Original Article

Construction reproducibility of a composite tooth model composed of an intraoral-scanned crown and a cone-beam computed tomography-scanned root

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Objective: To evaluate the construction reproducibility of a composite tooth model (CTM) composed of an intraoral-scanned crown and a cone-beam computed tomography (CBCT)-scanned root. **Methods:** The study assessed 240 teeth (30 central incisors, 30 canines, 30 second premolars, and 30 first molars in the maxillary and mandibular arches) from 15 young adult patients whose pre-treatment intraoral scan and CBCT were available. Examiner-Reference (3 years' experience in CTM construction) and Examiners-A and Examiner-B (no experience) constructed the individual CTMs independently by performing the following steps: image acquisition and processing into a three-dimensional model, integration of intraoral-scanned crowns and CBCT-scanned teeth, and replacement of the CBCT-scanned crown with the intraoral-scanned crown. The tooth axis angle in terms of mesiodistal angulation and buccolingual inclination of the CTMs constructed by the three examiners were measured. To assess the construction reproducibility of CTMs, intraclass correlation coefficient (ICC) assessments were performed. **Results:** The ICC values of mesiodistal angulation and buccolingual inclination among the 3 examiners showed excellent agreement (0.950–0.992 and 0.965–0.993; 0.976–0.994 and 0.973–0.995 in the maxillary and mandibular arches, respectively). **Conclusions:** The CTM showed excellent construction reproducibility in mesiodistal angulation and buccolingual inclination regardless of the construction skill and experience levels of the examiners.
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INTRODUCTION

Panoramic radiography has been considered to be accurate enough to evaluate the alignment of the dentition, including roots, even though it shows several shortcomings involving distortion, overlapping, and magnification.[1,2] However, clinicians need to examine the root position three-dimensionally (3D) in several clinical situations such as severe skeletal malocclusion and eruption disturbances in relation to adjacent roots.

With the introduction of cone-beam computed tomography (CBCT), examination of the root position in 3D coordinates has become possible. However, because this 3D imaging technology involves more radiation exposure than panoramic radiography, repeated CBCT scans during orthodontic treatment are not recommended.[3-5] In contrast, an intraoral scan can be performed without radiation exposure whenever it is required. Moreover, a crown image with a detailed occlusal surface can be obtained with a fast-capturing intraoral scanner, and its accuracy and reliability are known to be clinically acceptable.[6-8] The major drawback of this approach is the inability to represent the root.

By combining the complementary characteristics of these two 3D imaging technologies, construction of a 3D tooth model with a precise crown and root has been attempted, which we named the "composite tooth model" (CTM).[9] Initially, the primary applications of CTM were for diagnosis, treatment simulation, and customized appliance fabrication in cases requiring evaluation of the crown and root simultaneously.[10-12] Recently, using this CTM, monitoring root movement during and after orthodontic treatment was tried just by intraoral scanning (Figure 1).[13,14] This involves the ability of the individual CTM to superimpose onto the mid- or post-treatment intraoral scan via referencing of the unaltered crown morphology as an index. Because the incorporated root tracks the crown movement, the changed root position allows visualization of the root movement (Figure 2). Therefore, once CTMs are constructed, additional CBCT scans for examining the root position at the mid- and post-treatment stages would not be required.

Although many trials and efforts have been performed for constructing precise 3D tooth models using various methodologies,[10-15] the accuracy and reproducibility of the 3D tooth models are influenced by several steps and the construction procedures would be difficult for a novice operator. Therefore, the purposes of this study were to introduce an elaborate CTM construction procedure and to evaluate the construction reproducibility
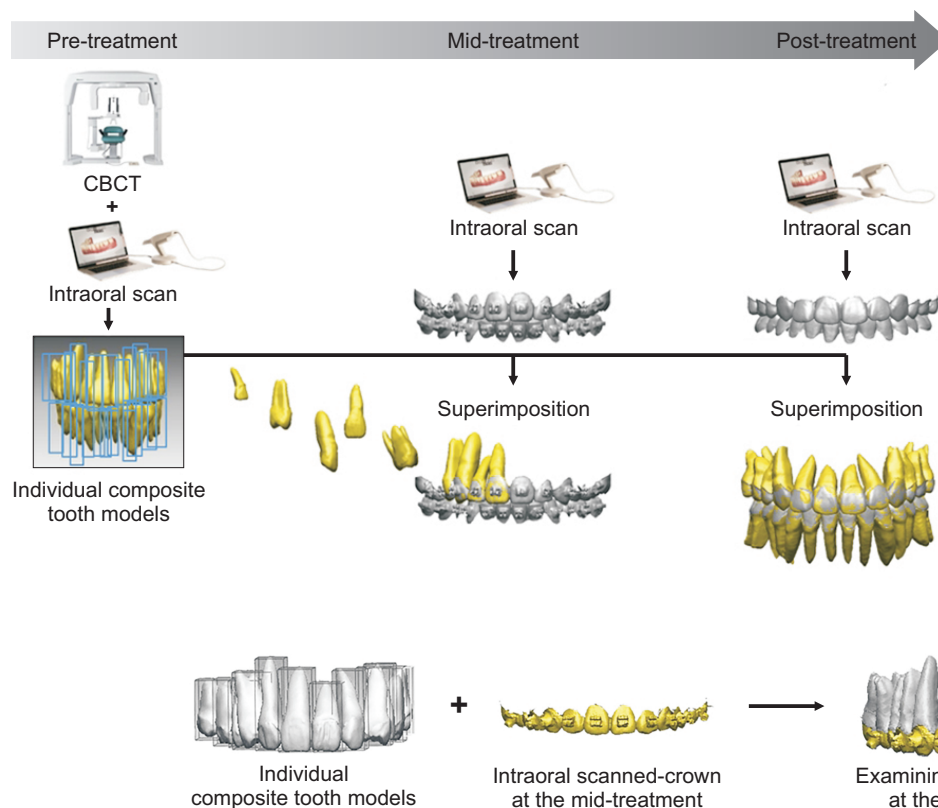
Figure 1. Clinical application of the composite tooth model (CTM). The CTMs constructed at the pre-treatment stage by combining cone-beam computed tomography (CBCT) and intraoral scan data can be used for evaluation of the root position at the mid- and post-treatment stages.

Figure 2. Evaluation of root position at the mid-treatment stage by superimposing individual composite tooth models onto the mid-treatment intraoral-scanned image using the crown as an index.

of CTMs composed of an intraoral scanned-crown and a CBCT-scanned root.

MATERIALS AND METHODS

Subjects

The protocol for this study was reviewed and approved by the Institutional Review Board of the Chonnam National University Dental Hospital in Gwangju, Korea (No. CNUDH-2019-0003). The study included patients whose pre-treatment intraoral scans and CBCT data were available. The exclusion criteria were patients who had (1) more than two missing and/or extracted teeth, (2) more than two metal or gold crown restorations, and (3) an arch length discrepancy greater than 8 mm in the maxillary and mandibular arches.

To determine the sample size, a power analysis was performed based on the classification of Fleiss.[16] The values of minimal and maximal intraclass correlation coefficients (ICC, $\rho 0$ and $\rho 1$) were set at 0.40 (fair agreement) and 0.80 (excellent agreement), respectively. With an α error probability of 0.05 and power of 0.8 (1-β error probability), the analysis yielded a minimal sample size of 15.21 subjects for intra- and inter-examiner reproducibility assessment. Thus, 15 Korean young adult patients (8 men and 7 women; mean age, 18.9 years) were recruited. A total of 240 teeth from the 15 patients (30 central incisors [CI], 30 canines [C], 30 second premolars [P2], and 30 first molars [M1] in the maxillary and mandibular arches) were tested.

Examiners

Three examiners participated in this study. One orthodontist (LSW) who had 3 years' experience in CTM construction was designated as Examiner-Reference (Examiner-Ref). Two orthodontic residents who had no experience in CTM construction were designated as Examiner-A (CIS) and Examiner-B (KHM).

To evaluate the intra-examiner reproducibility of CTM construction performed by Examiner-Ref, this examiner independently constructed the individual CTMs of all subject teeth and repeated the construction one month later. In addition, Examiner-A and Examiner-B independently constructed the individual CTMs of all subject teeth. The three sets of 240 CTMs constructed by the 3 examiners were used to evaluate the inter-examiner reproducibility in CTM construction (Figure 3).

Composite tooth model construction procedure

Step 1: Image acquisition and processing into 3D model

Intraoral scanning was performed using an optical intraoral scanner (TRIOS®; 3Shape, Copenhagen, Denmark). After scanning of the maxillary and mandibular arches and removing the gingival area, the clinical crowns of maxillary and mandibular arches were converted into the stereolithography (STL) format using the OrthoAnalyzer™ software (3Shape) (Figure 4A).

Intraoral-scanned crown by independent single operator

Segmentation of CBCT teeth by 3 examiners

Individual composite tooth models by 3 examiners

Examiner-Ref
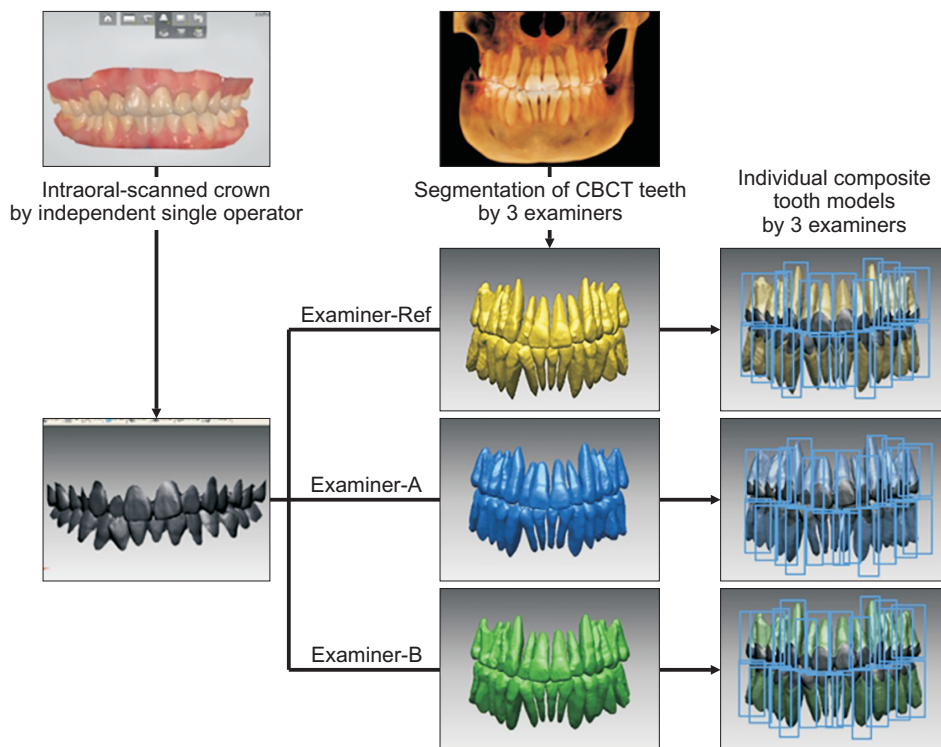
Examiner-A

Examiner-B

Figure 3. Study design for evaluation of inter-examiner reliability in construction of individual composite tooth models (CTMs). Examiner-Reference (Examiner-Ref), Examiner-A, and Examiner-B independently constructed the individual CTMs using the intraoral-scanned crown and the cone-beam computed tomography (CBCT)-segmented teeth.
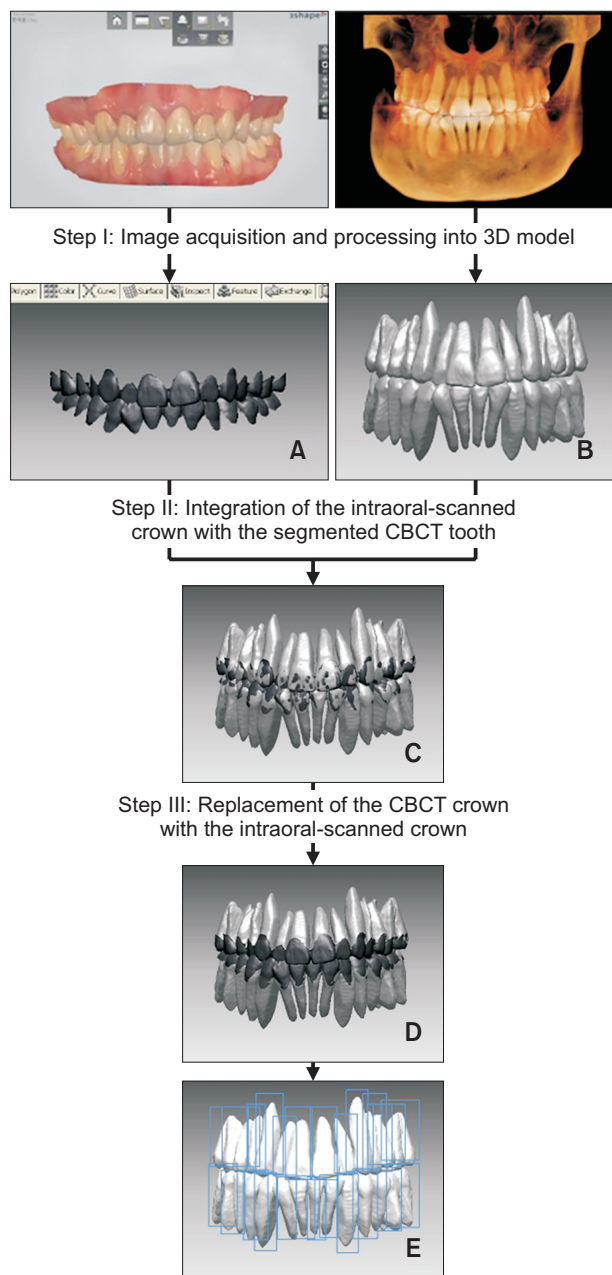
Step I: Image acquisition and processing into 3D model

Step II: Integration of the intraoral-scanned crown with the segmented CBCT tooth

Step III: Replacement of the CBCT crown with the intraoral-scanned crown

Figure 4. Construction procedure of the individual composite tooth models. **A**, Intraoral-scanned crown. **B**, Segmented cone-beam computed tomography (CBCT)-scanned teeth. **C**, Integration of A and B by crown registration. **D**, Intraoral-scanned crown with CBCT-scanned root. **E**, Individual composite tooth models. 3D, Three-dimensional.

CBCT scan (Alphard Vega; Asahi Roentgen, Kyoto, Japan; 80 kV and 5 mA; voxel size, 0.39 × 0.39 × 0.39 mm; and field of view, 200 × 179 mm) was performed and the digital imaging and communication in medicine (DICOM) file was exported to the InVivo5 software (ver.

5.1, Anatomage, San Jose, CA, USA) for 3D volume rendering. In the "MD (medical design) studio" module, the individual tooth including the root was segmented using the "Sculpt" function and converted into the STL format (Figure 4B).

Step II: Integration of the intraoral-scanned crowns and the segmented CBCT-scanned teeth

After the intraoral scans and CBCT 3D models from Step I were imported into the Rapidform™ 2006 program (INUS Technology, Seoul, Korea), crown registration was performed to integrate the intraoral-scanned crown and segmented CBCT-scanned teeth. First, the initial registration was performed by selecting more than three corresponding points on each image, resulting in a rough alignment. Second, a "Fine" automatic best-fit registration was used to finalize the matches. Once the whole CBCT-scanned teeth of the maxillary arch were registered with the intraoral-scanned crowns of the maxillary arch, the mandibular arch was registered using the same method (Figure 4C).

To verify the accuracy of integration, the registration errors were evaluated using the "shell/shell deviation" function, which measures the absolute values of the 3D Euclidean distances between the surface points on the two images (Figure 5). The registration errors of the crown constructed by the 3 examiners ranged from 0.20 to 0.21 mm in both maxillary and mandibular arches (Table 1). Because registration errors were under 0.22 mm,[9] we proceeded further steps below.

Step III: Replacement of the CBCT-scanned crown with the intraoral-scanned crown

To replace the CBCT crown image with the intraoral scan, the CBCT-scanned crown was removed from the integrated image (Figure 4D). Then, the intraoral-scanned crown and the CBCT-scanned root were merged using the "Merge" function of the program (Figure 4E).

Measurement

The tooth axis angle in terms of the mesiodistal angulation and buccolingual inclination of the individual CTMs was measured using two reference planes, the occlusal plane and tooth axis plane (Figure 6). The occlusal plane was defined by three points, including the midpoint of the vertical overlap between the right maxillary and mandibular CI and the mesiobuccal cusp tips of the left and right maxillary M1. The tooth axis plane was defined by three points, including the most apical point of the root apex and two points in the crown (Table 2 and Figure 6). Then, the distal and lingual side angles between the two reference planes were computed by using the "Angle-ref. plane/ref. plane" function of Rapidform™ 2006.
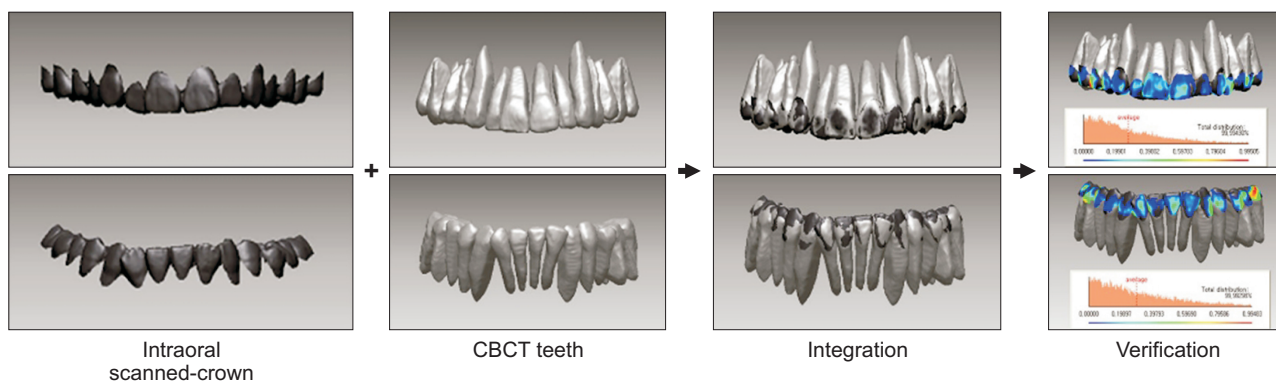
Figure 5. Verification of the integration accuracy. Registration errors were evaluated by measuring the absolute values of the three-dimensional Euclidean distances between the surface points on the two images.
CBCT, Cone-beam computed tomography.

Table 1. Shell/shell deviation of the crowns in the maxillary and mandibular arches to verify the accuracy of integration (n = 15)

Shell/shell deviation (mm)	Examiner-Ref		Examiner-A		Examiner-B		ICC (95% CI)
	Mean	SD	Mean	SD	Mean	SD	
Maxilla	0.20	0.02	0.21	0.03	0.20	0.03	0.936
Mandible	0.20	0.03	0.21	0.04	0.21	0.05	0.901

Intraclass correlation coefficient (ICC) test was performed.
Examiner-Ref, Examiner-Reference; SD, standard deviation; CI, confidence interval.

Statistical analysis

Intra-examiner reproducibility of constructions performed by Examiner-Ref

Since the intra-examiner reproducibility of Examiner-Ref demonstrated an excellent agreement in terms of the ICC values of the mesiodistal angulation and buccolingual inclination (range: 0.957–0.993 and 0.975–0.995, respectively; data are not shown), the CTMs constructed by Examiner-Ref were considered as the reference. Further evaluation of the inter-examiner reproducibility went on.

Inter-examiner reproducibility

Inter-examiner reproducibility of the mesiodistal angulation and buccolingual inclination was evaluated by the ICC test. Statistical analysis was performed using IBM SPSS ver. 23.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Inter–examiner reproducibility

The ICC values of the mesiodistal angulation were 0.950–0.992 and 0.965–0.993 in the maxillary and mandibular arches, respectively (range of difference, 0.01–0.79°; Table 3). The ICC values of the buccolingual inclination were 0.976–0.994 and 0.973–0.995 in the maxillary and mandibular arches, respectively (range of difference, 0.04–0.77°; Table 4).

DISCUSSION

With the application of CTMs constructed using single CBCT at the pre-treatment stage, the 3D root position during or after treatment can be examined by intraoral scanning alone (Figures 1 and 2). Many studies have attempted to construct 3D tooth models and apply them to clinical practice. Macchi et al.[10] constructed a 3D-setup model to visualize tooth movement before and after orthodontic treatment by integrating multi-slice computed tomography and laser scans. Guo et al.[11] applied a 3D-setup model constructed by integrating CBCT and optical scans to the indirect bonding system. Kihara et al.[12] demonstrated that prediction of the root position after treatment using the 3D tooth model was reliable. Lee et al.[13] used the *ex-vivo* typodont models to monitor tooth movement and demonstrated that root surface differences between the expected and true root position of composite teeth were 0.02 ± 0.32 mm and 0.09 ± 0.25 mm in the maxillary and mandibular teeth, respectively. Subsequently, Lee et al.[15] validated the accuracy and reliability of this methodology using a greater number of human subjects. Their tooth model exhibited mean differences of $1.39 \pm 1.05°$ and $1.30 \pm 0.92°$ in the me-

Mesiodistal angulation
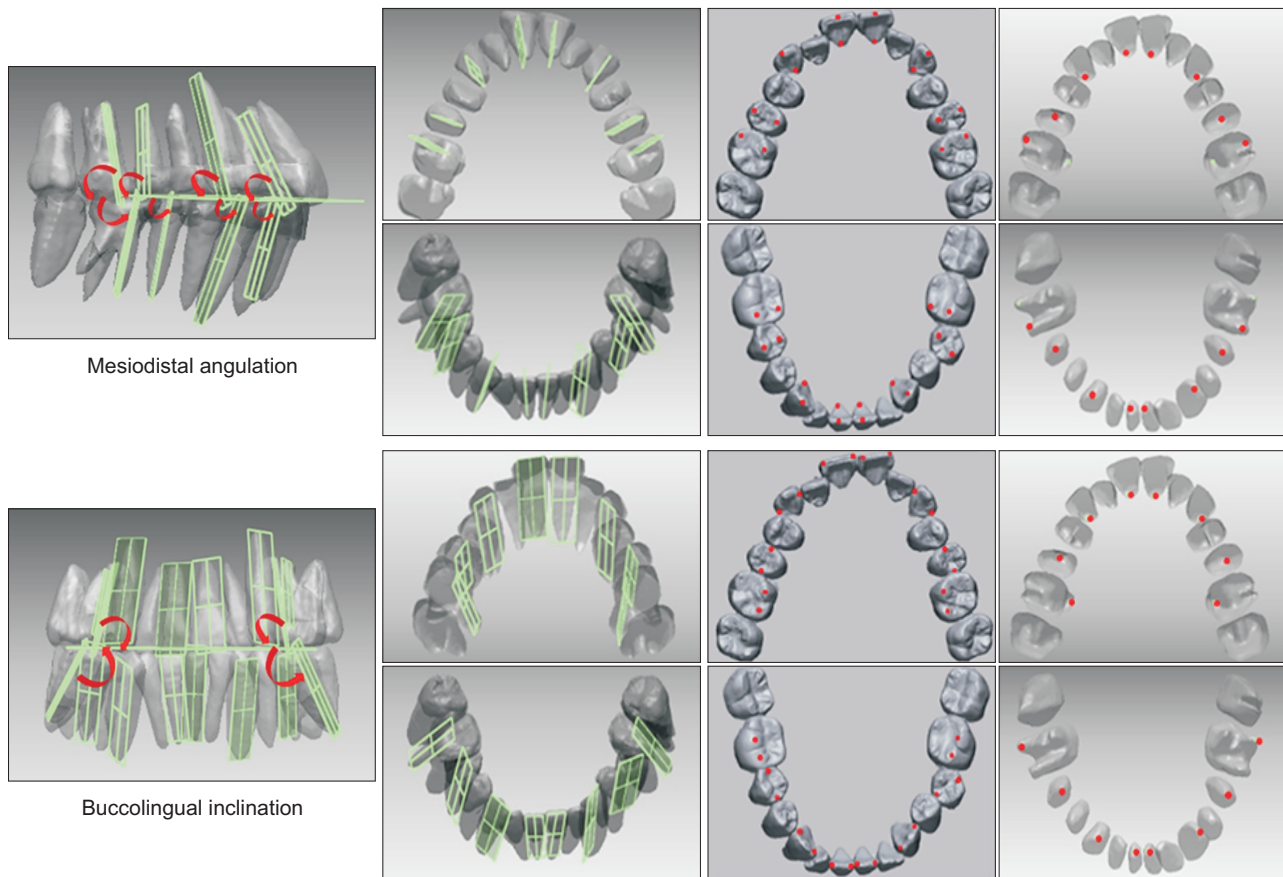
Buccolingual inclination

Figure 6. Measurements of tooth axis angle. The mesiodistal angulation was measured at the distal angle in conjunction with the occlusal plane and the tooth axis plane (upper row). The buccolingual inclination was measured at the lingual angle in conjunction with the occlusal plane and the tooth axis plane (lower row). The green square-shaped plane presents tooth axis planes constructed by two points in the crown and one point in the root apex.

siodistal angulation and the buccolingual inclination between the post-treatment CBCT scan and the expected root position setup, indicating high inter-operator reliability. However, 11.6% and 9.6% of teeth measured for the mesiodistal angulation and the buccolingual inclination were outside the ± 2.5° range of clinical acceptability.

The main idea of this study was to introduce an elaborate method for constructing CTMs and to verify the CTMs constructed by this method. In this study, to evaluate the inter-examiner reproducibility in construction of CTMs, the tooth axis angles of CI, C, P2, and M1 (n = 30/tooth type) in the maxillary and mandibular arches were compared. The mesiodistal angulation and the buccolingual inclination demonstrated a high degree of inter-examiner reproducibility (ICC, 0.950–0.992 and 0.965–0.993 in the maxillary and mandibular arches, respectively, Table 3; ICC, 0.976–0.994 and 0.973–0.995 in the maxillary and mandibular arches, respectively, Table 4). The mean differences in tooth axis angle between

examiners ranged from 0.01° to 0.79° in the mesiodistal angulation and 0.04° to 0.77° in the buccolingual inclination, which can be considered to be very small under clinical conditions. These results were better than those reported by Lee et al.[15] Therefore, the CTM construction methodology proposed in this study demonstrated excellent inter-examiner reproducibility regardless of the construction skill and experience level of the examiners. Although the differences between examiners were clinically acceptable (range: 0.01–0.79° and 0.04–0.77° in the mesiodistal angulation and buccolingual inclination, respectively), they were supposed to have originated from the tooth segmentation procedure from the CBCT. The inherent differences in root images might have resulted in inter-examiner differences (step I), and the differences in crown images also might have resulted in differences in the integration with the intraoral scan images (step II). As a result, steps I and II were mainly responsible for the inter-examiner differences.

In terms of the time required for CTM construction by

Table 2. Definitions of the landmarks in the crown and root for constructing the tooth axis plane

Tooth axis plane	Tooth	Definition of landmarks	
		Two points in the crown	One point in the root
Mesiodistal angulation	Central incisor	The most mesial and distal point of the incisor edge	The most apical point of the root
	Canine	The most mesial and distal point of the marginal ridge	The most apical point of the root
	Second premolar	The most mesial and distal point in the line of occlusion	Max: The most apical point of the palatal root
	First molar	Max: The mesiopalatal and distopalatal cusp tips Man: The mesiobuccal and distobuccal cusp tips	Max: The most apical point of the palatal root Man: The most apical point of the distal or distobuccal root
Buccolingual inclination	Central incisor	The midpoint of the incisor edge and the central pit of lingual surface	The most apical point of the root
	Canine	The cusp tip and cingulum	The most apical point of the root
	Second premolar	The buccal and lingual cusp tips	Max: The most apical point of the buccal root
	First molar	Max: The mesiobuccal and mesiopalatal cusp tips Man: The mesiobuccal and mesiolingual cusp tips	Max: The most apical point of the mesiobuccal root Man: The most apical point of the mesial or mesiobuccal root

Max, Maxilla; Man, mandible.

Table 3. Mesiodistal angulation (°) of composite tooth models constructed by the 3 examiners (n = 30/tooth type)

Tooth		Examiner-Ref		Examiner-A		Examiner-B		ICC (95% CI)
		Mean	SD	Mean	SD	Mean	SD	
Maxilla	Central incisor	88.28	4.83	88.04	5.46	88.51	5.38	0.950
	Canine	79.49	7.45	79.90	7.07	79.80	7.55	0.992
	2nd premolar	83.75	6.30	83.89	6.65	83.88	6.13	0.992
	1st molar	83.02	7.55	83.23	7.41	82.81	7.99	0.980
Mandible	Central incisor	91.39	5.13	91.83	5.33	91.04	5.59	0.965
	Canine	84.57	7.01	84.35	7.18	84.58	6.76	0.989
	2nd premolar	79.76	6.24	79.45	6.27	79.84	5.81	0.993
	1st molar	79.53	5.18	79.38	4.96	79.60	4.86	0.989

Intraclass correlation coefficient (ICC) test was performed.
Examiner-Ref, Examiner-Reference; SD, standard deviation; CI, confidence interval.

the novice operators, Examiners-A and Examiner-B, it took about 14–15 hours for the total of 28 teeth in one patient. On the other hand, for Examiner-Ref, who had had three years' experience in CTM construction, it took about 10–11 hours. Repeated construction improved the proficiency in construction, thereby reducing the operating time by the learning effect.[17] Unfortunately, we could not plot the learning curve. The most time-consuming procedure was tooth segmentation from CBCT scans, which occupied about two-thirds of the total time. Because fully automated tooth segmentation has not been verified yet,[18] human intervention was un-avoidable. Although the smaller voxel size results in an image with finer detail and higher contrast,[19] artifacts such as beam hardening, truncation, and scattered radiation can affect the contrast and definition of the bone and root.[20,21] Additionally, streak artifacts from brackets or metal restorations make it difficult to segment the crown from CBCT images.[21]

The application of the CTM would be clinically valu-able because no additional radiation exposure is re-quired after the initial CBCT. However, CTM construc-

Table 4. Buccolingual inclination (°) of composite tooth models constructed by the 3 examiners (n = 30/tooth type)

Tooth		Examiner-Ref		Examiner-A		Examiner-B		ICC (95% CI)
		Mean	SD	Mean	SD	Mean	SD	
Maxilla	Central incisor	55.44	4.22	54.81	4.20	55.01	4.02	0.992
	Canine	70.51	9.21	70.55	9.30	70.11	9.23	0.994
	2nd premolar	88.02	8.27	88.22	8.60	87.93	8.41	0.976
	1st molar	80.12	6.20	79.96	6.50	79.43	6.71	0.987
Mandible	Central incisor	71.04	8.50	71.50	7.71	70.91	8.86	0.993
	Canine	78.55	8.03	78.58	8.05	78.92	8.48	0.995
	2nd premolar	92.86	7.85	92.81	7.84	92.99	7.27	0.973
	1st molar	95.53	9.24	94.76	9.05	95.13	9.19	0.990

Intraclass correlation coefficient (ICC) test was performed.
Examiner-Ref, Examiner-Reference; SD, standard deviation; CI, confidence interval.

tion should be restricted to patients who underwent the initial CBCT for justified reasons, such as severe skeletal discrepancy, craniofacial deformity, and ectopic erupting teeth. Thus, the initial CBCT scans can be utilized not only for diagnosis, but also for examining changes in root position. Routine initial CBCT for orthodontic diagnosis cannot be justified, as reported in the 'guidelines on the CBCT for dental and maxillofacial radiology' by SEDENTEXCT.[22] All of the included subjects in this study were patients who were likely to be candidates for orthognathic surgery.

On the other hand, there are several shortcomings in CTM. To assess any pathologic changes such as external root resorption and bony change, additional radiography would be required. Moreover, numerous technical aspects need improvement before CTMs can be reliably used under clinical conditions. Most importantly, the labor-intensive and time-consuming nature of this approach remains to be addresses. In this regard, adoption of auto-segmentation technology and development of all-in-one software for CTM may help increase operation efficiency.

This study was a preliminary study for validation of CTM in root position estimation at the mid- or post-treatment stage. Investigation of the applications of CTMs at mid-treatment intraoral scans would be performed in the near future, as a next step.

CONCLUSION

CTM constructed by the proposed methodology showed an excellent construction reproducibility in tooth axis angle regardless of the construction skill and experience levels of the examiners.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

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