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A 3D computer-aided design system applied to diagnosis and treatment planning in orthodontics and orthognathic surgery

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SUMMARY The purpose of this article is to describe a newly developed 3D computer-aided design (CAD) system for the diagnostic set-up of casts in orthodontic diagnosis and treatment planning, and its preliminary clinical applications. The system comprises a measuring unit which obtains 3D information from the dental model using laser scanning, and a personal computer to generate the 3D graphics. When measuring the 3D shape of the model, to minimize blind sectors, the model is scanned from two different directions with the slit-ray laser beam by rotating the mounting angle of the model on the measuring device. For computed simulation of tooth movement, the representative planes, defined by the anatomical reference points, are formed for each individual tooth and are arranged along a guideline descriptive of the individual arch form. Subsequently, the 3D shape is imparted to each of the teeth arranged on the representative plane to form an arrangement of the 3D profile. When necessary, orthognathic surgery can be simulated by moving the mandibular dental arch three-dimensionally to establish the optimum occlusal relationship.

Compared with hand-made set-up models, the computed diagnostic cast has advantages such as high-speed processing and quantitative evaluation on the amount of 3D movement of the individual tooth relative to the craniofacial plane. Trial clinical applications demonstrated that the use of this system facilitated the otherwise complicated and time-consuming mock surgery for treatment planning in orthognathic surgery.

Introduction

The development of a CAD/CAM system using various 3D measuring systems in the manufacturing industry has been followed by the use of a CAD/CAM system of dentistry particularly in the field of prosthodontics using the laser scanning technique (Duret *et al.*, 1988; Mörmann *et al.*, 1989; Maeda *et al.*, 1993). A 3D dental model analysing system using laser scanning has also been developed and its clinical feasibility in the field of orthodontics has been reported (Kuroda *et al.*, 1996). However, the following problems of this system have been demonstrated in its clinical application: (1) difficulty in measuring beneath overhangs, such as the anterior oral vestibule in the dental model with severe labio-lingual tipping of anterior teeth; and (2) the need to develop software to automatically align the individual teeth for the computer simulation of the diagnostic cast.

The purpose of this presentation is to introduce an improved 3D measuring method and newly-developed software for the computer simulation of the diagnostic cast by demonstrating each clinical processing step.

Materials and methods

The system comprises a measuring unit (3D-VMS-250R, UNISN Inc., Osaka, Japan) which obtains 3D information from the dental model using laser scanning, and a personal computer

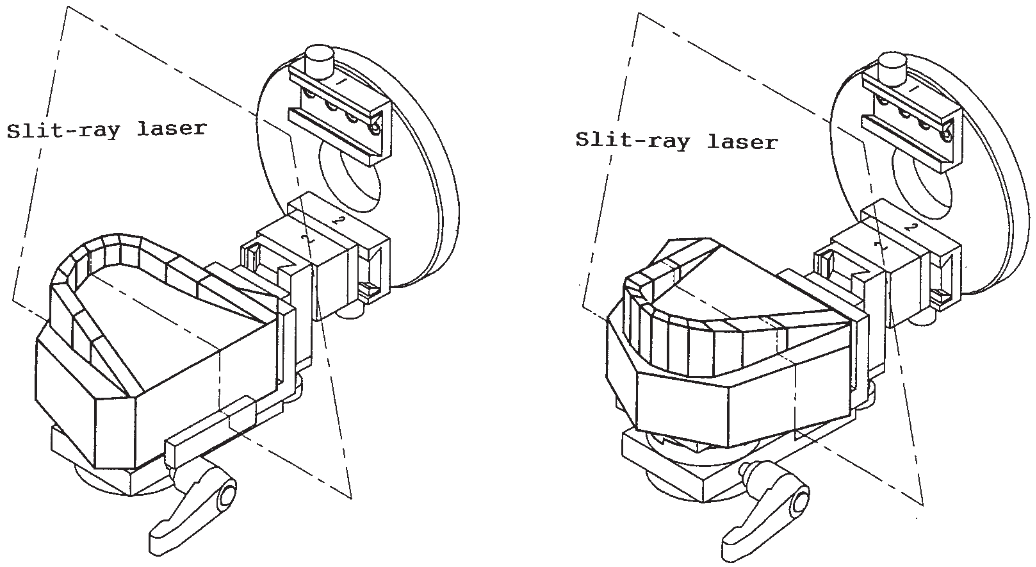

Figure 1 3D measuring using the slit-ray laser beam without a blind area. Left: measurement of anterior region of the dental model. Right: measurement of posterior region of the dental model.

(DEC CEREBRIS, Digital Equipment Corp., Maynard, USA) Windows-NT Workstation (Microsoft Corp., Redmond, USA) which creates 3D graphics of the diagnostic cast using the generated 3D graphic of the dental model. All measuring units are linked to a network.

Data acquisition and generation of 3D graphics

Although the basic algorithms of data acquisition and the generation of 3D graphics are similar to those reported previously (Kuroda *et al.*, 1996), the following improvements in 3D measuring, without a blind area, should be noted.

In this system, to minimize blind sectors, the dental model is scanned from two different directions with the slit-ray laser beam by rotating the mounting angle of the dental model on the measuring device (Figure 1). Two data files, composed of anterior and posterior regions of the dental model, are then merged into one file by amalgamating the 3D co-ordinates. Approximately 400 000 sets of X, Y, Z co-ordinates are stored in the main memory of the controller (PC-9821Ap, OS: Microsoft MS-DOS Ver. 5.0, CPU: Intel486DX2 66MHz, Memory: 3.6MB, NEC Corp., Tokyo, Japan). These 3D dot map data are relayed to the post processor (DEC CEREBRIS Windows-NT) on the network, and more than 800 000 polygon data are automatically constructed to generate a 3D graphic of the dental model by shading the polygon data. Generation of this 3D graphic of the dental model takes approximately 90 minutes using a 0.25-mm laser scanning pitch.

Basic algorithm for computer simulation of diagnostic cast

The software to automatically align the individual teeth is newly developed for the computed simulation of the diagnostic cast with the use of the Application Visualization System Express (Version 3.1), AVS (Advanced Visual Systems Inc., Waltham, USA) as core software.

Figure 2 demonstrates the basic algorithm for computer simulation of the tooth movement using this software. First, the representative plane defined by the anatomical medial contact point A, anatomical distal contact point A′, and the intermediate point E between the bucco-cervical point B and lingo-cervical point B′ are

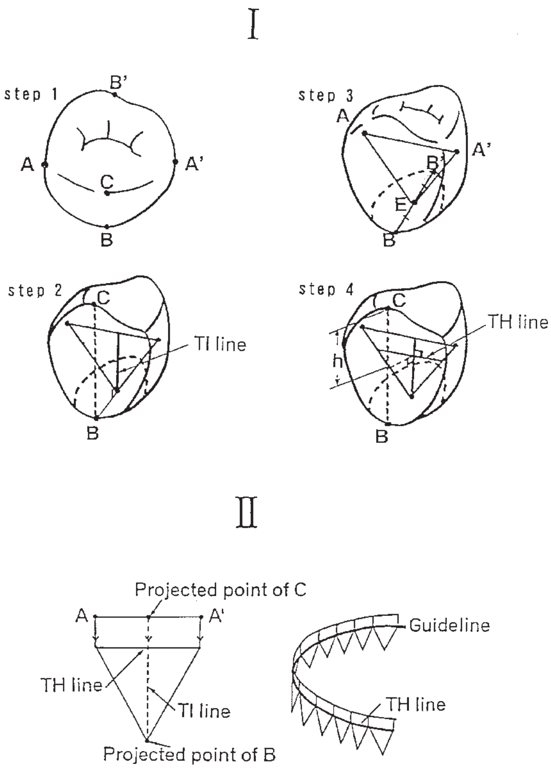

Figure 2 Basic algorithm for computed simulation of tooth movement. (I) Formation of representative plane. (II) Alignment of representative plane along a guideline.

formed for the individual teeth. Secondly, for each tooth, a TI line, which is a straight line connecting the bucco-cervical point B and a representative point C of a cusp or edge that has been projected onto the representative plane, and a TH line intersecting the TI line perpendicularly at a point spaced a predetermined distance (h) from the representative point C towards the dental alveolar ridge are formed. The length of this TH line is determined by the distance between medial and distal contact points (AA′). The TH lines for the respective teeth are then arranged on a plane along a guideline descriptive of an ideal individual dental arch form and the respective heights of the TH lines, for all teeth which have been lined up to a predetermined height, are adjusted to a predetermined level, followed by adjustment of the angle of inclination of the representative plane for each tooth relative to a reference line set up on the face.

Results of clinical application

Measurement reliability

The length of the TH line representing the tooth crown width using software for the computer simulation of the diagnostic cast is determined by computing the distance between the anatomical medial and distal contact points. In order to estimate the measurement accuracy of the CAD system, a graphic image of a dental model taken from a patient with mandibular protrusion was generated using a 0.25-mm laser scanning pitch. The measured values on a graphic model were then compared with those on a dental model measured by a sliding caliper (Point Vernier Caliper 536-121; Vernier reading: 0.05 mm; Accuracy: 0.05 mm, Mitsutoyo Corp.). The widths of each tooth crown were measured five times using the CAD system and the sliding caliper, respectively. Statistical values, including mean and standard deviations, were computed for each measurement obtained on the graphic and dental model, and the difference in each measurement was examined using the Student's *t*-test (Table 1).

There was no significant difference in each measurement at the 1 per cent level, and the absolute value of maximum and minimum difference between the graphic and dental models was 0.2 and 0.0 mm, respectively.

Clinical application

To demonstrate the clinical use of the CAD system, each step in the generation of a diagnostic cast is described using a cleft lip and palate patient with a total crossbite due to severe mandibular protrusion and a narrow upper dental arch. Figures 3 and 4 show oral photographs and computed dental model graphics of this patient. Each step in the procedure is performed on the user interface menu by clicking the corresponding button.

Table 1 Reliability of measurements based on the Student's *t*-test at the significance level of 1 per cent.

	Tooth crown width (mm) measured by CAD system		Tooth crown width (mm) measured with a sliding caliper		Absolute value (mm) of difference		Test of significance	
	Left side	Right side	Left side	Right side	Left side	Right side	Left side	Right side
Upper								
Central incisor	9.0 ± 0.1	8.8 ± 0.0	8.9 ± 0.0	8.8 ± 0.0	0.1	0.0	NS	NS
Lateral incisor	7.0 ± 0.2	7.4 ± 0.2	7.1 ± 0.0	7.3 ± 0.1	0.1	0.1	NS	NS
Canine	7.5 ± 0.1	7.5 ± 0.1	7.4 ± 0.1	7.5 ± 0.1	0.1	0.0	NS	NS
First premolar	8.0 ± 0.2	7.8 ± 0.1	7.8 ± 0.1	7.8 ± 0.0	0.2	0.0	NS	NS
Second premolar	7.5 ± 0.2	7.3 ± 0.1	7.4 ± 0.1	7.2 ± 0.1	0.1	0.1	NS	NS
First molar	10.1 ± 0.1	10.3 ± 0.1	10.1 ± 0.1	10.3 ± 0.1	0.0	0.0	NS	NS
Second molar	10.4 ± 0.1	10.1 ± 0.2	10.5 ± 0.0	10.3 ± 0.0	0.1	0.0	NS	NS
Lower								
Central incisor	5.4 ± 0.1	5.3 ± 0.1	5.3 ± 0.0	5.3 ± 0.0	0.1	0.0	NS	NS
Lateral incisor	6.5 ± 0.2	6.1 ± 0.1	6.5 ± 0.0	6.0 ± 0.0	0.0	0.1	NS	NS
Canine	6.7 ± 0.1	6.6 ± 0.2	6.6 ± 0.1	6.4 ± 0.1	0.1	0.2	NS	NS
First premolar	7.7 ± 0.1	7.9 ± 0.1	7.6 ± 0.0	7.8 ± 0.1	0.1	0.1	NS	NS
Second premolar	7.4 ± 0.1	7.3 ± 0.1	7.3 ± 0.1	7.3 ± 0.1	0.1	0.0	NS	NS
First molar	10.8 ± 0.2	11.1 ± 0.1	10.8 ± 0.0	11.1 ± 0.1	0.0	0.0	NS	NS
Second molar	11.0 ± 0.1	10.7 ± 0.1	11.1 ± 0.0	10.8 ± 0.1	0.1	0.1	NS	NS

NS = not significant.

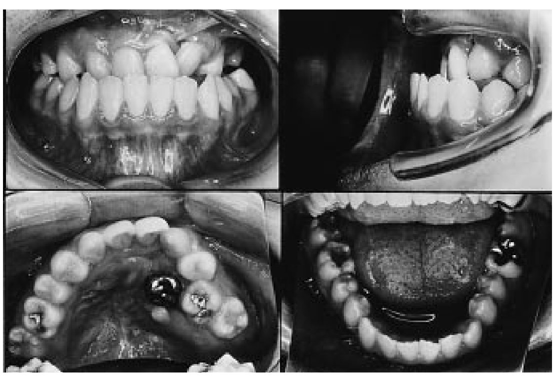

Figure 3 Oral photographs of a cleft lip and palate patient.

Step 1: Formation of representative plane and alveolar plane. Five anatomical reference points for each individual tooth are captured to form the representative plane on the monitor (Figure 5). An alveolar plane representative of contour data of the dental alveolar ridge is then formed by cutting the dental model in the vicinity of the root apex of the anterior and posterior teeth (Figure 6).

Step 2: Outline of the individual tooth. The individual tooth is cut into a hexagonal-sectioned columnar shape with the dental alveolar plane taken as the bottom of the tooth (Figure 7). This columnar shape has its side face containing the anatomical medial and distal contact points, and defining a boundary region of the tooth.

Step 3: Extraction of teeth. Extraction of teeth is carried out on the monitor (Figure 8). In this case, the upper second deciduous molar and second premolar are removed.

Step 4: Adjusting the position of anterior teeth. Central contour lines of the maxillary and mandibular central incisor, including the representative point of the edge, the labio-cervical point, and the lingo-cervical point, are positioned on the centreline connecting the representative point of the edge of the central incisor and the intermediate points of the labio-cervical and the lingo-cervical points, and are displayed together with the Frankfort horizontal plane on the monitor (Figure 9). The respective positions of the central incisors are adjusted by displacement of the central incisors including

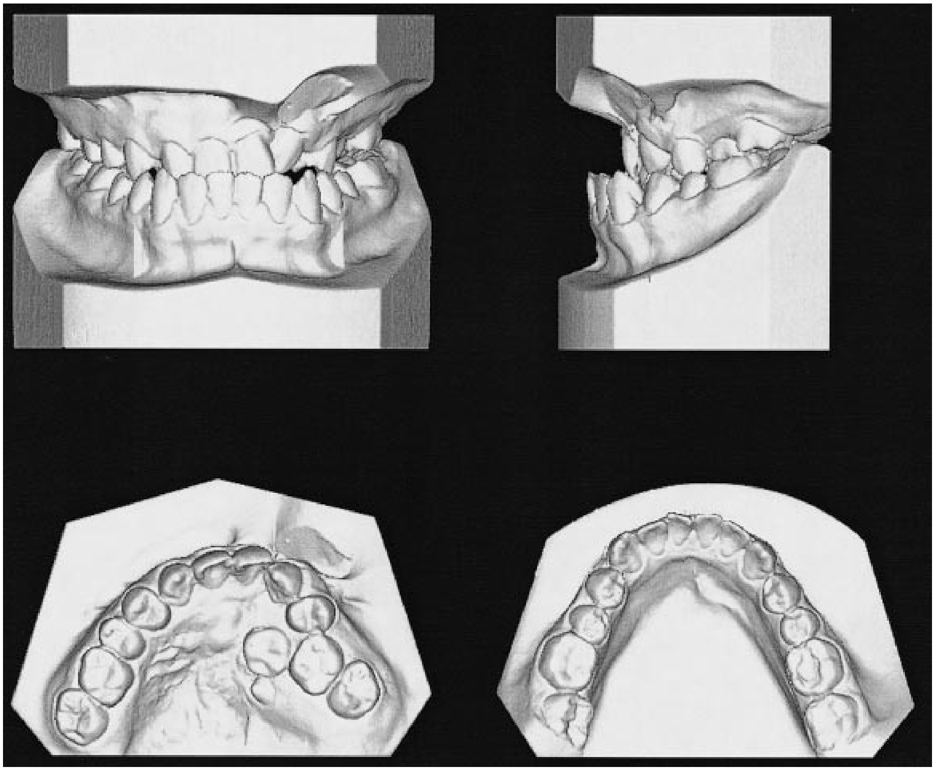

Figure 4 Computed graphic dental model of the patient in Figure 3.

parallel and rotational movements to achieve a normal overjet and overbite. An interference check is then made to avoid any possible overlap between the outer contour lines of the maxillary and mandibular central incisors. In this case, each of the upper and lower anterior teeth were tipped labially 14 and 9 degrees, respectively, from their original positions.

Step 5: Determination of the centreline. The centreline of the dental arch is determined on the dental alveolar plane by using the following algorithm (Figure 10). Temporary centrelines, based on the facial median line or the P–A cephalogram, are drawn from the median centre of the maxilla and the mandible in the vicinity of the anterior teeth, so as to intersect perpendicularly the posterior plane of the dental model. A symmetrical point on the distal contact point of the unilateral molar tooth about this temporary centreline is then determined, and an oval line, having the median centre as the vertex of its long axis and symmetrical points as the vertices of its short axis, are depicted on the alveolar plane automatically. Lastly, the final centreline is determined by rotating the temporary centreline round the median centre to fit the oval line to the alveolar plane.

Step 6: Determination of the dental arch guideline. In order to arrange the TH line, a guideline representing the ideal individual arch form is determined with reference to the ideal arch form of a Bonwill–Hawley diagram (Hawley, 1905). Using, as a radius, the sum of the respective lengths (inter-dental widths) of the TH lines of the central incisor, lateral incisor and canine on one side, a circle is depicted on the centreline so as to pass through the centre point of the anterior teeth. The TH lines of the central and lateral incisors and canines on both sides are placed along this circle, and the terminations of

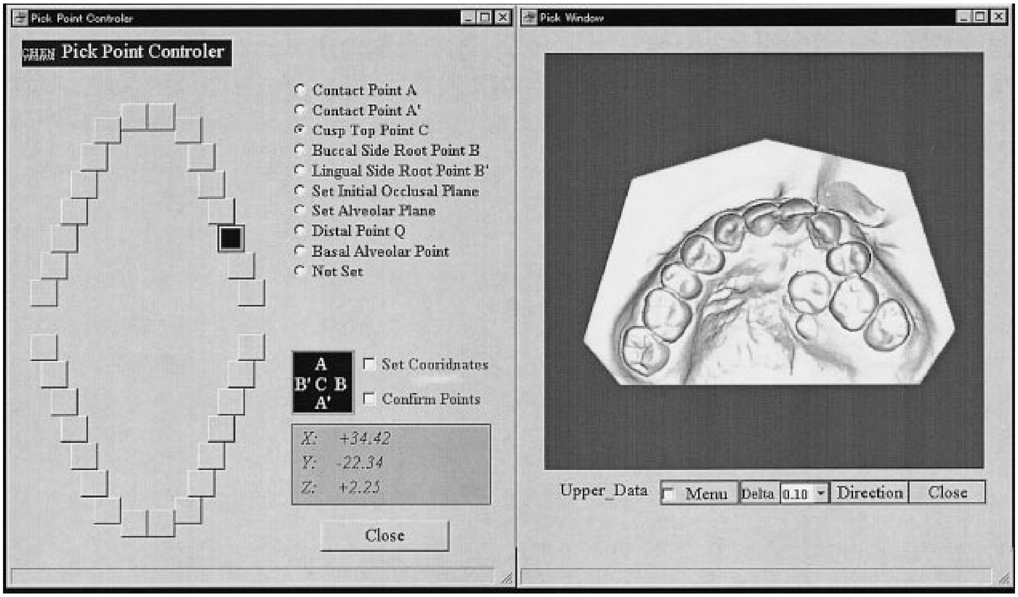

Figure 5 Input of the reference points.

the TH lines of the canines, and the left and right first molars are connected to each other by means of straight lines.

The guidelines prepared for the maxilla and the mandible are superimposed in order to check interference between the guidelines, and both the radius and the width between the bilateral molars can be adjusted with a measuring pitch of 1 mm. In this patient, the upper dental arch was laterally expanded 10.3 mm at the canines and 10.8 mm at the first molars to co-ordinate with the lower dental arch (Figure 11).

Step 7: Alignment of the individual tooth and movement of the dental arch. After determination of the guideline representing the ideal individual arch form, the individual TH line is arranged along this guideline, following the 3D arrangement of the corresponding individual respective plane (Figure 12). Subsequently, the 3D shape is imparted to each of the teeth arranged on the representative plane to form an arrangement of the 3D profile. The maxillary and mandibular dentitions are then allowed to close, and the resultant occlusal condition is confirmed with reference to the area of contact between the maxillary and mandibular teeth. If required, the 3D position of the individual teeth is corrected to obtain an ideal occlusion. Figure 13 shows a computed simulation of the pre-operative orthodontic treatment.

In orthognathic surgery cases, the mandibular dental arch is moved three-dimensionally to establish a correct occlusal relationship between the maxillary and mandibular teeth. Figure 14 shows a computed surgical simulation of this case. This surgical simulation suggested that the mandible should be moved 8.9 mm backwards coupled with 2.3 degrees counter-clockwise rotation to achieve a 2 mm overjet and 2 mm overbite. Finally, the amount of such 3D movement of the dental arch and these individual teeth is computed, and outputted as a text file. The time required in this case to generate a 3D dental model computer graphic was 90 minutes and for the diagnostic cast computer graphic 40 minutes.

Discussion

In conjunction with the recent development of computer graphics, the laser scanning technique

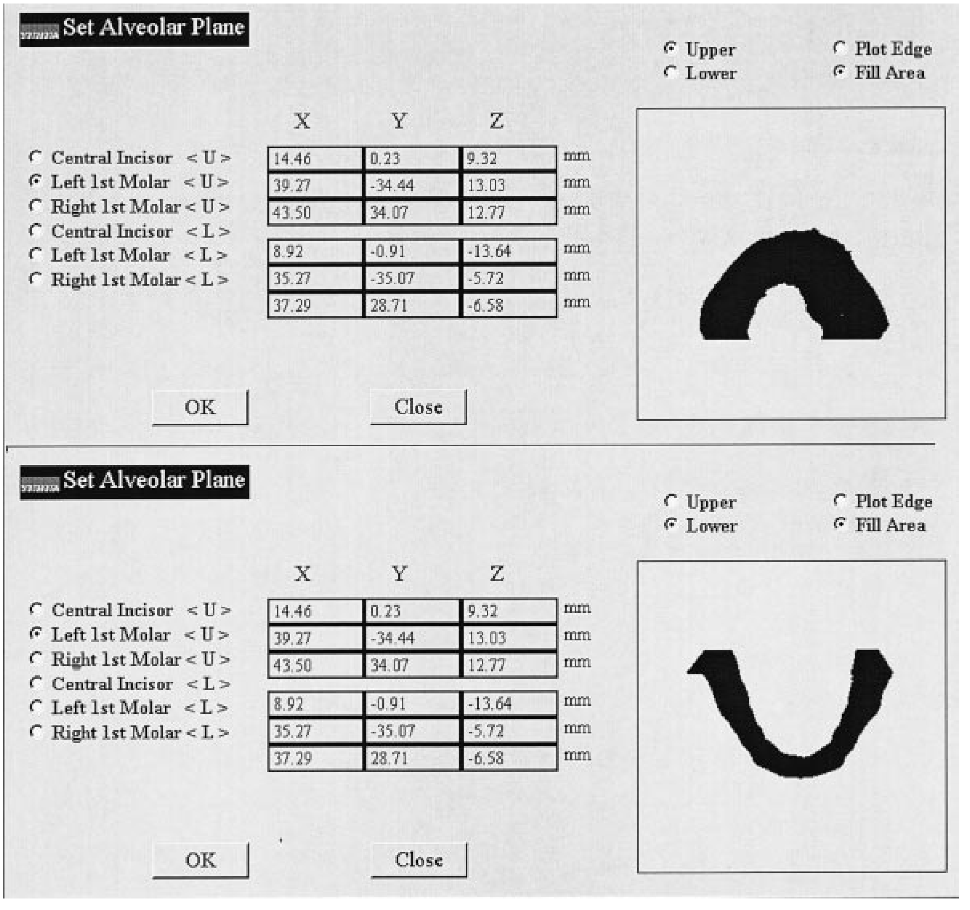

Figure 6 Formation of the alveolar ridge.

has been applied in the field of dentistry to obtain 3D information from dental models because of high-speed processing and high accuracy (Duret *et al.*, 1988; Mörmann *et al.*, 1989; Soma *et al.*, 1992; Maeda *et al.*, 1993; Kuroda *et al.*, 1996). However, an inherent disadvantage of this laser projection is the difficulty of sampling beneath undercuts, which results in blind regions around the anterior oral vestibule in the dental model. In this system, the blind sector is minimized by combining two data files taken from different laser emitter angles. Consequently, as demonstrated in the clinical application, the dental model of the cleft lip and palate patient characterized by the complicated shape of the upper anterior region due to the alveolar cleft, can be measured three-dimensionally without blind sectors. Furthermore, the results of comparing the measured values of tooth crown widths on a dental model by this system with those of a sliding caliper showed little difference between the two methods of measurement. Although it is suggested that dental models with an accurate shape can be obtained with this system, at least in the clinical application, further studies using a more rigorous system will be needed to improve the validity of measurement reliability. An additional advantage of the present CAD system would be the avoidance of the need for storage of plaster models. However, further studies regarding three essential functions, i.e. security, reproducibility, and accessibility will be needed to construct an electronic storage system for the plaster model.

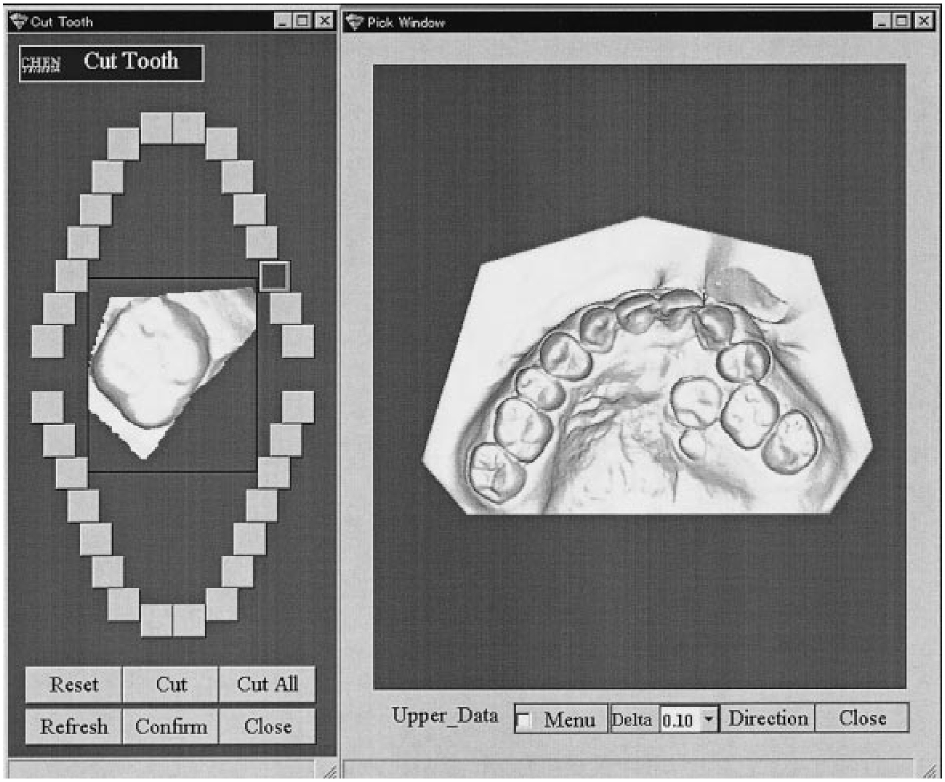

Figure 7 Section of an individual tooth.

When compared with the hand-made set-up model, the computer diagnostic cast system has the following advantages:

1. High-speed processing. Unlike the hand-made set-up model, an accurate automatic arrangement of the teeth is possible in a short time by replacing the individual teeth with the representative planes and arranging them on the guideline. In fact, since the amount of data associated with arrangement is only that of the representative plane, which is remarkably small compared with the amount of 3D shape data, it takes approximately 40 minutes to generate the computer set-up model. In addition, when several treatment procedures for achieving the orthodontic goals are possible, the task of making different diagnostic casts, and the time required to do so are greatly reduced.

2. Quantitative evaluation. Usually, it is difficult in the hand-made set-up model to evaluate quantitatively the amount of 3D movement of individual teeth relative to a craniofacial plane, such as the Frankfort horizontal plane. In this system, since the shape of each tooth is converted into dot map data in a 3D rectangular co-ordinate system, including the Frankfort horizontal plane as a co-ordinate axis, and each tooth is moved by using a representative plane constructed for each tooth with reference to the anatomical reference point, it is easy to calculate the amount of 3D movement of each tooth relative to the craniofacial plane. Similarly, the amount of 3D movement of the mandibular dental arch in an orthognathic surgery case is computed and the amount of such movement is printed as a text file after the generation of a computed graphic of the diagnostic cast.

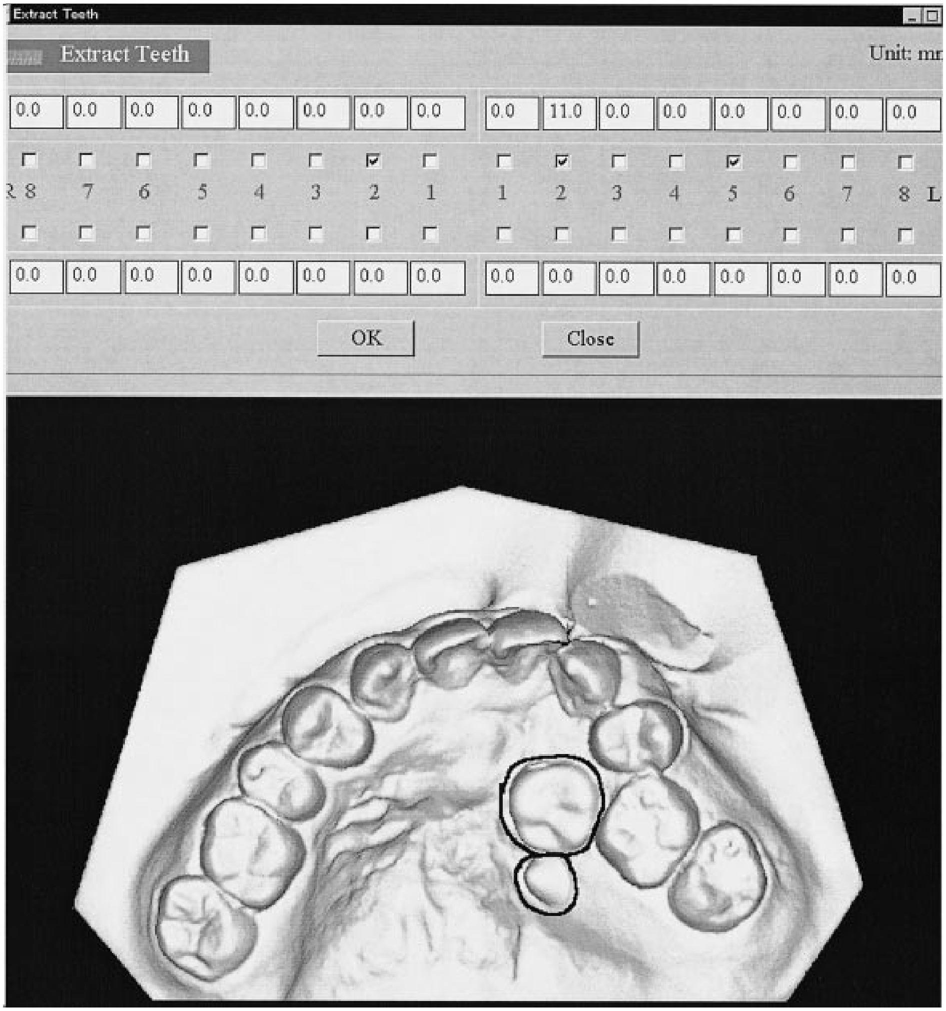

Figure 8 Extraction of teeth.

Many reports have been published regarding the analysis of dental arch form. A variety of regular geometric curves such as the ellipse (Izard, 1927; Currier, 1969), the parabola (Mills and Hamilton, 1965), the catenary (Scott, 1957; Burdi and Lillie, 1966), the form of equations (Hayashi, 1956; Kawata *et al.*, 1973), and polynomial equations (Lu, 1966; Pepe, 1975) have been used to quantitatively describe the shape of human dental arches. However, clinical use of these geometric arches for the predetermination of the individual dental arch might be inappropriate for the following reasons. (1) Most of these studies have examined the average fit of their respective geometric curves for data collected from the dental arch shape in subjects with normal occlusion. (2) The stability of the reconstructed dental arch after orthodontic treatment has not so far been fully investigated. Accordingly, the size and shape of the dental arch in the individual patient is usually predetermined based on the clinical experiences of each clinician. Although the Bonwill–Hawley diagram forms the basis of the dental arch in this system, the

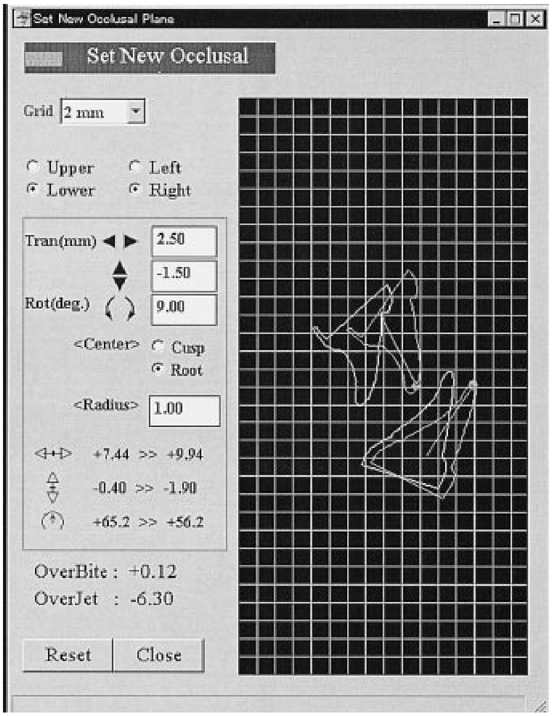

Figure 9 Adjusting the position of the anterior teeth.

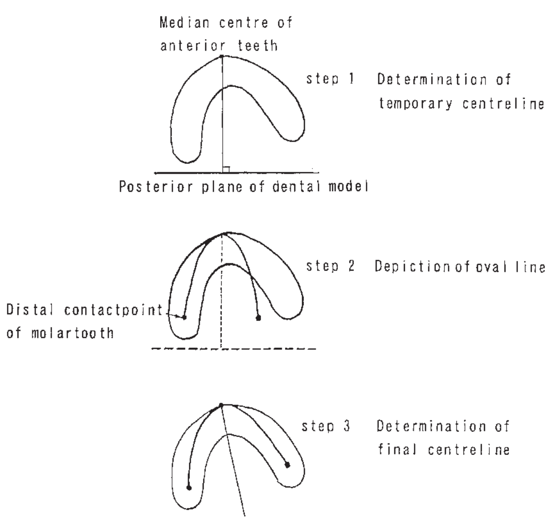

Figure 10 Algorithm to determine the centreline.

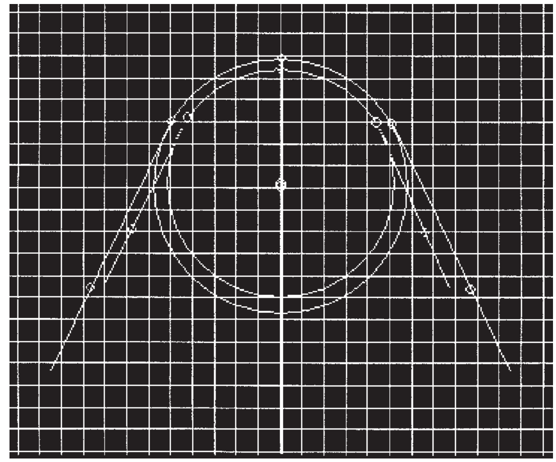

Figure 11 Determination of the dental arch.

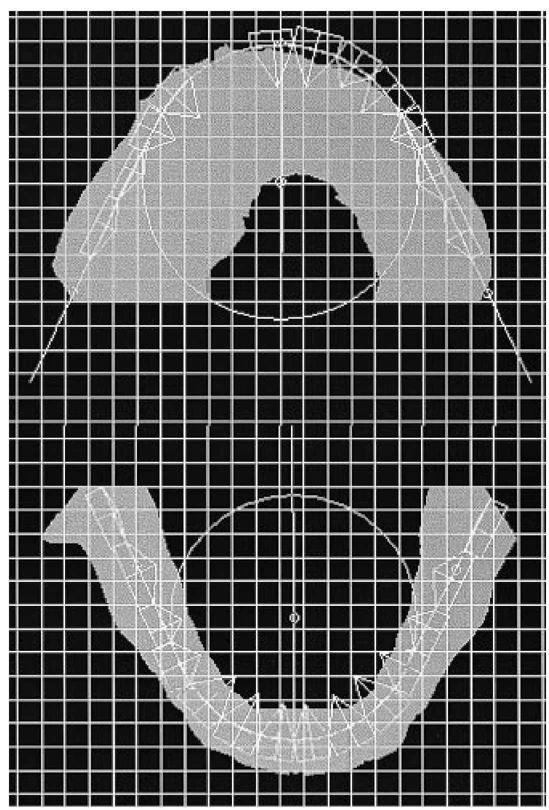

Figure 12 Alignment of the representative planes.

Figure 13 Computed simulation of the pre-operative orthodontic treatment for the patient in Figure 3.

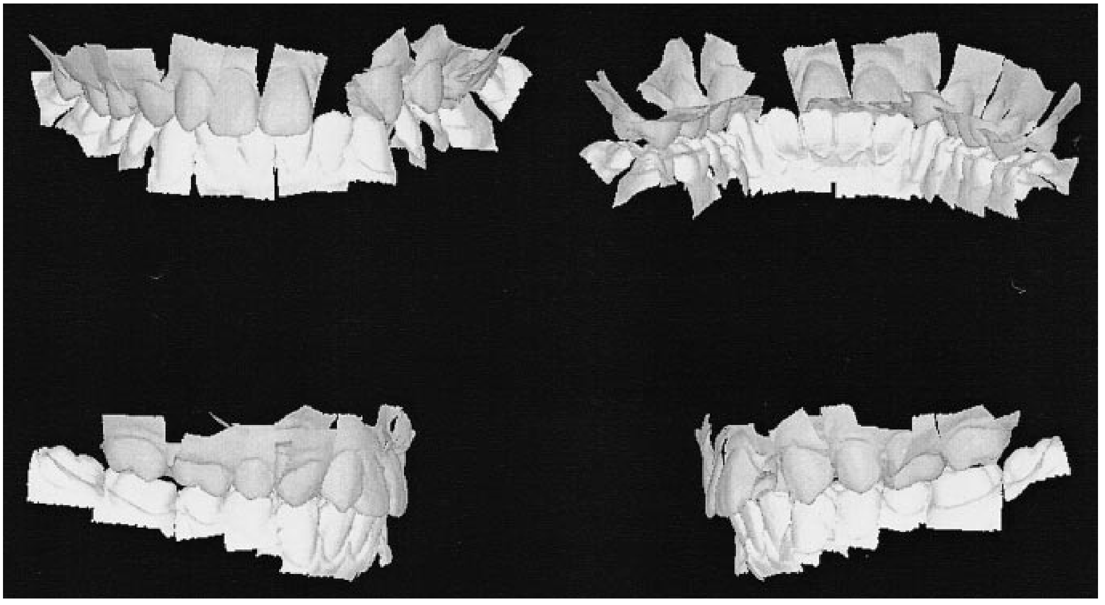

Figure 14 Computed surgical simulation for the patient in Figure 3.

radius to determine the circle size of the anterior teeth and the width between the bilateral molars is adjustable at a pitch of 1 mm to predetermine the individualized dental arch. However, for wider use of this software, an alternative such as the catenary curve or other arch form could be substituted if preferred by adjustment of the algorithm. For the future, careful studies in which the many variables such as genetics, morphology, and function are identified and critically analysed will be required for the predetermination of the individualized dental arch.

Conclusions

In this system, great efforts were made to minimize blind regions in the generation of a 3D computer graphic and to automatically align the individual teeth in the generation of the diagnostic cast. Clinical trials suggest that the use of this system is feasible not only for treatment planning and diagnosis, but also for saving time and labour required to make the diagnostic cast.

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References

Burdi A R, Lillie J H 1966 A catenary analysis of the maxillary dental arch during human embryogenesis. Anatomical Research 154: 13–20

Currier J H 1969 A computerized geometric analysis of human dental arch form. American Journal of Orthodontics 56: 164–179

Duret F, Blouin J L, Duret B 1988 CAD-CAM in dentistry. Journal of the American Dental Association 117: 715–720

Hawley C A 1905 Determination of the normal arch, and its application to orthodontia. Dental Cosmos 47: 541–552

Hayashi T 1956 A mathematical analysis of the curve of dental arch. Bulletin of Tokyo Medical and Dental University 3: 175–218

Izard G 1927 New method for the determination of the normal arch by the function of the face. International Journal of Orthodontics 13: 582–595

Kawata T *et al.* 1973 Statistical and dynamical analysis of dental arch form in adult human with normal occlusion. Journal of Osaka University School 13: 1–4

Kuroda T, Motohashi N, Tominaga R, Iwata K 1996 3D dental cast analysing system using laser scanning. American Journal of Orthodontics and Dentofacial Orthopedics 110: 365–369

Lu K H 1966 An orthogonal analysis of the form, symmetry and asymmetry of the dental arch. Archives of Oral Biology 11: 1057–1069

Maeda Y *et al.* 1993 A CAD/CAM system for removable dentures: Part 1. A system for complete denture fabrication. Journal of Japan Prosthodontic Society 37: 800–805

Mills L F, Hamilton P M 1965 Epidemiological studies of malalignment, a method for computing dental arch circumference. Angle Orthodontist 35: 244–248

Mörmann W H, Brandestini M, Lutz, F, Barbakow F 1989 Chairside computer-aided direct ceramic inlays. Quintessence International 20: 329–339

Pepe S H 1975 Polynomial and catenary curve fits to human dental arches. Journal of Dental Research 54: 1124–1132

Scott J H 1957 The shape of dental arches. Journal of Dental Research 36: 996–1003

Soma K, Hisano M, Kuroki T, Ishida T, Kuroda K 1992 High accuracy measuring device for dental cast—using device with flat laser beam. Journal of Stomatological Society, Japan 59: 259–264