Accuracy of cone-beam computed tomography in predicting the diameter of unerupted teeth

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Introduction: An accurate prediction of the mesiodistal diameter (MDD) of the erupting permanent teeth is essential in orthodontic diagnosis and treatment planning during the mixed dentition period. Our objective was to test the accuracy and reproducibility of cone-beam computed tomography (CBCT) in predicting the MDD of unerupted teeth. Our secondary objective was to determine the accuracy and reproducibility of 3 viewing methods by using 2 CBCT software programs, InVivoDental (version 4.0; Anatomage, San Jose, Calif) and CBWorks (version 3.0, CyberMed, Seoul, Korea) in measuring the MDD of teeth in models simulating unerupted teeth. Methods: CBCT data were collected on the CB MercuRay (Hitachi Medical Corporation, Tokyo, Japan). Models of unerupted teeth (n = 25), created by embedding 25 tooth samples into a polydimethylsiloxane polymer with a similar density to tissues surrounding teeth, were scanned and measured by 2 investigators. Repeated MDD measurements of each sample were made by using 3 CBCT viewing methods: InVivo Section, InVivo Volume Render (both Anatomage), and CBWorks Volume Render (version 3.0, CyberMed). These measurements were then compared with the MDD physically measured by digital calipers before the teeth were embedded and scanned. Results: All 3 of the new methods had mean measurements that were statistically significantly less (P < 0.0001) than the physical method, adjusting for investigator and tooth effects. Specifically, InVivo Section measurements were 0.3 mm (95% CI, −0.4 to −0.2) less than the measurements with calipers, InVivo Volume Render measurements were 0.5 mm less (95% CI, −0.6 to −0.4) than those with calipers, and CBWorks Volume Render measurements were 0.4 mm less (95% CI, −0.4 to −0.3) than those with calipers. Conclusions: Overall, there were high correlation values among the 3 viewing methods, indicating that CBCT can be used to measure the MDD of unerupted teeth. The InVivo Section method had the greatest correlation with the calipers. (Am J Orthod Dentofacial Orthop 2011;140:e59-e66)

An essential factor in orthodontic diagnosis and treatment planning is the ability to predict the size of unerupted teeth during the mixed dentition period. An accurate prediction of the mesiodistal diameter (MDD) of the erupting permanent teeth will help to determine whether there will be sufficient space for the permanent teeth to erupt unimpeded and properly aligned in their respective arches. In particular, it is necessary to predict the MDD of the crowns of the unerupted canines and premolars (C, P1, and P2). A previous study comparing the MDD of deciduous canines and molars to their permanent successors found that permanent canines are significantly broader and permanent premolars are smaller than their predecessors. Overall, the sum of the crown widths of these permanent teeth has been reported to be lower than that of their deciduous predecessors. A discrepancy between the space required for the dentition and the space available in the dental arch will result in excessive spacing or crowding. Hence, an accurate estimate of the sum of crown widths vs available space is necessary for making competent decisions concerning eruption guidance, serial extractions, space maintenance, space regaining, and other options in orthodontic treatment planning.

Different methods for estimating the sizes of unerupted teeth have been developed. In the literature, 4 groups of methods are commonly used to predict the MDD of the permanent C, P1, and P2 before eruption: analyses based on mean values of the C, P1, and P2 by using established tables of average tooth sizes; regression equations based on high linear correlations between relevant groups of teeth; measurements of the unerupted teeth taken directly from radiographs; and analyses with a combination of regression equations and radiographic methods.
Numerous studies have been conducted to compare the accuracy of various methods of predicting the MDD of the C, P1, and P2. Despite the diversity and numbers of available methods, no single method has been shown to deliver high accuracy, precision, and reliability; all have limitations. For example, a study comparing 8 commonly used regression methods found that prediction methods either overestimated (Legovic and Hautz, Droschl et al., Tanaka and Johnston, and Moyers) or underestimated (Bachmann, Trankmann et al., and Gross and Hasund) the sums of crown widths of the C, P1, and P2. Gardner compared 4 methods (Nance, Tanaka and Johnston, Moyers, and Hixon and Oldfather) and also found that the methods either overestimated or underestimated the crown widths of the canines and the premolars. Another significant limitation of existing regression methods is their inability to be applied universally when variations occur between populations. Some methods are less reliable for female patients, raising the question of sex variations.

There is a clear need for a highly accurate and reliable method for predicting the crown widths of unerupted permanent canines and premolars for orthodontic purposes. In this study, we examined whether a significant diagnostic advancement in clinical diagnosis, cone-beam computed tomography (CBCT), can be used to provide accurate and reliable measurements of simulated unerupted teeth. We hypothesized that images from CBCT will provide accurate and reliable linear measurements of MDD and eliminate limitations based on individual variations. Support for this hypothesis is provided by the following factors.

1. CBCT allows an area of interest to be observed from many angles.
2. In addition to advanced image reconstruction algorithms, the subject can be reconstructed in 3 dimensions at high resolution. These images are precise in locating and measuring the desired details.
3. Few studies have shown distortion and errors across the scan volumes produced by CBCT.
4. Furthermore, a study indicated that segmented volumes of craniofacial structures from CBCT data are accurate model representations of the objects with respect to linear measurements.

Numerous studies have been performed to assess the applications and benefits of CBCT (including treatment planning in dental implant and airway studies). Although the accuracy and reliability of linear dental measurements on CBCT have been well assessed, no one, to the best of our knowledge, has studied the accuracy and reliability of CBCT in predicting the size of unerupted teeth. The primary aim of this study was to investigate the accuracy of the MDD of the C, P1, and P2 measured by using CBCT scans compared with physical measurements from digital calipers, which is the current gold standard.

Our secondary aim was to compare the accuracy and reproducibility of 2 CBCT software programs, InVivo Dental and CBWorks (version 3.0; CyberMed, Seoul, Korea), in measuring the MDD of teeth in models simulating unerupted teeth.

**MATERIAL AND METHODS**

Twenty-five extracted teeth (11 premolars, 14 molars) were selected. Two investigators (E.N. and M.O.) first measured each tooth’s MDD using digital calipers (Mitutoyo Canada, Toronto, Ontario, Canada) with a nominal resolution of ±0.01 mm. The measurement with calipers is a physical measurement and was considered the gold standard for the purpose of this study. Each investigator recorded measurements made at 3 times to allow calculation of arithmetic means and associated errors. The measurement sessions were 1 week apart.

All 25 teeth were embedded in Aquasil Easy Mix Putty (Dentsply, Des Plaines, Ill), simulating the supporting structures of the teeth in the dental arches. Aquasil is a hydrophilic addition-reaction silicone impression material composed of polydimethylsiloxane polymer, calcium sulfate, silicon dioxide, polymethylhydrogen silicone, surfactant, plasticizer, and pigments. It has a density of 250 to 600 Hounsfield units (HU); this is similar to the density of the supporting dental tissues (bone and soft tissues, 200-700 HU). Tooth enamel, with a density of approximately 2100 to 4000 HU, can be easily discriminated from the surrounding tissues in the CBCT images. The rigidity of Aquasil allowed for retention of the teeth and prevented movement.

The dental arch models were scanned by using the CB MercuRay scanner with these settings is 0.4 mm, and the physical spatial resolution is 0.7 mm. The volumetric data were then analyzed with the 2 CBCT software programs, InVivo Dental and CBWorks. Two measurement methods were used with the InVivo Dental software and 1 method with CBWorks, each described below. Two investigators measured 25 teeth at 3 times using each of the 4 methods: physical measurement, InVivo Section, InVivo Volume Render, and CBWorks Volume Render.

With InVivo Dental, 2 analyzing modes were used as methods of measuring the MDD of the embedded teeth: the Section mode and the Volume Render mode.
In the InVivo Section mode, the x, y, and z sections (axial, coronal, sagittal) were combined simultaneously for 2-dimensional visualization. A 3-dimensional (3D) volume visualization was displayed on the same screen as the 2-dimensional visualization. In this mode, the scalar value of selected voxels is displayed in Hounsfield units; this allows soft tissue to be distinguished from enamel when taking measurements with the “Distance” tool. By using the 2-dimensional and 3D visualizations simultaneously, the image of each tooth of interest was oriented perpendicular to the occlusal plane to allow the largest MDD to be visualized and measured (with measurements recorded to the nearest 0.1 mm) (Fig 1).

With the InVivo Volume Render mode, it is possible for the scanned region to be reconstructed 3 dimensionally. This mode has presets that allow for the display of structures according to their specified densities. For this study, it was determined that the “Bone” and “Teeth” presets would be used because they allowed visualization of the hard tissues (embedded teeth) but prevented visualization of the surrounding impression material. We then used the “Sculpting” tool in the Volume Render mode to allow the image of each tooth requiring measurement to be segregated from the surrounding tissues and adjacent teeth. Finally, the “Measure 3D Distance” tool in the software was used to measure the MDD from the 3D image, with measurements recorded to the nearest 0.1 mm (Fig 2).

In CBWorks, the Volume Render mode was used to measure the MDD in this study. This mode creates a 3D image (volume-rendering image) from the volumetric data. A histogram in CBWorks’ on-screen control panel was used to adjust the images for optimal opacity. Similar to InVivo, each tooth of interest was then “sculpted out” for individual display with the “Sculpt” tool, and MDD measurements for each tooth were recorded to the nearest 0.1 mm with the “Measuring” tool (Fig 3).

RESULTS

For each of the 3 CBCT methods and the physical method, the reproducibility of all measurements was first determined. For each investigator and each method, data were analyzed by using 1-way analysis of variance (ANOVA) with tooth as the fixed effect. The intraclass correlation (ICC) was also calculated. The ICC values ranged from 0 to 1. Values close to 1 indicate strong evidence of reproducibility. The results are displayed in Table I. For both 2 users, all 4 methods yielded an ICC greater than 0.95, indicating high reproducibility for any user of any of the 4 methods.

We then determined the reproducibility (or agreement) of values recorded by each investigator for each CBCT method and the physical method. An arithmetic mean of the 3 measurements made by each investigator on each tooth using each method was calculated. Then, the correlation coefficient (r) comparing the means of
the 2 investigators for each method was determined. A correlation coefficient can range from 0 (no agreement) to 1 (perfect agreement). Of the 3 CBCT methods, the greatest agreement was obtained with the CBWorks Volume Render method, with a correlation of 0.97 (95% CI, 0.94 to 0.99), and the least agreement with the InVivo Volume Render method, with a correlation of 0.91 (95% CI, 0.80 to 0.96). The results are shown in Table II.

The third goal was to determine the discrepancies between the measurements taken with each of the 3 CBCT methods and the physical method. An arithmetic mean of the 6 measurements taken by the 2 investigators for each tooth using each of the 3 CBCT methods was calculated. Correlation coefficients, relating the mean value for each CBCT method to the mean value for the physical method, were then determined. The InVivo Section method had the highest correlation (0.98) with the physical method. The results are displayed in Table III.

Any 2 methods that are designed to measure the same parameter—in this case, tooth MDD—will have good correlation when a set of samples is chosen so that the property to be determined has much variation between them; thus, Bland-Altman plots were created because a high correlation does not automatically imply good agreement between the 2 methods. Bland-Altman plots show the difference against the average measurements for a particular CBCT method and physical method. The average difference is interpreted as the bias. The farther away from zero, the greater the amount of bias, meaning that the methods are producing different results. The standard deviation values on the plot are used to calculate the limits of agreement for each method. Overall, each CBCT method underestimated the MDD compared with the physical measurements. Figure 4 shows the Bland-Altman plots comparing each CBCT method with the physical method.

To further assess how close the measurements made by each CBCT method were to the standard measurements, a mixed model was fit to the measurement data, with method and investigator as the fixed effects and tooth as the random effect. All 3 methods had mean measurements that were statistically significantly less ($P < 0.0001$) than the physical method, adjusting for investigator and tooth effects. Specifically, InVivo Sections View measurements were 0.3 mm (95% CI, −0.4 to −0.2) less than the physical measurements, InVivo Volume measurements were 0.5 mm less (95% CI, −0.6 to −0.4) than the physical measurements, and CBWorks Volume measurements were 0.4 mm less (95% CI, −0.4 to −0.3) than the physical measurements. This mixed model also gave the overall estimated mean difference between investigators 1 and 2 as −0.2 mm ($P < 0.0001$), adjusting for method (fixed effect) and tooth (random effect). The results are given in Table IV.

The amount of variability that each factor in the model contributed to the measurements was also estimated. The estimated variances for measurements made by 1 investigator for all methods were 0.2% and 0.3%, statistically significantly greater than zero ($P < 0.0001$). This means that less than 1% of the variability in measurements was attributable to conditions inherent in the measurement process, regardless of method, tooth, or user. The estimated variances between users were 4.4% and 8%, a statistically significant source of variation in measurement ($P < 0.0001$). In other words, 8% of the variability in measurements was attributable to operator differences.

**DISCUSSION**

Previous studies have shown that all the classic methods of predicting the crown widths of the C, P1, and P2 have limitations. Some tend to overestimate...
(Moyers, Tanaka and Johnston, Droschl et al, and Legovic and Hautz), and others underestimate their predictions (Gross and Hasund, Bachmann, and Trankmann et al). In this study, we assessed the accuracy of measurements of MDD of the C, P1, and P2 taken from CBCT images (using 3 methods) compared with the true anatomic dimensions of teeth in models simulating unerupted teeth. We also determined

Fig 3. A CBCT CBWorks view.
the accuracy and reproducibility of using 2 CBCT software programs, InVivoDental and CBWorks, in measuring the MDD of teeth in models simulating unerupted teeth.

Although Aquasil Easy Mix Putty and the supporting structures of teeth have similar radiographic densities, there are variations in the density of the supporting structures (particularly alveolar bone) that do not exist in the putty because of its macroscopic structure.31

In addition, a concern that arises with the use of the CB MercuRay scanner is the radiation dose. The radiation dose generated by the MercuRay during image acquisition is several times greater than that generated when taking a conventional panoramic radiograph.32 Although it is possible to reduce the level of exposure by adjusting the scanner settings or using other scanners that emit less radiation, doing so would result in a loss of physical spatial resolution in the images produced and a greater possibility of errors in the measurements.31

We first determined the reproducibility of each of the 3 CBCT methods. The ICC results showed high correlations (all, >0.95) between multiple measurements by the same investigator. This indicates that an investigator using any CBCT method or the physical method can adequately reproduce the measurements. After determining that an investigator can replicate his or her findings, the agreement between investigators was determined. Each of the 3 CBCT methods yielded Pearson correlation coefficients greater than 0.91, indicating a high agreement between values measured by different investigators. These results are important in concluding that the tools are usable and reliable across several users.

The results showed that the CBCT methods have a high degree of accuracy in predicting the true MDD of a tooth (determined by the arithmetic mean of the physical measurements). The InVivo Section method yielded the highest correlation with the physical method and the least amount of bias as determined in the Bland-Altman mean-difference plot with the smallest limits of agreement. In other words, it yielded the results closest to the true MDD values as well as the least amounts of variation and bias. All 3 CBCT methods yielded high correlation values against the true MDD measurements (>.90) and, on average, had a bias of −0.4 mm, meaning that CBCT methods tended to undermeasure a tooth’s MDD by 0.4 mm. Although the results were statistically significant, this does not necessarily imply that a bias of −0.4 is great enough to be clinically significant.

The methods of predicting the crown widths of the C, P1, and P2 have been examined and compared in several studies, which have shown that each method has limitations.2 For example, a frequently used method, that of Moyers,10 tended to overpredict values of MDD of the C, P1, and P2 in various populations. Also, Moyers’s method has been demonstrated to be less reliable for female patients than for male patients.2 Yet another limitation is exemplified by a study by Nourallah et al21 in which Tanaka and Johnston’s method was modified to assess a population comprising solely Syrian patients between 14 and 22 years of age. Although Tanaka and Johnston’s tables, approximations, and equations were modified by the authors, the results of that study might not apply to any other population. A significant advantage of using CBCT is that a clinician can directly measure the MDD of a specific patient, thereby eliminating discrepancies related to population variations that affect methods with regression equations. Relative to all previous methods, the 3 CBCT methods used in this study show greater correlations (0.91-0.98) with the actual MDD of the C, P1, and P2. By comparison, Legovic et al2 studied 8 methods and found that “the method of Tanaka and Johnston proved to be the most reliable with correlations between 0.54 and 0.77,” although the predicted values were generally higher than the measured values. Legovic et al also found that “Bachmann’s method showed the highest correlations for both the maxilla and mandible for males and in the maxilla for females.” Correlations ranged between 0.51 and 0.81, similar to those for the Tanaka and Johnston method. However, predicted values tended to be lower than actual values for the Bachmann method.2

Of all current methods of predicting crown widths, it appears that the CBCT method eliminates population variations, since measurements are made individually as opposed to regression models or tables of average tooth sizes that might not be valid for certain populations.

Because of the favorable results of this study, we noted that each of the 3 CBCT methods used to assess the MDD of the C, P1, and P2 required some training and expenditure of time that might not be desirable for many practitioners. As CBCT becomes more widely used in orthodontic clinics, perhaps CBCT software

### Table I. Reproducibility of measurements of each user for each method

<table>
<thead>
<tr>
<th>Method</th>
<th>Investigator</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>InVivo Section</td>
<td>1</td>
<td>0.98</td>
</tr>
<tr>
<td>InVivo Volume Render</td>
<td>1</td>
<td>0.98</td>
</tr>
<tr>
<td>CBWorks Volume Render</td>
<td>1</td>
<td>0.95</td>
</tr>
<tr>
<td>Physical (calipers)</td>
<td>1</td>
<td>0.99</td>
</tr>
<tr>
<td>InVivo Section</td>
<td>2</td>
<td>0.98</td>
</tr>
<tr>
<td>InVivo Volume Render</td>
<td>2</td>
<td>0.98</td>
</tr>
<tr>
<td>CBWorks Volume Render</td>
<td>2</td>
<td>0.97</td>
</tr>
<tr>
<td>Physical (calipers)</td>
<td>2</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Although Aquasil Easy Mix Putty and the supporting structures of teeth have similar radiographic densities, there are variations in the density of the supporting structures (particularly alveolar bone) that do not exist in the putty because of its macroscopic structure.31
programs will be modified to provide more user-friendly tools for clinicians to quickly and accurately assess these important dimensions.

Although this study demonstrates a promising method of accurately measuring the MDD of unerupted teeth, it has yet to be determined whether the added precision of this method over the alternatives discussed would justify exposing a patient to radiation solely for this purpose.

**CONCLUSIONS**

CBCT can be used to measure the MDD of unerupted teeth in orthodontic patients with smaller errors than any other method to date.

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**Table II.** Pearson correlations indicating agreement between investigators 1 and 2 for each CBCT and physical method

<table>
<thead>
<tr>
<th>Investigator 1 Method</th>
<th>Investigator 2 Method</th>
<th>n</th>
<th>Pearson correlation</th>
<th>Pearson 95% CI lower</th>
<th>Pearson 95% CI upper</th>
<th>Pearson P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>InVivo Section view method</td>
<td>Mean, measure 1</td>
<td>25</td>
<td>0.96</td>
<td>0.92</td>
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<td>0.91</td>
<td>0.80</td>
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</tr>
<tr>
<td>InVivo Volume Render method</td>
<td>Mean, measure 1</td>
<td>25</td>
<td>0.91</td>
<td>0.80</td>
<td>0.96</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Mean, measure 2</td>
<td>25</td>
<td>0.97</td>
<td>0.94</td>
<td>0.99</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>CBWorks Volume Render method</td>
<td>Mean, measure 1</td>
<td>25</td>
<td>0.97</td>
<td>0.94</td>
<td>0.99</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Mean, measure 2</td>
<td>25</td>
<td>0.99</td>
<td>0.98</td>
<td>1.00</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Physical method (calipers)</td>
<td>Mean, measure 1</td>
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<td>0.99</td>
<td>0.98</td>
<td>1.00</td>
<td>&lt;0.0001</td>
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**Table III.** Pearson correlation showing agreement between the CBCT methods and the physical method

<table>
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<tr>
<th>IVar</th>
<th>JVar</th>
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<th>Pearson correlation</th>
<th>Pearson 95% CI lower</th>
<th>Pearson 95% CI upper</th>
<th>Pearson P value</th>
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<tr>
<td>Physical</td>
<td>CBWorks Volume Render</td>
<td>25</td>
<td>0.94</td>
<td>0.87</td>
<td>0.97</td>
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</tr>
<tr>
<td>Physical</td>
<td>InVivo Sections view</td>
<td>25</td>
<td>0.98</td>
<td>0.96</td>
<td>0.99</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Physical</td>
<td>InVivo Volume Render</td>
<td>25</td>
<td>0.97</td>
<td>0.93</td>
<td>0.99</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

*IVar, I variable, JVar, J variable.*

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**Fig 4.** Bland-Altman plots comparing each CBCT method vs the physical method. Bland-Altman plots show the difference between the averages of measurements for a particular CBCT method and the physical method. The average difference is interpreted as the bias. The farther from zero, the greater the bias, meaning that the methods produce different results. The **solid lines** are the mean difference lines. The **broken lines** represent the mean difference ± 2 SD. Overall, each CBCT method undermeasured the MDD compared with the physical measurements.
REFERENCES

6. NGUYEN, BOCHEK, and Orellana

Table IV. Mixed model, adjusting for method and tooth

<table>
<thead>
<tr>
<th>Effect</th>
<th>Method</th>
<th>Estimate</th>
<th>SE</th>
<th>df</th>
<th>t value</th>
<th>P &gt; t</th>
<th>Lower bound</th>
<th>Upper bound</th>
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</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>InVivo Sections</td>
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<td>571</td>
<td>−5.98</td>
<td>&lt;0.0001</td>
<td>−0.4</td>
<td>−0.2</td>
</tr>
<tr>
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<td>571</td>
<td>−10.71</td>
<td>&lt;0.0001</td>
<td>−0.6</td>
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<td>Method</td>
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<td>571</td>
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<td>Method</td>
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<td>571</td>
<td>−5.34</td>
<td>&lt;0.0001</td>
<td>−0.2</td>
<td>−0.1</td>
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</table>

Method (fixed effect) and tooth (random effect that gives estimates of differences of measurements made by each CBCT method vs the standard, physical method).