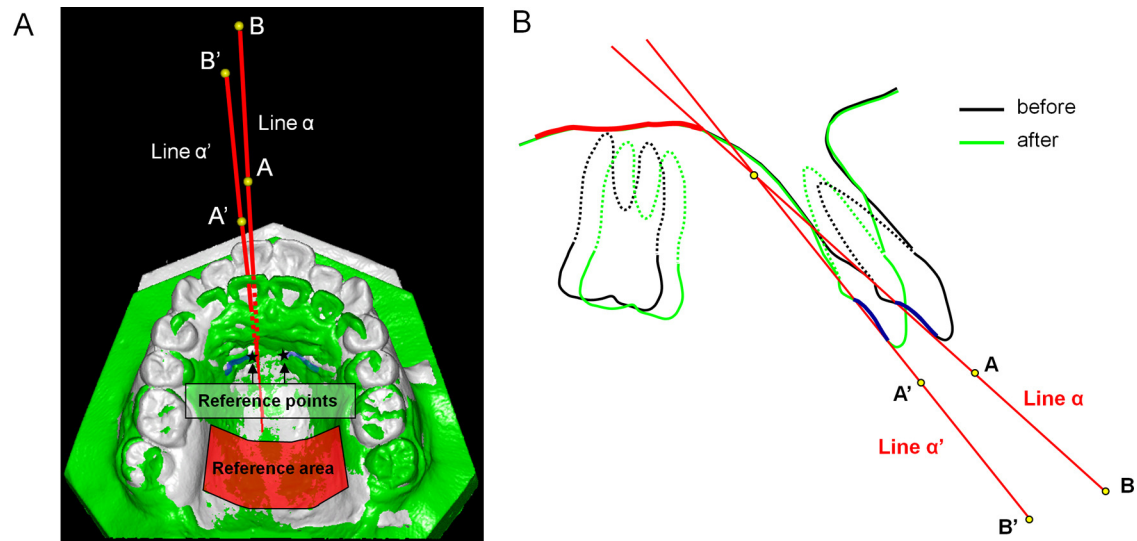
### 2.3. Procedure of superimposition of 3D images of dental casts

The superimposition of initial and final dental cast images was performed twice using different reference areas. In the first step, the 3D images of the dental casts before and after orthodontic treatment were superimposed on the right maxillary central incisor (Fig. 2). At this time, the concave area of the lingual surface of the incisor was used as a reference area for superimposition (Fig. 3A). 3D surface-to-surface matching (best-fitting technique) between initial and final dental cast images was performed based on the least-squares method using a function of Imageware 9.

After the first superimposition, four landmarks were established on the maxillary right central incisor. The landmarks were arbitrarily marked on the incisal and gingival sides of the marginal ridge on both the mesial and distal sides of the incisor, respectively (Fig. 3A). The midpoints between the two points were determined on both the incisal and gingival sides. Then, a line was drawn that connected the two determined midpoints and extended beyond the incisal edge to the incisal side. Two spherical objects were constructed at arbitrary points A and B at a certain distance on the extension of the created line, which was referred to as a reference axis representing the position and inclination of the incisor. The image data of the reference line including the two points were integrated or grouped into each image of dental casts before and after treatment. In this manner, the first superimposition



**Fig. 3 – First superimposition registered on the central incisor and construction of a reference axis. (A) Occlusal view. The area marked in gray on the lingual surface represents a reference area for superimposition. Four landmarks created on incisal (1, 2) and gingival sides (3, 4) on mesial and distal sides of the marginal ridge. A reference axis was created by connecting the midpoint of two points (1, 2) and another (3, 4). Two spherical objects were constructed at arbitrary points A and B at a certain distance on the extension of the reference axis. (B) Schematic representation of lateral view of the first superimposition projected onto the sagittal plane combined with a reference axis (Line  $\alpha$ ).**



**Fig. 4 – Second superimposition registered on the medial points of the third palatal rugae and the palatal vault as reference landmarks and area according to the method established by Jang et al. [14]. (A) Occlusal view. (B) Schematic representation of lateral view of the second superimposition projected onto the sagittal plane. Lines  $\alpha$  and  $\alpha'$  represent reference axes before and after treatment.**

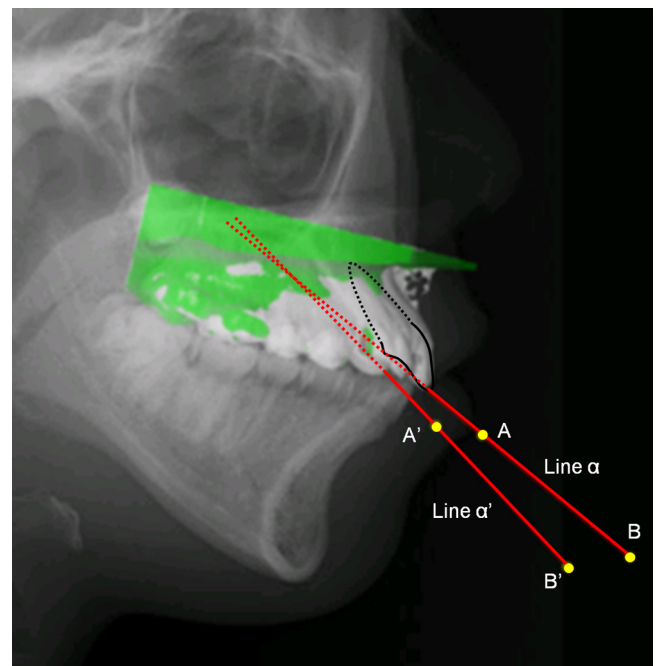
was performed to construct two points on a reference axis whose relative position to the incisor is kept at the same configuration between the initial and final 3D images of dental casts. In later steps, the reference axis is used to analyze the incisor tooth movement. Fig. 3B shows the lateral view of a superimposed image of the initial and final dental casts registered on the maxillary central incisor.

In the second step, another superimposition was performed. Each 3D image of a dental cast combined with the image of the reference axis before and after treatment was superimposed on the medial points of the third palatal rugae and the palatal vault as reference landmarks and area according to the method described in a previous study [14], which was found to be reproducible and reliable, is shown in Fig. 4. To incorporate the positional information of the root apex of the incisor into the 3D image of a dental cast as digital coordinate data, the projected image of the initial dental cast combined with the reference axis onto the sagittal plane was integrated into the image of the initial cephalogram by superimposing the two images on the occlusal plane at the incisal edge of the incisor (Fig. 5). The occlusal plane was defined as a plane which includes the incisal edge of the central incisor and the mesio-buccal cusp tips of the first molars on both sides in the maxillary dentition. The sagittal plane was defined as a vertical plane which passes through midline of the maxillary dentition perpendicularly to the occlusal plane.

The coordinate data of the root apex of the incisor on the initial dental cast image was determined in this way. Furthermore, the coordinate value of the root apex after displacement should be calculated in case the tooth movement is assessed during the course of treatment without taking an additional cephalogram.

#### 2.4. Numerical expression for tooth displacement

Equations for linear transformation between two vectors are composed of rotational and translational components. In two dimensions, trigonometric functions containing the angle of  $\theta$  formed by the two vectors are expressed by the



**Fig. 5 – Lateral view of 3D image of dental cast integrated with cephalogram.**



inner product and the outer product between the vectors  $p$  and  $q$  as follows:

$$\vec{p} = \vec{AB} = (c - a, d - b), \quad \vec{q} = \vec{A'B'} = (g - e, h - f)$$

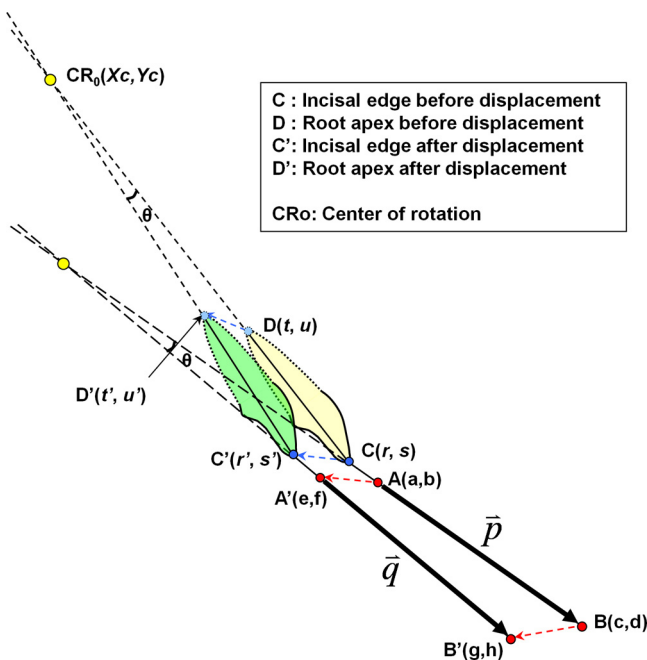
$$\cos \theta = \frac{(c - a)(g - e) + (d - b)(h - f)}{|\vec{p}||\vec{q}|}, \quad \sin \theta = \frac{(c - a)(h - f) - (d - b)(g - e)}{|\vec{p}||\vec{q}|}$$

When the vector  $\vec{AB}$  is displaced to  $\vec{A'B'}$ , the coordinate system is to be rotated around the point A by an angle  $\theta$  using the obtained rotation matrix, and then translated along the vector  $\vec{AA'}$  (Fig. 6). Consequently, displacement of an arbitrary point in this system can be expressed by the following equations as transformation of the coordinate value from  $(x_0, y_0)$  to  $(x, y)$ .

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x_0 - a \\ y_0 - b \end{pmatrix} + \begin{pmatrix} a \\ b \end{pmatrix} + \vec{AA'} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x_0 - a \\ y_0 - b \end{pmatrix} + \begin{pmatrix} e \\ f \end{pmatrix}$$

$$\therefore \vec{AA'} = (e - a, f - b)$$

From the obtained equations for transformation, the coordinate values of the incisal edge ( $r', s'$ ) and root apex ( $t', u'$ ) after displacement are calculated from those of the incisal edge ( $r, s$ ) and root apex ( $t, u$ ) before displacement, respectively. The coordinate value of the CRo ( $Xc, Yc$ ), which is



**Fig. 6 – Numerical expression for degree of tooth tipping and the location of CRo of the central incisor before and after treatment.**

defined as the intersection of two lines coincident with the extensions of the tooth axis before and after displacement [15],

thereby represents the type of tooth movement, is calculated using the following equations:

$$Xc = \frac{(s' - s)(t - r)(t' - r') + r(u - s)(t' - r') - r'(u' - s')(t - r)}{(u - s)(t' - r') - (u' - s')(t - r)}$$

$$Yc = \frac{(r' - r)(u - s)(u' - s') + s(t - r)(u' - s') - s'(t' - r')(u - s)}{(t - r)(u' - s') - (t' - r')(u - s)}$$

Thus, it is possible to visualize the movement of the maxillary central incisor projected onto the sagittal plane

including information of the location of the root apex before and after treatment.

### 2.5. Statistical analysis

In the first step, a paired t-test and correlation analysis were performed to verify whether the two measurements obtained from cephalograms and 3D images of dental casts were significantly different, and whether there were systematic errors in the two measuring methods. The null hypothesis was that the difference between the measurements was zero.  $P < 0.05$  was considered statistically significant.

In the second step, the Dahlberg formula was used to evaluate the error of measurement in the two measuring methods. The Dahlberg formula is defined as  $EM = \sqrt{\sum d^2 / 2n}$ , where  $d$  is the difference between first and second measurements,  $n$  is the number of sample [16,17]. All measurements were performed by one examiner and repeated twice with an interval of two weeks. All statistical analyses were performed using SPSS software (version 16.0, IBM SPSS, Chicago, IL, USA).

### 3. Results

Table 1 shows the changes in the degree of inclination of the central incisor before and after treatment, which were measured on the cephalograms and the 3D images of dental cast. Descriptive statistics are shown in Tables 2 and 3. Analysis using a paired t-test showed no significant difference in the degree of incisor tipping between times (Time 1 and Time 2) for cephalometric analysis and 3D model analysis, and between the averaged (Time 1 and Time 2) measurements from cephalograms and those from 3D models (Table 2).

**Table 1 – Degree of incisor tipping (°) measured from cephalogram and 3D model.**

Case No.	Cephalogram		3D model	
	Time 1	Time 2	Time 1	Time 2
1	-11.9	-10.2	-7.8	-8.5
2	-25.5	-27.7	-21.9	-20.5
3	-15.4	-17.8	-18.3	-19.7
4	-11.2	-7.3	-14.4	-15.4
5	-15.8	-21.0	-14.2	-14.1
6	-6.3	-2.4	-5.3	-4.5
7	-3.0	-4.3	-2.0	-2.3
8	-5.0	-6.5	-9.5	-8.9
9	-24.3	-26.9	-23.5	-23.4
10	3.5	3.0	2.4	2.8

+, labial crown tipping; -, lingual crown tipping.

Pearson’s correlation coefficients between times for cephalograms and 3D models, and between the averaged measurements from cephalograms and from 3D models were all substantially high (0.966, 0.984, 0.936, respectively) as shown in Table 2.

Table 3 shows error of measurement for the two measuring methods obtained from Dahlberg formula. The value indicating error of measurement for 3D model analysis was 0.58°, and 95% confidence interval (CI) was [-0.62, 0.62]. The corresponding values for cephalometric analysis were 2.02° and [-1.49, 2.73] (95% CI).

#### 4. Discussion

Cephalometric and model analyses have both been essential tools for evaluation of orthodontic treatment progress as well as diagnosis and treatment planning. Although cephalometric superimposition has been widely used to assess the changes in dental and skeletal components in the course of treatment, this method is limited to 2D evaluation and includes some disadvantages due to the fact that the radiograph is a 2D projection of a 3D object.

Recent developments in imaging modalities have allowed measurements of dental cast profiles in 3D [5-7]. A superimposition of serial digital models provides 3D information regarding changes in tooth position, including changes in

bucco-lingual inclination of the posterior teeth or mesio-distal rotation of each tooth, which cannot be evaluated using cephalometric superimposition [14]. Other advantages are that an impression for a dental cast can be taken at frequent intervals and evaluation of the treatment progress can be made without unnecessarily exposing the patient to radiation.

One significant shortcoming in the model analysis is that the points of root apices of teeth cannot be identified. Two different kinds of images could provide complementary information as a solution for this problem. In other words, positional information can be obtained by mapping the root apex of the central incisor onto the 3D digital model by integration of images of cephalogram and dental cast taken from the initial records.

A further advantage of the 3D model superimposition method established in this study is that the movement of the incisor is expressed by displacement of a line segment, which is referred as a reference axis, constructed on the target tooth. In cephalometric analysis, identification of the point of incisal edge of the central incisor on the initial and final radiographs is quite difficult particularly in case of winged or rotated incisors, which could cause random errors in the measurements. Since the reference axis was constructed so that its relative position and direction to the outer surface of the incisor was kept at the same configuration on the initial and final digital models, errors of identification could be eliminated. This procedure may contribute to a higher reproducibility of measurements and a reduction of errors of measurement.

In the present study, the concave area of the lingual surface of the incisor was used as a reference area for superimposition. When the treatment outcome is evaluated during the course of treatment, this procedure would be widely applicable in case the brackets are placed on the labial surfaces of teeth and thereby impossible to take a precise impression of the labial side. In case of lingual appliances, it would be preferable to employ the labial surface as the reference area.

There was no significant difference between Time 1 and Time 2 measurements both for cephalometric analysis and 3D model analysis, and correlation coefficients between times for the two methods were very high (Table 2). These findings indicate that both measurements performed by these two different methods were properly reproduced. The measurements of the central incisor tipping obtained from the cephalometric analysis were not statistically different

**Table 2 – Descriptive statistics for measured values from cephalogram and 3D model using paired t-tests and correlation analysis.**

	Cephalogram			3D model			Cephalogram vs. 3D model Times averaged difference
	Time 1	Time 2	Difference	Time 1	Time 2	Difference	
Mean	-11.49	-12.11	0.62	-11.45	-11.45	0.00	0.35
SD	9.19	10.62	2.95	8.52	8.60	0.86	3.52
t			0.67			0.00	0.31
p			0.52			1.00	0.76
r		0.966			0.984		0.936

SD, indicates standard deviation.

**Table 3 – Comparison of errors of measurement between two methods.**

	Error of measurement (°)	95% CI	
		Lower	Upper
Cephalogram	2.02	–1.49	2.73
3D model	0.58	–0.62	0.62

CI indicates confidence interval.

from those measured by the 3D model analysis. Moreover, there was high correlation between the averaged measurements from cephalometric analysis and those from the 3D model analysis. Thus, the measurements of the tipping of the incisor obtained from the 3D models were considered to be the same as those from cephalograms. This suggests that there is no systematic error in either measuring method.

Error of measurement identified using the Dahlberg formula for 3D model analysis was substantially smaller than that for cephalometric analysis (Table 3). Moreover, the width of CI for 3D model analysis was much narrower than that for cephalometric analysis. Therefore, 3D model analysis is considered to provide more precise measurements than cephalometric analysis. Since the previous study [18] investigating the error of measurement of 3D model analysis on angular measurements of teeth showed that the value varied from 0.72° to 1.25°, which was larger than that obtained in the present study, this method is considered to be reliable enough to determine the degree of tipping and the location of the CRo of the incisor before and after orthodontic treatment.

To date, no method has been established for describing tooth movement in a simple way by processing an enormous amount of data obtained from 3D model analysis. The present study showed the method to represent the incisor movement projected onto the sagittal plane by integrating the image of cephalogram with that of 3D model, and to calculate the degree of tipping and the location of the CRo. A method to express posterior teeth movement will be required to evaluate its effect of anchorage under various loading conditions during space closure for future study.

### Conflict of interest

None of the authors have conflict of interests to declare.

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