A new method to measure mesiodistal angulation and faciolingual inclination of each whole tooth with volumetric cone-beam computed tomography images

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Introduction: The purpose of this study was to develop a methodology to measure the mesiodistal angulation and the faciolingual inclination of each whole tooth (including the root) by using 3-dimensional volumetric images generated from cone-beam computed tomography scans. Methods: A plastic typodont with 28 teeth in ideal occlusion was fixed in position in a dry human skull. Stainless steel balls were fixed to the occlusal centers of the crowns and to the apices or bifurcation or trifurcation centers of the roots. Cone-beam computed tomography images were taken and rendered in Dolphin 3D (Dolphin, Chatsworth, Calif). The University of Southern California root vector analysis program was developed and customized to digitize the crown and root centers that define the long axis of each whole tooth. Special algorithms were used to automatically calculate the mesiodistal angulation and the faciolingual inclination of each whole tooth. Angulation measurements repeated 5 times by using this new method were compared with the true values from the coordinate measuring machine measurements. Next, the root points of 8 selected typodont teeth were modified to generate known angulation and inclination values, and 5-time repeated measurements of these teeth were compared with the known values. Results: Intraclass correlation coefficients for the repeated mesiodistal angulation and faciolingual inclination measurements were close to 1. Comparisons between our 5-time repeated angulation measurements and the coordinate measuring machine’s true angulation values showed 5 teeth with statistically significant differences. However, only the maxillary right lateral incisor showed a mean difference that might exceed 2.5° for clinical significance. Comparisons between the 5-repeated measurements of 8 teeth with known mesiodistal angulation and faciolingual inclination values showed no statistically significant differences between the measured and the known values, and no measurement had a 95% confidence interval beyond 1°. Conclusions: We have developed the novel University of Southern California root vector analysis program to accurately measure each whole tooth mesiodistal angulation and faciolingual inclination, in a clinically significant level, directly from the cone-beam computed tomography volumetric images. (Am J Orthod Dentofacial Orthop 2012;142:133-43)

The basic objectives of orthodontic treatment are to obtain proper positions of all teeth by using various orthodontic appliances, to form a functional and stable occlusion, and to display the teeth in proper relationships to one another and in harmony with the maxillofacial hard and soft tissues after treatment. Six parameters describe each tooth location in 3-dimensional space. Three are positional (mesiodistal, faciolingual, and occlusogingival), and 3 are angular (mesiodistal angulation, faciolingual inclination, and axial rotation). Nearly half a century ago, Andrews1,2 studied 120 patients with optimal occlusions and obtained the positional and angular norms for all teeth by measuring their crowns on the study models. Various types of preadjusted appliances that are used
by most orthodontists today are, to a certain degree, derived from the original straight-wire appliances he developed based on these crown norms.\textsuperscript{1-4} However, although 4 of the 6 parameters defining tooth positions are dictated by the crowns and are easy to monitor clinically, later research has shown that crowns might not provide clear indications for the angulation and the inclination of the whole teeth, including the roots.\textsuperscript{5-8} Moreover, straight-wire techniques rely heavily on precise bracket positioning during initial bonding, and yet orthodontists at various experience levels have found difficulties in accurately placing brackets directly on patients’ teeth or even indirectly on the teeth of stone models.\textsuperscript{9-12} So far, the roots that constitute about half of the whole tooth have been mostly ignored. It is speculated that the roots might also need to be assessed to achieve ideal whole tooth angulation and inclination.

Traditionally, panoramic x-rays have been used at the initial, progress, and finishing stages of orthodontic treatment to diagnose, monitor, and finalize the angulations of the teeth.\textsuperscript{13,14} However, studies have indicated that panoramic x-rays have distortions and do not reflect the true 3-dimensional teeth angulations because the x-ray beam is not always orthogonal to the target teeth.\textsuperscript{15-18} For faciolingual inclinations, the only assessment tool available is the lateral cephalogram for the maxillary and mandibular central incisors.\textsuperscript{19,20} A posteroanterior cephalogram might capture the faciolingual inclinations of a few molars, but the image quality is usually poor and rarely used.

As we know, the position of teeth is a 3-dimensional issue. Andrews\textsuperscript{1-3} did not measure the angulation and the inclination of teeth from 2-dimensional x-rays but from study models that are 3-dimensional. Fortunately, the development and use of cone-beam computed tomography (CBCT) in orthodontics in recent years have allowed us see the roots of teeth in 3 dimensions as well. This lets us accurately evaluate the mesiodistal angulation and the faciolingual inclination of each whole tooth (crown and root) rather than just the crown. However, there is no clinically useful tool currently available to systemically measure whole tooth angulation and inclination in 3 dimensions. Van Elslande et al\textsuperscript{21} had to construct 2-dimensional panoramic-like images from 3-dimensional CBCT images to measure the angulation of the typodont teeth. They compared these measurements with those taken directly from a coordinate measuring machine, the gold standard coordinate measuring machine’s measurements for a few teeth. The coordinate measuring machine was also used in an earlier study by Garcia-Figueroa et al\textsuperscript{18} to show the effect of changing the faciolingual inclination of a few selected teeth on their mesiodistal angulation measurements. However, the gold standard coordinate measuring machine cannot be used on patients, since the tip of the machine’s probe cannot be brought in contact with the patients’ root apices.

We have collaborated with the Dolphin company (Chatsworth, Calif) and developed the University of Southern California (USC) root vector analysis program in the Dolphin 3D module to directly measure the mesiodistal angulation and the faciolingual inclination of each whole tooth using CBCT volumetric images. To test the validity of our methodology, we also collaborated with the research group from the University of Alberta, Edmonton, Alberta, Canada, who provided the typodont CBCT images and the coordinate measuring machine’s mesiodistal angulation measurement data for the typodont teeth to compare with our results.

**MATERIAL AND METHODS**

We measured the mesiodistal angulation of the typodont teeth with the coordinate measuring machine (Faro International, Lake Mary, Fla). The typodont was based on a modification of the model previously reported by McKee et al\textsuperscript{16} and Garcia-Figueroa et al.\textsuperscript{18} It consisted of transparent plastic anatomic typodont maxilla and mandible (Kilgore International, Coldwater, Mich) with synthetic teeth in idealized occlusion from the second molar to the second molar. As shown by Van Elslande et al,\textsuperscript{21} the typodont was mounted on a dry human skull. Stainless steel balls (Small Parts, Miramar, Fla), 1.58 mm in diameter, were placed at the approximate mesiodistal and faciolingual centers of the occlusal surfaces, and at the approximate centers of the root apices for single-rooted teeth or the centers of the bifurcation or trifurcation at the level of the root apices for multi-rooted teeth. A line connecting the 2 centers on each tooth represented its long axis.

The coordinate measuring machine was used to determine the actual mesiodistal angular measurement of each whole tooth with reference to the archwires that were held in place on the plastic molds of the maxilla and the mandible at approximately the middle of the roots. A mesiodistal plane was created for each tooth that was perpendicular to the horizontal (archwire) plane. This tooth-specific reference plane passed through the mesial and distal interproximal points marked on the archwires with crimpable stops. The
mesiodistal angulation of a tooth was the measurement of the angulation between the projection of the tooth’s long axis on the mesiodistal plane and the vertical line.

One investigator (D.V.E.) made repeated measurements on 5 separate occasions, 5 days apart, and the intraclass correlation coefficient values were calculated to determine the reliability of the coordinate measuring machine’s angulation measurements. The coordinate measuring machine was reported by the manufacturer to be accurate to within 0.013 mm. For angular measurements, the machine was found to be accurate to within 0.031°. The average of the 5-time repeated coordinate measuring machine’s angulation measurements were used as the true values.

The typodont teeth’s mesiodistal angulations and faciolingual inclinations were also measured by using the custom USC root vector analysis program. For the CBCT scan of the same typodont used above, a NewTom 3G volume scanner (AFP, Elmsford, NY) was used according to the manufacturer’s instructions as shown also by Van Elslande et al.21 Twenty-five independent images were obtained from separate CBCT scans for the previous study, and 5 of them were randomly selected and imported into the Dolphin Imaging 3D program. The USC root vector analysis program was developed in the Dolphin 3D module to measure both the mesiodistal angulation and the faciolingual inclination of each whole tooth as shown below.

Once the typodont digital imaging and communications in medicine (DICOM) data were imported into Dolphin 3D, a 3-dimensional global coordinate system was first generated for the proper orientation of the head and the maxillofacial structures. This coordinate system included the midsagittal plane, the coronal plane, and the axial plane, each perpendicular to the other 2 planes (Fig 1). The midsagittal plane evenly divided the right and left halves of the skull; the coronal plane passed through the maxillary first molar buccal grooves on both sides, and the axial plane was the archwire plane. Since the maxillary and mandibular teeth had separate archwire planes, there were also 2 separate 3-dimensional global coordinates: 1 saved for the maxilla, and 1 saved for the mandible.

The digitization of each tooth’s long axis was done in all 3 plane views, each perpendicular to the other 2 views. Parallel movements of the sagittal, coronal, and
axial planes were made so that each would pass through the center of the white stainless steel marker representing either the crown or the root point of each tooth (Figs 2 and 3). A red dot was digitized at the intersection of the 3 perpendicular planes in 1 of the 3 plane views; it would also appear automatically in the other 2 views. The order of digitization was from the maxillary right second molar to the maxillary left second molar, and from the mandibular left second molar to the mandibular right second molar. Figure 4 shows all the white stainless steel markers replaced by the red digitization points. The green lines represented the long axes of the teeth after the digitization was completed in both arches.

Next we digitized the archwires. For the maxillary arch, the global coordinate saved for the maxillary teeth was restored first, and the maxillary archwire was digitized in the axial plane view set at the archwire level (Fig 5). Four teeth on the right side were digitized along the archwire: midincisor, canine, second premolar, and second molar. The software program would add the mirror image of the right side half arch to the left side, constructing a symmetrical arch form. The mandibular archwire was digitized in the same way after the global coordinate saved for the mandibular arch was restored.

Then the tooth-specific coordinate system for the mesiodistal angulation and the faciolingual inclination measurements was set up. Once the arch form was digitized, the custom USC root vector analysis program would automatically construct another 3-plane coordinate system consisting of multiple coordinates, each specific for only 1 tooth for its mesiodistal angulation and faciolingual inclination measurements (Fig 5): the transverse plane was the same axial plane at either the maxillary or the mandibular archwire level as in the global coordinate system; the straight green line represented the faciolingual plane that passed through each tooth crown point (dark blue dot) and was perpendicular to the archwire; the short light blue line represented the mesiodistal plane that also passed through each tooth crown point, but was perpendicular to the faciolingual plane. The mesiodistal angulation and the faciolingual inclination were measured for each tooth in its corresponding tooth-specific coordinate.

As shown in Figure 6, A, the mesiodistal angulation was measured from the projection of the tooth’s long
axis on the mesiodistal plane to the vertical line formed by the intersection of the mesiodistal and faciolingual planes. If the root center was distal to the crown center, the measurement would be positive; otherwise, it would be negative. The faciolingual inclination was measured from the projection of the tooth’s long axis on the faciolingual plane to the vertical line formed by the same intersection of the mesiodistal and faciolingual planes (Fig 6, B). If the root center was lingual to the crown center, the measurement would be positive; otherwise, it would be negative.

At this point, the custom USC root vector analysis program would use algorithms to measure the mesiodistal angulation and the faciolingual inclination values for all teeth automatically.

Teeth with known mesiodistal angulation and faciolingual inclination values were measured. The same 5 typodont images above were used again, except that the root points of the maxillary right first molar and first premolar, the maxillary left central incisor and second molar, the mandibular right second molar and canine, and the mandibular left lateral incisor and first molar were not digitized at the stainless steel balls representing

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was rotated so that for the tooth to be digitized, the faciolingual direction was shown vertically and the mesiodistal direction was shown horizontally; (2) in the mesiodistal (Fig 7, B) or faciolingual (Fig 7, C) slice view, the transverse plane at the crown point level was moved 20 mm apically; and (3) in the mesiodistal slice view (Fig 7, B), the faciolingual plane was moved 5 mm distally, and in the faciolingual slice view (Fig 7, C), the mesiodistal plane was moved 10 mm lingually. After these parallel movements of the reference planes, the 3-plane intersection would be at a point that was 20 mm apical, 10 mm lingual, and 5 mm distal from the crown point. The root point was digitized at this intersection. Trigonometric calculation should give the tooth 14.04° of mesiodistal angulation and 26.57° of faciolingual inclination. For the maxillary right first molar and the mandibular left lateral incisor, the root points were placed mesially instead of distally to reflect their distal angulation; for the 2 mandibular molars, the root points were placed buccally instead of lingually to reflect their lingual crown inclinations.

**Statistical analysis**

To ensure that the measurement methodology described above was reliable, the principal investigator (H.T.) randomly chose 5 images from the 25 independent scans of the same typodont obtained from the University of Alberta. Digitizations were done a week apart, and intraclass correlation coefficients for the mesiodistal angulation and faciolingual inclination measurements were calculated.

One-sample t tests were used to check for statistically significant differences between our 5-time repeated mesiodistal angulation measurements and the coordinate measuring machine’s true mesiodistal angulation values for each tooth. The α level was adjusted to 0.05/28 = 0.001786 for the multiple t tests based on the Bonferroni adjustment. One-sample t tests were also used to compare the 5-time repeated mesiodistal angulation and faciolingual inclination measurements with the given mesiodistal angulation and faciolingual inclination values for each of the 8 selected teeth. The α level was adjusted to 0.05/8 = 0.00625.

**RESULTS**

The intraclass correlation coefficients for the 5-time repeated mesiodistal angulation and faciolingual inclination measurements with our USC root vector analysis in Dolphin 3D were 0.998 and 1.000, respectively, with 95% confidence intervals of 0.996 to 0.999 for the angulations, and 0.999 to 1.000 for the inclinations. The intraclass correlation coefficient for the 5 repeated angulation measurements with the coordinate measuring machine was 0.995 with a 95% CI of 0.991 to 0.997.

Differences between our angulation measurements and the coordinate measuring machine’s true angulation values were calculated, and the 5-time mean differences, the standard deviations of the mean differences, and the 95% confidence intervals are shown in Table I, along with the P values from the 1-sample t test for each tooth. Five teeth (maxillary right lateral incisor and canine, maxillary left first premolar, and mandibular left canine and first premolar) of the 28 teeth showed statistically significant differences between our angulation measurements and the coordinate measuring machine’s true values. The mean differences of our 5-time measurements from the coordinate measuring machine’s true values and the 95% confidence intervals for these teeth were the following: maxillary right lateral incisor, 2.15° (95% CI, 1.439°-2.861°); maxillary right canine, 0.876° (95% CI, 0.585°-1.168°); maxillary left first premolar, 1.098° (95% CI, 0.914°-1.282°); mandibular left canine, 1.97° (95% CI, 1.486°-2.454°); and mandibular left first premolar, 1.286° (95% CI, 0.97°-1.603°). However, only the maxillary right lateral incisor measurement might be close to 2.5° for clinical significance. Faciolingual inclination measurements were not made with the coordinate measuring machine.
For the teeth with known mesiodistal angulation and faciolingual inclination values, measurements were also done 5 times, and the intraclass correlation coefficient was 1 for both the angulation and the inclination. Differences between measured values and the known values were calculated, and the 5-time mean differences, standard deviations of the mean differences, and 95% confidence intervals are shown in Table II, along with the P values from the 1-sample t test for each tooth. None of the 8 teeth for both angulation and inclination showed any statistically significant difference between the measured and the known values. None of the teeth had a 95% confidence interval above 1°.

DISCUSSION

High-quality orthodontic treatment requires that all teeth are placed in their proper positions for a stable and functional occlusion and an esthetic appearance after treatment. The focus of the specialty of orthodontics has been mostly on the positions of the crowns of teeth, and little attention has been given to the roots.5-8 This is because the positions of the roots rarely pose esthetic or functional problems, since they are mostly invisible and away from the occlusal contacts. Although the correct positioning of the roots in the basal bone might reduce the amount of relapse, however, research has indicated that long-term stability cannot be expected even with high-quality orthodontic finishing.22-25 Even a naturally occurring normal occlusion might not be maintained for life.26 However, orthodontists still strive to obtain proper root positions for the best treatment outcome. Since the use of preadjusted appliances does not guarantee ideal root positions, most orthodontists take initial, progress, and final panoramic radiographs to check for root alignment in addition to checking for pathology. This is because minor crown tipping that might have evaded visual inspection can be magnified in the misalignment of the roots and become easily detectable.13,14

Until just recently, there have been only a few radiographic methods to check root position, each with some problems. To measure the mesiodistal angulation of each tooth accurately, the x-ray beam must be aimed at the target tooth orthogonally. Periapical radiographs cannot be taken with an orthogonal view of multiple teeth on a curved dental arch at the same time. Panoramic x-rays, although designed to follow the curvature of the dental arch, might show orthogonal images of only a few teeth.27 Various studies have indicated its limitations, especially in the canine and first premolar areas.16-18 However, the American Board of Orthodontics still recommends the use of panoramic x-rays in assessing the angulation of the roots.28 General root parallelism is required, and points are deducted if the roots of adjacent teeth are not parallel or come in contact with one another. Exceptions have been made for the canine areas recently.

Fig 6. A. Mesiodistal angulation was measured in the mesiodistal plane and defined as the angle formed by the projection of the tooth’s long axis (green line) and the red line that represented the faciolingual plane and the mesiodistal plane intersection; B, faciolingual inclination was measured in the faciolingual plane and defined as the angle formed by the projection of the tooth’s long axis (short green line) and the long green line that represented the mesiodistal plane and the faciolingual plane intersection. The blue line in A and B represented transverse planes that were parallel to the occlusal plane.
The American Board of Orthodontics does not have special requirements for the faciolingual inclination of the roots. The assessments of the root or the whole tooth angulation and inclination really require that we see the whole tooth in 3 dimensions. A coordinate measuring machine has been used to measure the angulation and the inclination of typodont teeth directly. Although considered a gold standard 3-dimensional measuring device, the coordinate measuring machine cannot be used on patients clinically, since direct contact of the root apices of the patients’ teeth by the machine’s probe is not possible. In recent years, CBCT technology has been used in orthodontics, and the volumetric images obtained from CBCT scans have been shown to display dentofacial structures in a 1:1 ratio, and distortions, if any, are clinically insignificant. Van Elslande et al measured the angulation of the typodont teeth from the panoramic-like images constructed from CBCT scans and compared them with the coordinate measuring machine’s measurements. It was concluded that the constructed panoramic-like images were more accurate than the conventional panoramic radiographs in assessing tooth angulation. Although this new technique takes care of the nonorthogonal problem of the conventional panoramic radiograph, other problems arise: image formation is 1:1 only at the center of the selected arch trough, structures lingual to the center
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Table I. Comparison between the USC mesiodistal angulation measurements and the coordinate measuring machine’s true values of the typodont teeth

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Mean difference (°)</th>
<th>SD</th>
<th>95% CI (upper and lower)</th>
<th>P value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>UR 1</td>
<td>0.309</td>
<td>0.691</td>
<td>−0.548 to 1.167</td>
<td>0.373</td>
</tr>
<tr>
<td>UR 2</td>
<td>−2.150</td>
<td>0.573</td>
<td>−2.861 to −1.439</td>
<td>0.001*</td>
</tr>
<tr>
<td>UR 3</td>
<td>−0.876</td>
<td>0.235</td>
<td>−1.168 to −0.585</td>
<td>0.001*</td>
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<tr>
<td>UR 4</td>
<td>0.339</td>
<td>0.300</td>
<td>−0.034 to 0.711</td>
<td>0.065</td>
</tr>
<tr>
<td>UR 5</td>
<td>0.677</td>
<td>0.647</td>
<td>−0.126 to 1.480</td>
<td>0.079</td>
</tr>
<tr>
<td>UR 6</td>
<td>0.455</td>
<td>0.295</td>
<td>0.088 to 0.821</td>
<td>0.026</td>
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<tr>
<td>UR 7</td>
<td>−0.667</td>
<td>0.336</td>
<td>−1.084 to −0.249</td>
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<tr>
<td>LL 1</td>
<td>0.733</td>
<td>0.618</td>
<td>−0.035 to 1.500</td>
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</tr>
<tr>
<td>LL 2</td>
<td>0.365</td>
<td>0.730</td>
<td>−0.541 to 1.272</td>
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<tr>
<td>LL 3</td>
<td>−0.572</td>
<td>0.377</td>
<td>−1.040 to −0.027</td>
<td>0.027</td>
</tr>
<tr>
<td>LL 4</td>
<td>1.098</td>
<td>0.198</td>
<td>0.914 to 1.282</td>
<td>&lt;0.001</td>
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<tr>
<td>LL 5</td>
<td>0.112</td>
<td>0.321</td>
<td>−0.287 to 0.510</td>
<td>0.479</td>
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<tr>
<td>LL 6</td>
<td>0.571</td>
<td>0.379</td>
<td>0.078 to 1.065</td>
<td>0.032</td>
</tr>
<tr>
<td>LL 7</td>
<td>−0.457</td>
<td>0.313</td>
<td>−0.846 to −0.069</td>
<td>0.031</td>
</tr>
<tr>
<td>LR 1</td>
<td>−0.295</td>
<td>0.415</td>
<td>−0.810 to 0.220</td>
<td>0.187</td>
</tr>
<tr>
<td>LR 2</td>
<td>−1.300</td>
<td>0.650</td>
<td>−2.107 to −0.494</td>
<td>0.011</td>
</tr>
<tr>
<td>LR 3</td>
<td>−1.356</td>
<td>0.432</td>
<td>−1.893 to −0.819</td>
<td>0.002</td>
</tr>
<tr>
<td>LR 4</td>
<td>1.018</td>
<td>0.390</td>
<td>0.534 to 1.502</td>
<td>0.004</td>
</tr>
<tr>
<td>LR 5</td>
<td>−0.045</td>
<td>0.311</td>
<td>−0.431 to 0.342</td>
<td>0.764</td>
</tr>
<tr>
<td>LR 6</td>
<td>−0.484</td>
<td>0.329</td>
<td>−0.892 to −0.076</td>
<td>0.030</td>
</tr>
<tr>
<td>LR 7</td>
<td>−0.247</td>
<td>0.540</td>
<td>−0.918 to 0.424</td>
<td>0.365</td>
</tr>
<tr>
<td>LL 1</td>
<td>0.216</td>
<td>0.374</td>
<td>−0.249 to 0.681</td>
<td>0.266</td>
</tr>
<tr>
<td>LL 2</td>
<td>−0.819</td>
<td>0.901</td>
<td>−1.938 to 0.300</td>
<td>0.112</td>
</tr>
<tr>
<td>LL 3</td>
<td>−1.970</td>
<td>0.390</td>
<td>−2.454 to −1.486</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LL 4</td>
<td>−1.286</td>
<td>0.255</td>
<td>−1.603 to −0.970</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LL 5</td>
<td>0.023</td>
<td>0.500</td>
<td>−0.598 to 0.644</td>
<td>0.924</td>
</tr>
<tr>
<td>LL 6</td>
<td>−0.407</td>
<td>0.396</td>
<td>−0.899 to 0.085</td>
<td>0.083</td>
</tr>
<tr>
<td>LL 7</td>
<td>0.144</td>
<td>0.606</td>
<td>−0.608 to 0.896</td>
<td>0.623</td>
</tr>
</tbody>
</table>

U, Upper (maxillary); L, lower (mandibular); R, right; L, left; 1, central incisor; 2, lateral incisor; 3, canine; 4, first premolar; 5, second premolar; 6, first molar; 7, second molar.

*One-sample t test: level of α = 0.05/28 = 0.001786 (Bonferroni adjustment for multiple comparisons).

Table II. Comparison between the USC mesiodistal angulation and faciolingual inclination measurements and the known values of the typodont teeth

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Mean difference (°)</th>
<th>SD</th>
<th>95% CI (upper and lower)</th>
<th>P value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>UR 4</td>
<td>−0.16</td>
<td>0.335</td>
<td>−0.576 to 0.256</td>
<td>0.345</td>
</tr>
<tr>
<td>UR 6</td>
<td>0.40</td>
<td>0.344</td>
<td>−0.027 to 0.827</td>
<td>0.060</td>
</tr>
<tr>
<td>UL 1</td>
<td>−0.46</td>
<td>0.370</td>
<td>−0.920 to 0.000</td>
<td>0.050</td>
</tr>
<tr>
<td>UL 5</td>
<td>−0.32</td>
<td>0.396</td>
<td>−0.812 to 0.172</td>
<td>0.145</td>
</tr>
<tr>
<td>LR 3</td>
<td>0.04</td>
<td>0.356</td>
<td>−0.403 to 0.483</td>
<td>0.814</td>
</tr>
<tr>
<td>LR 7</td>
<td>0.32</td>
<td>0.270</td>
<td>−0.016 to 0.656</td>
<td>0.057</td>
</tr>
<tr>
<td>LL 2</td>
<td>−0.08</td>
<td>0.217</td>
<td>−0.349 to 0.189</td>
<td>0.456</td>
</tr>
<tr>
<td>LL 6</td>
<td>−0.08</td>
<td>0.270</td>
<td>−0.416 to 0.256</td>
<td>0.544</td>
</tr>
</tbody>
</table>

U, Upper (maxillary); L, lower (mandibular); R, right; L, left; 1, central incisor; 2, lateral incisor; 3, canine; 4, first premolar; 5, second premolar; 6, first molar; 7, second molar.

*One-sample t test: level of α = 0.05/8 = 0.00625 (Bonferroni adjustment for multiple comparisons).

even though minor but statistically significant differences existed for some teeth between our measurements and those of the machine. We were unable to explain these differences, which appeared almost randomly and never happened in the same teeth on the contralateral side. Our measurements of selected typodont teeth with known angulation and inclination values were also highly accurate. A number of factors might have contributed to this high precision in our methodology. Taking orthogonal views of the teeth and digitization of the crown and root points at the intersection of 3 perpendicular planes simultaneously helped to ensure precision; the special algorithms used to set up the tooth-specific coordinate system for automatic measurements was another way to reduce human errors to a minimum. Our study showed that the reliability and the accuracy of our program were comparable to those of the coordinate measuring machine’s gold standard.

This new tool can be used to measure the mesiodistal angulation and the faciolingual inclination of each whole tooth in patients with normal occlusion, an important step toward establishing a clinical standard that could provide guidance for orthodontic finishing. Such standards might be helpful in designing new orthodontic appliances that will no longer ignore the roots. Some new treatment systems such as Invisalign (Align Technology, San Jose, Calif), SureSmile (Orametrix, Richardson, Tex),
Incognito (3M-Unitek, Monrovia, Calif), and Insignia (Ormco, Orange, Calif) might benefit from this as well by being root conscious while setting up the teeth virtually before treatment. In addition, this new tool can also be used to compare the outcomes of various treatment modalities: eg, surgical treatment vs camouflage, and extraction vs nonextraction. We can also compare the norms of different ethnic groups to set ethnic-specific goals for patients with different backgrounds.

Our custom program has certain limitations. It cannot be used for patients with malocclusions, since setting up the global coordinate system and digitization of the maxillary and mandibular dental arches require the subjects to have normal or near normal occlusions. Modifications to the program might need to be made if malocclusions, especially asymmetries, are present. Another potential limitation might be that the 3-dimensional image quality of the patients’ teeth is not as good as those of the stainless steel balls used in this typodont study because of more complicated overlapping of structures, restorations, patient movement, and so on. Radiation safety should always be a concern. Exposing patients even to a slightly elevated amount of radiation might be justified only if its use leads to better treatment; this still remains to be seen. However, the newer generation of CBCT devices has already shown promising improvement in image resolution with reduced radiation.

CONCLUSIONS

We developed the custom USC root vector analysis program to measure the mesiodistal angulation and the faciolingual inclination of each whole tooth from a typodont.

1. Measurements made with the USC root vector analysis program compared well with the gold standard of the coordinate measuring machine’s measurements.
2. The USC root vector analysis program could also measure accurately the teeth with known values of angulation and inclination.
3. The USC root vector analysis program is valid and can be applied to patients clinically.

We thank Swann Liao for writing the custom USC root vector analysis program, Carlos Flores-Mir for a critical review of this article, and Victoria Rodriguez for assistance with CBCT.

REFERENCES