Construction of orthodontic setup models on a computer

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Introduction: Orthodontic setup models are usually limited to the display of teeth, with no information about the roots. The purpose of this article is to present a method for visualizing the tooth roots in setup models by integrating information from cone-beam computed tomography and a laser scanner. The reproducibility of the integration was evaluated. Methods: The records of 5 patients were used in this study. Three-dimensional digital models were generated from the dental casts. Tooth models were generated from the cone-beam computed tomography slices. The 3-dimensional models were superimposed on the crowns of the teeth in the tooth models and integrated. The integrated 3-dimensional tooth model and 3-dimensional setup model were registered. The reproducibility of the integration was evaluated for each tooth. Unpaired Student t tests were performed on the data between the anterior and posterior teeth, and between the right and left teeth. Results: The discrepancy among the integrated 3-dimensional models at the final positions after we used this technique was 0.025 ± 0.007 mm. There was a significant difference in the distance between the anterior and posterior teeth (P < 0.05). However, the average distances between the anterior and posterior teeth were small: 0.023 ± 0.007 and 0.028 ± 0.007 mm, respectively. No significant difference was found between the right and left teeth (P = 0.831). Conclusions: The methods presented in this study provide a reproducible visualization of tooth roots in virtual setup models by registering accurate crown models to cone-beam computed tomography scans. (Am J Orthod Dentofacial Orthop 2012;141:806-13)

The goal of orthodontic treatment is to improve the malocclusion and the relevant functions of the orofacial system. Successful orthodontic treatment should be based on extensive diagnosis and treatment planning. Essential information for diagnosis is obtained from dental casts, photographs, and radiographs. In addition, the setup model, which is used to predict tooth alignment after treatment, is also useful for diagnosis and plays an important role in the 3-dimensional (3D) diagnosis. Currently, the setup model is often limited to showing the alignment of the crowns, with no information regarding the morphology or the direction of the roots or the surrounding bone. Accordingly, root resorption and fenestration of cortical bone might be due to mutual interference between tooth roots and cortical bone and compression of cortical bone. Therefore, orthodontists must make diagnoses and treatment-planning decisions with special attention not only to individual crowns but also to the roots and craniofacial structures. A system for visualizing tooth roots might be useful for observing the positional relationships between the tooth roots and the alveolar bone. Moreover, clinicians could check root parallelism easily in the setup model.

Three-dimensional technology has generated extensive fields of application in dentistry. In orthodontics, various studies have demonstrated automatic tooth alignment, quantitative evaluations for tooth movement, and facial profile and stress analyses. Some research groups have attempted to integrate 2 different structures. Macchi et al reported a method to represent complete 3D views of the maxilla, the mandible, and the setup model with individual anatomic roots with conventional computed tomography.
Although their method is ideal, computed tomography has some limitations in dentistry because of its high cost, low vertical resolution, and high dose of radiation. Recently, cone-beam computed tomography has become more widely used in dental clinics to obtain 3D images.\(^{10,21}\) The radiation dosage is considerably lower with cone-beam computed tomography than in conventional computed tomography scanning.\(^{22,23}\)

Cone-beam computed tomography also has other advantages, including shorter acquisition times and reduced costs. Although the precision of the tooth crown on cone-beam computed tomographs is low, this disadvantage would be offset by integrating the tooth crown of the dental cast with that of the cone-beam computed tomographs. However, to our knowledge, the reconstruction of tooth roots from cone-beam computed tomography scans and superimposition of the dental cast and the setup model has not yet been reported. Moreover, no reports have been published on the reproducibility of superimposition.

The purposes of this study were to establish a method for visualization of the tooth roots in a setup model with cone-beam computed tomography and noncontact 3D scanning, and to assess the reproducibility of this method.

**MATERIAL AND METHODS**

Dental casts and cone-beam computed tomography slices were obtained from 5 patients (1 male, 4 female) who were diagnosed with maxillary canine impaction and preparing for treatment at the Department of Orthodontics at Hiroshima University Hospital in Japan. Their ages ranged from 15 to 25 years. This study was approved by the Ethical Committee for Epidemiology of Hiroshima University (number 329).

Figure 1 shows the algorithm for visualization of the tooth roots in the setup model. The procedure consists of 4 stages: (1) acquisition of the 3D dental cast model, (2) reconstruction of the 3D cone-beam computed tomography tooth model, (3) integration of the 3D dental cast model with the 3D cone-beam computed tomography tooth model, and (4) visualization of the tooth roots in the setup model and the surrounding bone. The details of each step are described below.

The surface of the dental cast obtained from each patient’s dentition was archived by means of a noncontact 3D surface scanner (RexcanDS, Solutionix, Seoul, Korea) to create the corresponding 3D dental cast model. The RexcanDS measuring system is based on the principle of a phase-shifting optical triangulation. An object is scanned with halogen light stripes, and the twin cameras receive the light reflected from the surface of object (Fig 2). RexcanDS has a reported manufacturing accuracy of 0.016 mm. The generated 3D dental cast model was exported to the stereolithography format containing the 3D coordinates. The stereolithography format is a polygon mesh and list of the triangular surfaces that describes the generated 3D model.

Cone-beam computed tomography (CB MercuRay, Hitachi Medical, Tokyo, Japan) images taken of the patients previously for their orthodontic treatment were used. The isotropic voxel size was 0.1 mm (D-mode, 120 kV, 15 mA) for this device. Scanning time was 9.6 seconds. All slice data were exported with the digital imaging and communication in medicine (DICOM) format. Since all cone-beam computed tomography images used in this study were taken for diagnosis of the maxillary impacted teeth in these orthodontic patients, the measured area of the cone-beam computed tomography was focused on the maxilla and did not cover the whole maxilla and mandible. The 3D cone-beam computed tomography tooth models consisting of the teeth including the roots were segmented and reconstructed with ZedView software (LEXI, Tokyo, Japan). Segmentation refers to the manual process of outlining and masking the shape of structures visible in the cross-sections of volumetric data. The difficulty of segmenting the teeth from cone-beam computed tomography data is attributed to their similarity in intensity with the surrounding bone. It took approximately 2 hours on average for the segmentation of the cone-beam computed tomography tooth model with manual outlining. The generated 3D cone-beam computed tomography model was exported to the stereolithography format containing the 3D coordinates.

The data from the 3D dental cast model and the 3D cone-beam computed tomography tooth model were imported with stereolithography format on the same 3D coordinates by using reverse modeling software (RapidForm 2006; INUS Technology, Seoul, Korea). RapidForm 2006 enables data processing and analysis such as cutting, displacement, and calculation of distances. To superimpose the 3D dental cast model on the 3D cone-beam computed tomography tooth model, the crown of each tooth was used as the index of superimposition. This surface-to-surface matching used the iterative closest point algorithm as a function of RapidForm 2006. The iterative closest point algorithm finds the transformation that brings a model into the best possible alignment with the other model by iteration.\(^{11}\)

It is desirable that the crowns of the teeth and the setup model are the same form for superimposing the teeth onto the setup model. However, the crowns of the 3D dental cast model have superior reproducibility compared with the 3D cone-beam computed
tomography tooth model. Thus, the crowns were eliminated from the 3D cone-beam computed tomography tooth model and merged with the crown of the 3D dental cast model with software (FreeForm, SensAble Technologies, Woburn, Mass) (Fig 3, A). Integration of the 3D dental cast model with the 3D cone-beam computed tomography tooth model was completed (the integrated tooth 3D model) (Fig 3, B).

In general, a setup model consists of the teeth made of plaster and paraffin wax to fix the teeth. The setup 3D model was generated in the same way, acquiring the 3D dental cast model with the RexcanDS. The 3D tooth information was transferred from the integrated 3D tooth model to the setup 3D model by using the RapidForm 2006. Moreover, the surrounding bone 3D model was segmented and reconstructed with ZedView and superimposed on the integrated 3D tooth model. Accordingly, the teeth in a setup model can be observed with the surrounding bone displayed.

Reproducibility of the technique was evaluated with RapidForm 2006. The technique was performed in triplicate, and the discrepancy among the integrated tooth 3D models at the final positions after this technique was calculated with a shell-to-shell deviation map as the intraexaminer error. A shell-to-shell deviation map calculates a distance in whole 3D models between each point on the 3D model and the nearest neighbor point on another 3D model (Fig 4). The calculation was computed and automatically completed. The results included the average distance and the standard deviation among the integrated 3D tooth models at the final positions with this technique.

The reproducibility of superimposition might be important, but the dimension of any discrepancy would be expected to depend on the site or region of the dentition. Thus, unpaired Student t tests were carried out on the data between the anterior and posterior teeth, and between the right and left teeth with SPSS software (version 15.0J; SPSS Japan, Tokyo, Japan).
RESULTS

The results of the registration for a patient are shown in Figure 5. For all 5 patients, the tooth roots did not protrude outside the surface of the mucosa and the bone. Also, the tooth roots of the setup models were parallel.

The average distance between the integrated 3D tooth models at the final positions after we used this technique was 0.025 ± 0.007 mm. Figure 6, A, shows the reproducibility of this technique for the anterior and posterior teeth. The average distances of the anterior and posterior teeth were 0.023 ± 0.007 and 0.028 ± 0.007 mm, respectively. There was a significant difference in the distance between the anterior and posterior teeth ($P < 0.05$). Figure 6, B, shows the reproducibility of the technique on the right and left teeth. The average distances of the right and left teeth were 0.026 ± 0.007 and 0.024 ± 0.007 mm, respectively. There was no significant difference in the distance between the right and left teeth ($P = 0.831$).

DISCUSSION

In this study, a method to visualize tooth roots and surrounding bone in a setup model was demonstrated; it uses a 3D model reconstructed from cone-beam computed tomography. In addition, the reproducibility of
this technique was assessed. Since this approach allows visualization of the tooth roots, it could provide useful insights that could lead to more precise fabrication of the setup model.

With the automatic scan function, the RexcanDS used for the measurement of dental casts set the optimum path and several values of swing and rotation at that stage, and automatically measured an object of similar shape by using the previously saved path. Furthermore, it was also possible to measure objects conveniently by automatically carrying out registrations without a matching marker attached, and it requires no separate data postprocessing. Accordingly, the whole shape was measured and generated easily. The 3D dental cast model could be generated accurately and used as an alternative to dental casts.10,24,25

The scattered radiation of cone-beam computed tomography is greater than conventional computed tomography because of the plane detector of the cone-beam computed tomography. Several artefacts such as beam hardening, truncation, and inhomogeneity influence model contrast and bone border definition in cone-beam computed tomography.26 Thus, human intervention was needed to separate the teeth manually from the surrounding bone because cone-beam computed tomography has no computed tomography value, and the tooth model has vague boundaries at certain cross sections. Reproducibility of the tooth could not be evaluated in this study because the subjects were patients who were undergoing orthodontic treatment. In terms of reproducibility of the teeth from cone-beam computed tomography, Baumgaertel et al27 found no significant difference in the measurements between the cone-beam computed tomography images and the anatomic structures. Liu et al28 demonstrated that the

in-vivo differences in tooth volumes between cone-beam computed tomography and the actual tooth volume were ~4% to 7%, and these data would not be likely to influence the study model analysis for diagnosis and treatment planning. Therefore, in this study, the 3D cone-beam computed tomography tooth model was considered to reproduce the patients’ tooth morphology with sufficient precision. Furthermore, if patients’ maxillary and mandibular teeth are in close contact, segmentation of the occlusal surfaces of the teeth from cone-beam computed tomography might be difficult. In this case, a thin wax bite is used during the cone-beam computed tomography scan as a countermeasure. We want to address this point in a future study.

The 3D dental cast model and the 3D cone-beam computed tomography tooth model were positioned differently on the 3D coordinate system because of different acquisition methods. Accordingly, the 3D dental cast model and the 3D cone-beam computed tomography tooth model were superimposed on the crowns of the teeth, and the gap between the 2 models was minimized. Several studies have used fiducial markers as the main registration tool for the integration of 3D models from computed tomography and a 3D scanner.18,29 However, some practical problems remain that are relevant to the clinical setting because of its complexity involving multilevel processes. Thus, the integration of 3D models by markerless registration might be needed. Kim et al17 found that the average differences between patients’ digital dental and maxillofacial models were 0.12 mm for the maxilla and 0.13 mm for the mandible by a point-based and surface-based markerless registration.

To improve the reproducibility of the 3D cone-beam computed tomography tooth model, the 3D dental cast
model and the 3D cone-beam computed tomography tooth model should be merged to generate an integrated 3D tooth model with almost the same crowns as the setup model. The junction of the integrated 3D tooth model was deformed slightly, but the crowns and roots were not obviously deformed. Therefore, this potential error did not affect the next step.

It is impossible to capture the gingival area in the setup model correctly with a phase-shifting optical triangulation because halogen light stripes used to reconstruct a 3D model interfere with light reflection in the lenses with paraffin wax. The gingival area can be captured if a special powder is applied on this area, but this was not done in this study because the method of visualization could be carried out. The teeth in the setup 3D model have same shape as the 3D dental cast model because the setup model was fabricated by using the teeth of the pretreatment dental cast, with only a small error.

The reproducibility of this method calculated with a shell-to-shell deviation map would be acceptable for clinical use in orthodontics. The reasonable value that is acceptable is considered to be 0.1 mm or less because of the fabrication order for the setup model. The significant difference in the reproducibility between the anterior and posterior teeth might be caused by deformation of the impression and the dental cast. Another reason might be the reproducibility of cone-beam computed tomography or the segmentation of the teeth. No

Fig 5. The 3D teeth of the dental cast (left) and the setup model (right) for a patient.

Fig 6. Reproducibility: A, anterior and posterior teeth (*P <0.05); B, right and left teeth.
significant difference in the reproducibility between the right and left teeth indicates that the superimposing function with RapidForm 2006 is stable and has a favorable balance. Because of our technical limitations at this time, the occlusion could not be simulated in the setup model by using cone-beam computed tomography in this study. However, 3D technology has been applied in several previous studies on the occlusion of patients.31,32 Thus, the setup model could also represent the occlusion.

In addition, there are various advantages in this technique for 3D models. Plaster models require physical space for storage, adding financial and logistic burdens. The electronic storage of patients’ dental casts as 3D models will eliminate the problems of storage, retrieval, and maintenance of the casts; office management; and communication between the various specialties, thus allowing for easier consultations.33 Clinicians would be able to check the parallelism of the tooth axis during orthodontic treatment via the root visualizing system without additional cone-beam computed tomography scans. This is because the 3D data taken from the tooth crowns of the study cast can be integrated with the 3D data of the tooth roots. Therefore, this method would provide additional information on the tooth roots without exposing the patient to additional radiation.

CONCLUSIONS

It is feasible to visualize tooth roots in a setup model from dental cast and cone-beam computed tomography data. The method provides sufficient reproducibility to visualize tooth roots in a setup model and allows clinicians to easily observe the relationship of the tooth roots in a setup model and the surrounding tissues.

REFERENCES