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Analysis of tooth movement in extraction cases using three-dimensional reverse engineering technology

Bong Kuen Cha*, Jae Yong Lee*, Paul-Georg Jost-Brinkmann** and Noriaki Yoshida***

*Department of Orthodontics, College of Dentistry, Kangnung National University, Gangneung, South Korea, **Department of Orthodontics and Dentofacial Orthopedics, Centre for Dental and Craniofacial Sciences, Charité—Universitätsmedizin Berlin, Germany and ***Department of Orthodontics, College of Dentistry, Nagasaki National University, Japan

SUMMARY Despite inherent errors, cephalometric superimpositions are currently the most widely used means for assessing sagittal and vertical tooth movements. The purpose of this study was to compare three-dimensional (3D) digital model superimposition with cephalometric superimposition. The material was collected from initial and final maxillary casts and lateral cephalometric radiographs of 30 patients (6 males, 24 females, mean age 17.7 years) who underwent orthodontic treatment with extraction of permanent teeth. Each pair of cephalograms was traced and superimposed according to Ricketts' four-step method.

3D scanning of the maxillary dental casts was performed using INUS dental scanning solution®, which consists of a 3D scanner, an autoscan system, and 3D reverse modelling software. The 3D superimposition was carried out using the surface-to-surface matching (best-fit method) function of the autoscan system. The antero-posterior movement of the maxillary first molar and central incisor was evaluated cephalometrically and on 3D digital models. To determine whether any difference existed between the two measuring techniques, paired *t*-tests and correlation analysis were undertaken.

The results revealed no statistical differences between the mean incisor and molar movements as assessed cephalometrically or by 3D model superimposition. These findings suggest that the 3D digital orthodontic model superimposition technique used in this study is clinically as reliable as cephalometric superimposition for assessing orthodontic tooth movements.

Introduction

The dental cast is the traditional three-dimensional (3D) patient record for measuring linear changes in the dental arch. However, it does not provide important information such as structural and volumetric changes in the palate or 3D measurements of orthodontic tooth movement.

Many studies have reported on the stability of the palatal rugae as reference points for pre- and post-treatment comparisons on stone casts (Peavy and Kendrick, 1967; van der Linden, 1978; Almeida *et al.*, 1995; Hoggan and Sadowsky, 2001). However, views differ regarding the stability of the rugae as a reference for dental cast measurements, and their role as a reference for serial records of growth or treatment change is highly questionable. This is due to problems with measuring procedures, difficulties in establishing reference planes for superimposition of serial data, and inherent errors.

Superimposition of serial cephalograms has thus far been the most widely used method for measuring tooth movements after orthodontic treatment. However, its drawbacks include difficulties in evaluating 3D dental movement and identifying inherent landmarks. Further disadvantages are tracing errors, frequent radiation exposure, and high costs (Ghafari *et al.*, 1998).

Since the introduction of CAD/CAM systems with various 3D scanning techniques, efforts have been directed towards developing modalities such as CEREC® for its clinical application in conservative dentistry (Mormann *et al.*, 1987; Mehl and Hickel, 1999).

Until recently, in orthodontics, stone casts were the only way to accurately document malocclusions. However, digital alternatives have now become available in the form of 3D computerized models (Commer *et al.*, 2000; Cha *et al.*, 2002).

Another example for digital 3D data acquisition in orthodontics is the bending art system (BAS)® (Fischer-Brandies *et al.*, 1997) for automated bending of orthodontic archwires, which is based on an intraoral data-acquisition method. The Invisalign system® is a new treatment modality that utilizes computer-based virtual orthodontic models to create a series of clear removable aesthetic appliances (Sachdeva, 2001).

In the area of orthodontic diagnosis, however, the technique has not been used in many studies other than simple model analysis, digitized data storage, and processing. Several ways of applying 3D reverse engineering technology for model analysis have been explored and it has been suggested that it could be a viable alternative to the conventional cephalometric technique for more accurate and convenient evaluation of orthodontic tooth movement (Cha *et al.*, 2002).

The purpose of the present study was to test the hypothesis that the mean horizontal and vertical movements of the upper molars and incisors assessed by digital model superimpositions closely correspond to those determined cephalometrically in extraction cases.

Materials and methods

Sample

In this retrospective investigation, the pre- (T1) and post- (T2) treatment maxillary study casts and cephalograms of 30 patients (6 males and 24 females) treated orthodontically with four premolar extractions at Kangnung, National University Dental Hospital, were studied. Details of their ages and the treatment periods are shown in Table 1.

Cephalometric analysis

Cephalometric radiographs were taken with a cephalometric X-ray unit with a magnification of 1.1 (ASAHI CX 90 SP-II®, Kyoto, Japan). The pre- and post-treatment cephalograms were traced on conventional translucent acetate paper using a transilluminating light box. All bilateral structures were bisected. The measuring points and reference lines used for evaluating dental changes were modified from those described by Ricketts (1975) and Pancherz (1984; Figures 1 and 2). On the pre-treatment tracing, a co-ordinate system was established with the occlusal plane (OL), a line through the central maxillary incisor tip and the mesio-buccal cusp tip of the first maxillary molar, as the *X*-axis, and the occlusal plane perpendicular (OLP) through sella as the *Y*-axis. The co-ordinate axes were transferred from the pre- to the post-treatment tracing by superimposition along the palatal plane registered at ANS. Positional changes in the maxillary incisor tip and the mesio-buccal cusp tip of the first maxillary molar were evaluated. The net antero-posterior and vertical changes in landmarks were defined as the distances between the pre- and post-treatment landmarks parallel to the OL (*X*-axis) and the OLP (*Y*-axis), respectively (Figure 2). The measurements were made to the nearest 0.5 mm. To test the reliability of the measurements, 10 radiographs were re-traced and re-digitized again after an interval of at least 2 weeks by one author (JYL). The method error was calculated from the repeated measurements using Dahlberg's (1940) formula. The mean tracing error of length was 0.27 mm.

Table 1 Sample description (n = 30).

Gender (n)	
Male	6
Female	24
Initial age (years/months)	
Mean	17/07
Minimum	11/01
Maximum	29/10
Treatment time (months)	
Mean	35.3
Minimum	26
Maximum	51
Interval between records (months)	
Mean	39.6
Minimum	30
Maximum	54

3D scanning

The scanning method used in this study has been described previously (Cha *et al.*, 2002). 3D scanning of the maxillary

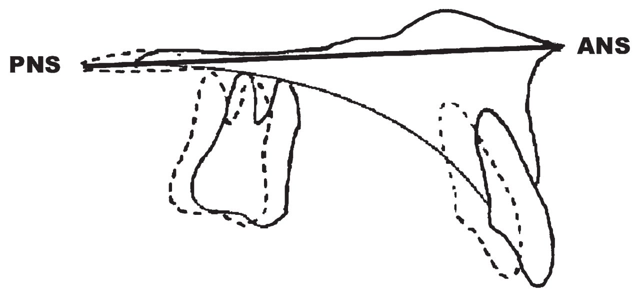

Figure 1 Superimposition of the maxilla along the palatal plane registered at ANS according to Ricketts (1975).

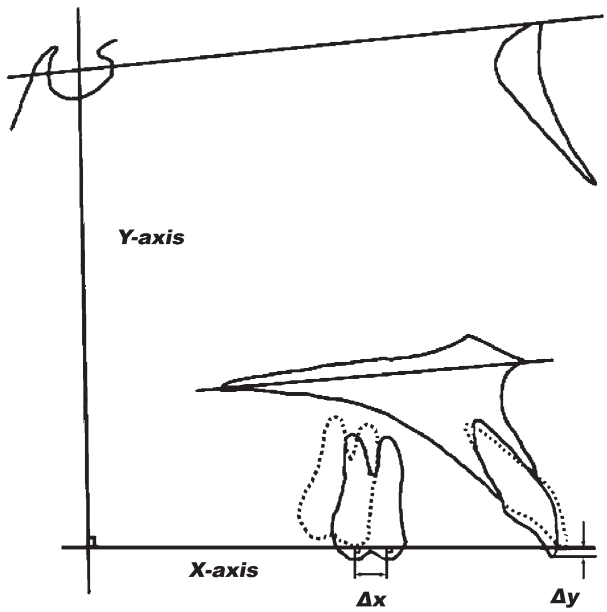

Figure 2 Reference co-ordinate system for cephalometric superimposition on the palatal plane. *X*-axis: a line through the maxillary central incisor tip and the mesio-buccal cusp tip of the first maxillary molar on the initial cephalogram; *Y*-axis: plane perpendicular to *X*-axis through sella; Δ*x*: horizontal movement of the mesio-buccal cusp tip of upper first molar; Δ*y*: vertical movement of the maxillary central incisor tip.

dental casts was performed using INUS dental scanning solution®, which consists of a 3D scanner (topometric and photometric 3D scanner, Breuckmann Inc., Germany, resolution 8 μm, reliability ±15 μm) and a 3D reverse modelling software program (Rapidform 2002®, INUS Technology Inc., Seoul, South Korea).

3D model superimposition and co-ordinate system

To measure orthodontic tooth movement, pre- and post-treatment scans were superimposed on the surface across the palate. This procedure, designated as a 3D surface-to-surface matching (best-fit method), employed a least-mean-squared technique using a function of the Rapidform 2002® (Commer *et al.*, 2000; McDonagh *et al.*, 2001; Cha *et al.*, 2002; Figure 3a). The accuracy of measurement was evaluated by calculating the superimposition discrepancies between pre- and post-treatment 3D models. The results were as follows: mean error 0.0399 mm, standard error 0.0289 mm, and standard deviation 0.1583 mm. Therefore, the surface-to-surface matching (best-fit method) is sufficiently accurate for dental cast analysis.

A change from 0 to 2.1 is represented by a colour progression from blue to red (Figure 3b). A co-ordinate system modified from the proposal of Ashmore *et al.* (2002) was established on the pre-treatment digital model with the junction of the incisive papilla and palatine raphe as the origin (0, 0, 0), resulting in an *X*-, *Y*-, *Z*-axis and three planes (Figure 4).

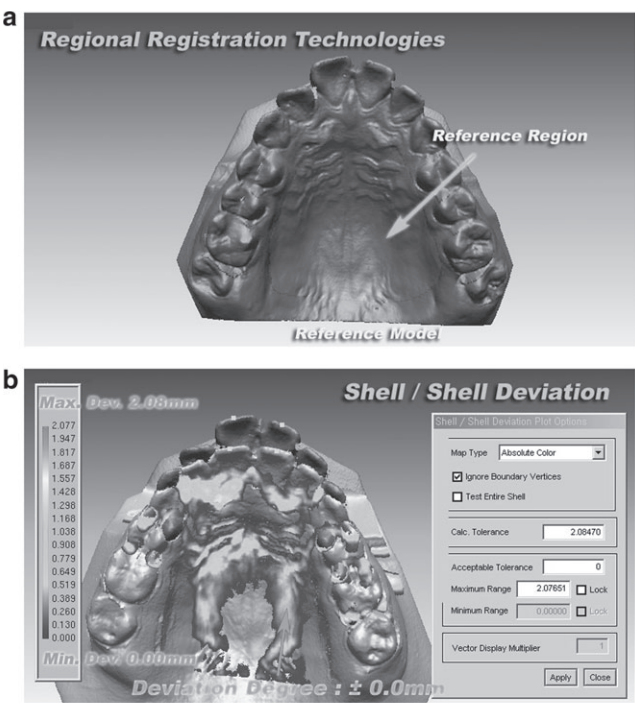

Figure 3 Superimposed model with differences displayed in colours on a millimetre scale. (a) Reference surface for superimposition. (b) The degree of surface matching is described by the colour-coding system.

Measuring and statistics

The measuring points in the co-ordinate system of the superimposed 3D models were the midpoint on the edge of the upper right and left central incisor and the mesio-buccal cusp tip of the right and left upper molar (Figure 5). Measurements of tooth movement along the *X*- and *Y*-axis

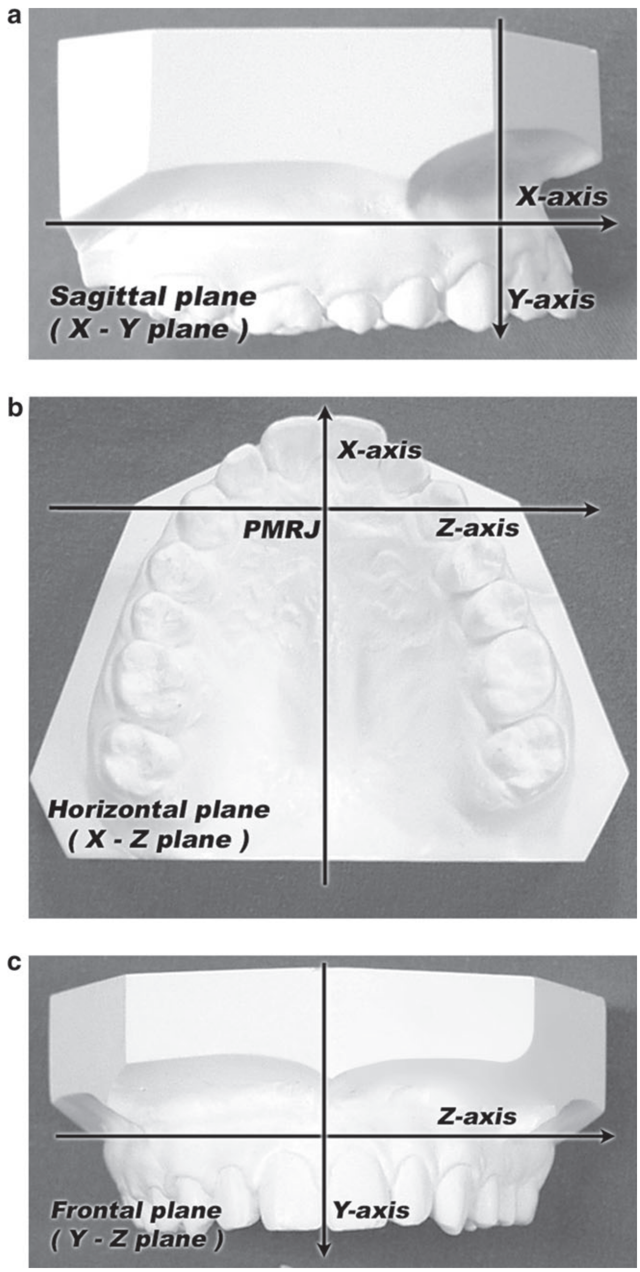

Figure 4 The co-ordinate system. (a) *X-Y* sagittal plane is made up of two arbitrary points on the mid-palatal suture and the junction of the inclusive papilla and palatine raphe (PMRJ). (b) *X-Z* horizontal plane is the section inclusive of PMRJ, perpendicular to the sagittal plane and parallel to the occlusal plane constructed by connecting the buccal cusp tips of the right and left maxillary first and second premolars and mesio-buccal cusp tips of the first molars using the best-fitting process. (c) The *Y-Z* frontal plane is the section inclusive of PMRJ and perpendicular to both the sagittal and the horizontal planes.

in the superimposed digital models of left and right teeth were averaged as in the cephalometric analysis. This study excluded measurements of tooth movements along the *Z*-axis, i.e. movements in the frontal plane. Positive values along the *X*- and *Y*-axis indicated mesial and extrusive tooth movements.

The mean sagittal and vertical molar movements measured on the cephalometric radiographs were compared with that measured on the superimposed 3D models. Similarly, the mean horizontal and vertical incisor movements measured on the cephalometric radiographs were compared with those measured on the superimposed models. Paired *t*-tests and correlation analysis were performed to determine whether a significant difference existed between the two measuring techniques. The null hypothesis assumed a zero difference between the cephalometric variables and the corresponding 3D model variables.

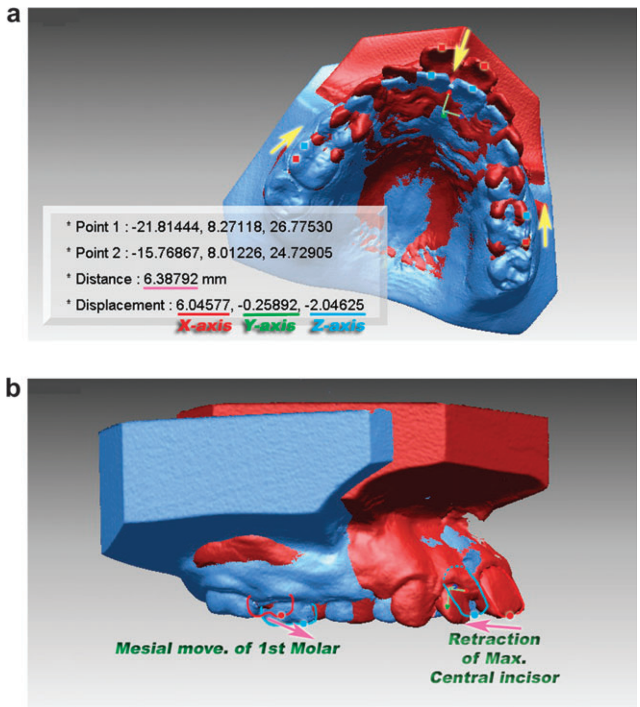

Figure 5 Tooth movement of superimposed three-dimensional models. (a) Palatal view and (b) sagittal view (red: before treatment, blue: after treatment).

Results

The results are shown in Table 2. Descriptive statistics [including mean, standard deviation, and range (Min, Max)] were calculated for the 3D model variables (averages for the right and left sides) and the cephalometric variables that describe upper molar and upper incisor movement. Paired *t*-tests showed no statistical differences ($P > 0.05$) between the vertical and horizontal upper first molar or upper incisor movements assessed by cephalometric and 3D model superimposition.

Pearson correlation coefficients between 3D variables and cephalometric variables are also shown in Table 2. Correlation analysis revealed that the *r* value was highest at 0.994 for upper molar horizontal movement and lowest at 0.932 for upper molar vertical movement. Figures 6a–d show the regression lines for tooth movements as determined cephalometrically and by 3D model superimposition. Adequate correlations were obtained for all tooth movements. This means that the molar and incisor movements were the same, whether measured from the 3D digital model or by cephalometric superimposition.

Discussion

Orthodontic study models have played an important role as an essential component of 3D diagnostic records. However, model analysis is performed manually with a number of limitations in terms of accuracy and measuring ability. In other words, analysis of a 3D object by simple linear measurements not only fails to consider diagnostic

Table 2 Paired *t*-tests comparing (a) central incisor and (b) first molar movement measured from cephalograms and three-dimensional digital models.

Variable	Mean (mm)*	SD (mm)*	Max (mm)*	Min (mm)*	*r*	*t*	*P*
(a) Central incisor							
U1 CEPH—Horizontal	−2.7	2.1	1.0	−7.0	0.993	0.58	0.56
U1 3D—Horizontal	−2.7	2.1	0.9	−7.0			
U1 CEPH—Vertical	1.0	1.6	4.0	−3.5	0.990	1.51	0.14
U1 3D—Vertical	0.9	1.5	3.8	−3.3			
(b) First molar							
U6 CEPH—Horizontal	3.6	1.6	7.0	0.5	0.994	1.59	0.12
U6 3D—Horizontal	3.5	1.6	6.7	0.3			
U6 CEPH—Vertical	−0.1	1.3	4.5	−2.0	0.932	1.14	0.26
U6 3D—Vertical	−0.2	1.3	3.7	−2.4			

SD, standard deviation.
*Negative horizontal measurement = distal movement, Negative vertical measurement = intrusion.

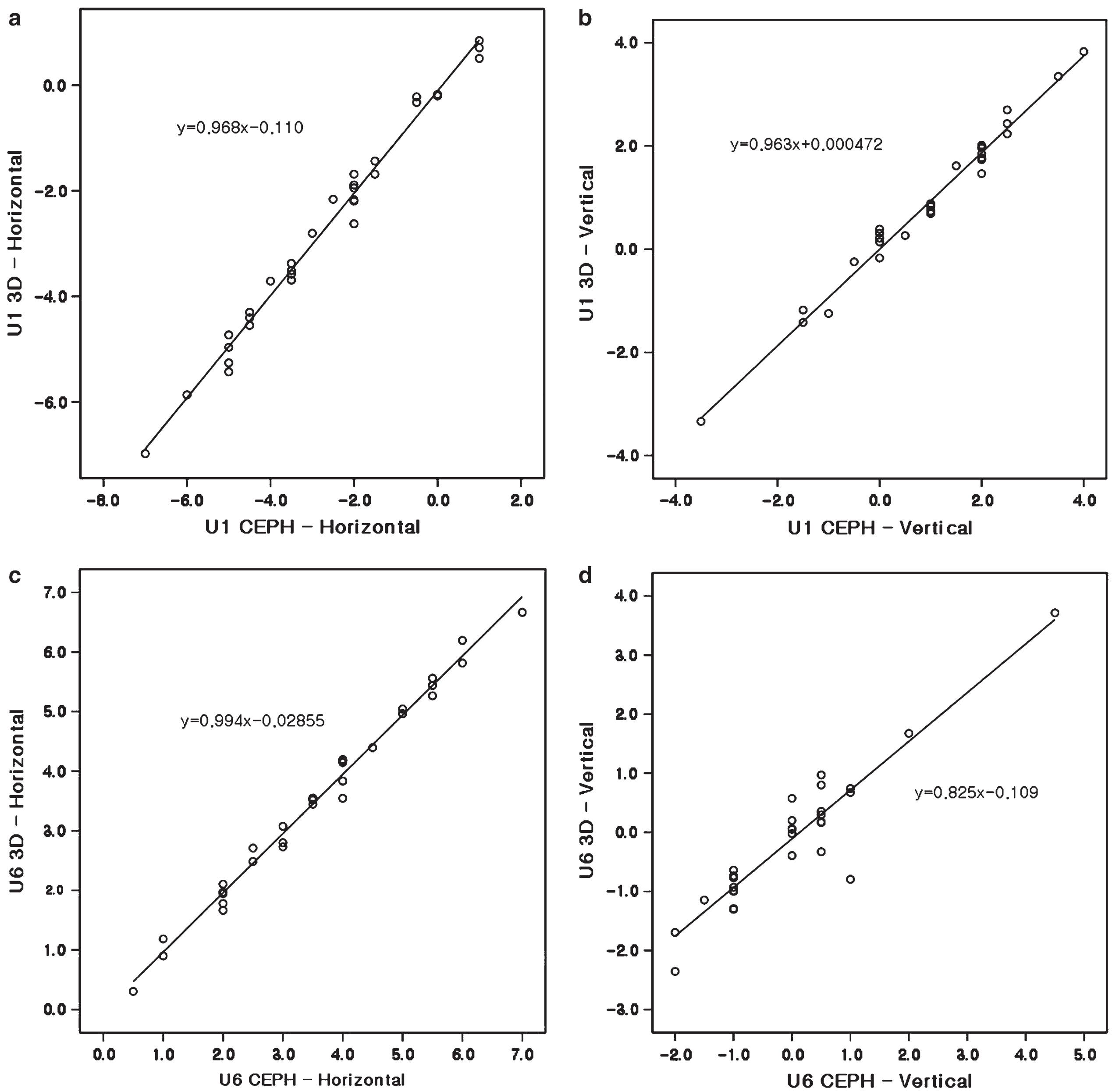

Figure 6 (a–d) Scattergrams and regression lines for the central incisor and first molar movements measured on the cephalograms and three-dimensional digital models.

information such as surface morphology and volumetric palatal changes but also requires considerable time and energy. Efforts have been made to overcome these problems. In particular, photography (Schirmer and Wiltshire, 1997), holographic technology (Ryden *et al.*, 1982), and a precise 3D co-ordinate measuring technique (Almeida *et al.*, 1995) were introduced to improve conventional model analysis. More recently, laser scanning was introduced to digitize the dental arch (Motohashi and Kuroda, 1999; Hayashi *et al.*, 2002, 2004). However, these methods were applied only for research because of the slow rate of raw data acquisition and operational difficulties.

In this study, a maxillary model was reconstructed using a 3D scanner. There are basically two types of optical 3D scanners: the white-light pattern projection type and the laser type (point, stripe). The white-light pattern projection type scanner is a system for scanning objects of varying size. Using fringe projection techniques, white-light pattern type scanners produce very dense, accurate point cloud data which permit rapid surface and tool path generation. On the other hand, laser-type scanners using white light detects diverse linear patterns projected on an object with a CCD camera and then creates 3D image through triangulation and image processing.

In this study, a stripe pattern projection type 3D scanner was used since it is less affected by light interferences on white stone models, data acquisition can be carried out in a relatively short time, and measurement can be performed at a resolution as high as 8 μm, depending on the degree of calibration, which is well beyond what is normally required for measuring the mesio-distal diameter of a tooth or the arch width or length in model analysis. It took approximately 10 minutes to complete the scanning of a maxillary model. The scanning speed increases when the resolution is reduced and is expected to improve even more by further advancements of hardware.

Several investigators have studied the potential use of the palatal rugae for superimposition of serial models (Peavy and Kendrick, 1967; van der Linden, 1978; Ashmore *et al.*, 2002). Palatal rugae form their pattern within 12–14 weeks of intrauterine life and have been assumed to remain stable throughout life. They have thus served as reference points when studying serial casts (Lebret, 1962).

Friel (1949) demonstrated a growth-dependent forward movement of the dentition in relation to the rugae. Peavy and Kendrick (1967) used a symmetrograph to study 15 subjects in whom the first premolars were extracted and concluded that the lateral end of the rugae close to the teeth tended to follow the teeth in the sagittal plane and thus could not be used as a reference point. They recommended the so-called O point on the midsagittal plane for reference on the assumption that this part of the palate is least affected by growth. Investigations by Almeida *et al.* (1995), using the reflex metrograph, suggest that the transverse offsets and distances between medial rugae points are generally stable, particularly for the first rugae. They, therefore, recommend this area as a reference point for the superimposition of serial models. As a reference plane, however, they used only the median palatal raphe on the assumption that it is a stable area. This limits the interpretation of the results, especially for sagittal changes of the rugae. In a study measuring antero-posterior molar movement, Hoggan and Sadowsky (2001) reported that the median end of the third palatal rugae landmark can be used as reliably as cephalometric superimposition. Ashmore *et al.* (2002) employed a mechanical 3D digitizer for a 3D analysis of molar movement during headgear treatment. They used their own specific co-ordinate system but again superimposed models on the palatal rugae.

The above-mentioned results indicate that the evaluation of tooth movement using the palatal rugae has many clinical limitations because of the difficulty in establishing reference points and the complicated measuring process (Cha *et al.*, 2002). In addition, 3D changes of the rugae have not been considered in most previous studies. Errors may also derive from two-dimensional measurements of the 3D curvature of the palatal vault. Moreover, there seems to be no consensus as to the stability of the palatal rugae in conjunction with growth or treatment. Future research should evaluate the 3D positional stability of palatal rugae using another stable reference plane. The microscrew used to reinforce anchorage may serve as an alternative reference landmark, but only in limited cases (Cha *et al.*, 2002).

3D surface scanning systems have been suggested for assessing morphological changes in maxillo-facial surgery or dentofacial orthopaedics (Arridge *et al.*, 1985; Moss *et al.*, 1987, 1988, 1994, 1995; Ayoub *et al.*, 1998; Schwenzer *et al.*, 1998; Nute and Moss, 2000; McDonagh *et al.*, 2001; Ismail *et al.*, 2002). In the present study, the possibility of clinically assessing tooth movements with a 3D registration method, which is mainly used in the field of engineering, was evaluated. Registration refers to a process of merging scanned images from many different angles to create a single 3D image (Rekoff, 1985). The software used in this study automatically extracted shape information from overlapping images as the position that minimizes the mean distance (Figures 3 and 5). On superimposed models, an area of less than 0.2 mm difference, represented by an antero-posterior spread of blue colour, was the constant section of the midsagittal contour. This confirms the findings of Korkhaus (1959), whose line of superimposition was the midsagittal curvature from a few millimeters behind the incisive foramen to the palatal region near the first molar.

The mean horizontal and vertical incisor and molar movements measured by the 3D scanned superimposed model did not differ statistically from those obtained by cephalometric assessment (Table 2). There was a high correlation between cephalometric and 3D measurements (Table 2). These results suggest that the 3D maxillary superimposition model is clinically applicable and just as reliable as cephalometric superimposition for assessing orthodontic tooth movement in extraction subjects. Further studies may be required for the assessment of subjects treated with expansion mechanics or for the mandible.

With the co-ordinate system used in this study, it is likely that a simple mouse click will enable computer-assisted evaluation not only of the simple mesio-distal or vertical movements observed on cephalograms but also of all 3D movements, including transverse movements or rotation of diverse dental landmarks. 3D models have opened up many new possibilities ranging from novel treatment modalities to treatment evaluation methods that were until recently still at the theoretical stage. The problem of storing orthodontic casts could thus be solved, and the internet-based data transmission system will facilitate an efficient and convenient exchange of orthodontic data and patients' records.

Conclusion

This study assessing tooth movements for the upper molars and incisors in extraction cases was carried out to compare two dimensional cephalometric and 3D digital model superimpositions. The mean incisor and molar movement measurements did not differ statistically between cephalometric and 3D model superimposition. These findings suggest that 3D digital model superimposition is clinically as reliable as cephalometric superimpositions for assessing orthodontic tooth movement.

Address for correspondence

Bong Kuen Cha
Department of Orthodontics
College of Dentistry
Kangnung National University
120 Gangneung Daehangno
Gangneung city
Gangwon province, 210-702
South Korea
E-mail: korth@kangnung.ac.kr

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