Three-dimensional monitoring of root movement during orthodontic treatment

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**Introduction:** A significant objective of orthodontic treatment is to achieve proper and stable tooth positions that involve not only the crowns, but also their roots. However, the current methods of clinically monitoring root alignment are unreliable and inaccurate. Therefore, the purpose of this study was to develop a methodology that can accurately identify root position in a clinical situation. **Methods:** Pretreatment and posttreatment cone-beam computed tomography (CBCT) and extraoral laser scans of study models of a patient were obtained. Threshold segmentation of the CBCT scans was performed, resulting in 3-dimensional surface models. The pretreatment CBCT teeth were isolated from their respective arches for individual tooth manipulation. These isolated pretreatment CBCT teeth were superimposed onto the posttreatment surface scan depicting the expected root position setup. To validate the accuracy of the expected root position setup, it was compared with the true root position represented by the posttreatment CBCT scan. Color displacement maps were generated to measure any differences between the expected and true root positions. **Results:** Color map analysis through crown superimposition showed displacement differences of 0.148 ± 0.411 mm for the maxillary roots and 0.065 ± 0.364 mm for the mandibular roots. **Conclusions:** This methodology has been demonstrated to be an accurate and reliable approach to visualize the 3-dimensional positions of all teeth, including the roots, with no additional radiation applied. (Am J Orthod Dentofacial Orthop 2015;147:132-42)

The principal aims of orthodontic treatment are to maneuver teeth from malocclusion to an esthetic, functional, and stable occlusion with each whole tooth, crown and root included, positioned properly in 3 dimensions. To achieve this ideal occlusion, orthodontists often use Andrews’ 6 keys as general guidelines. Four of Andrews’ keys (mesiodistal, faciolingual, and occlusal gingival positions, and axial rotation) are governed solely by the crowns of the teeth and are straightforward to monitor clinically. However, because crowns do not always accurately indicate the whole tooth angulation and inclination, the remaining keys (mesiodistal angulation and faciolingual inclination) are better judged by involving the roots. Therefore, the ability to visualize the roots of the teeth would significantly help orthodontists to achieve all 6 keys.

The gold standard for monitoring and finalizing root position is to check panoramic x-rays at the initial, progress, and finishing stages of orthodontic treatment. However, panoramic x-rays may be inaccurate in depicting the true root positions. Numerous studies have shown that panoramic radiographs contain distortions because of nonorthogonal x-ray beams directed at the target teeth. Yet most orthodontists still use panoramic radiographs to visualize and correct root positions as shown in a 2008 survey, which found that 67.4% and 80.1% of American orthodontists take progress and posttreatment panoramic x-rays, respectively, because better alternatives are not readily available. Therefore, the development of a new and accurate approach for visualizing the position and angulation of roots is necessary.
Cone-beam computed tomography (CBCT) is a technique that has recently become more commonly used in orthodontics. Unlike panoramic radiographs, CBCT scans depict the true root positions and angulations in 3 dimensions. Furthermore, any distortions in the CBCT scans have been shown to be clinically insignificant. However, clinicians often take progress and posttreatment records, which would require multiple CBCT scans. Multiple scans would expose the patient to higher levels of radiation; this is not recommended clinically, especially in children.

Recently, a new methodology was reported that combines a single CBCT image with intraoral scans with the capability to track the root position at any stage of orthodontic treatment. However, this approach was demonstrated only in an ex-vivo typodont model. The aim of this study was to translate this previously reported methodology from a bench-top typodont model to a patient to develop an accurate approach to monitor root positions clinically throughout orthodontic treatment with minimal radiation.

**MATERIAL AND METHODS**

We obtained records from the patient database of the Department of Orthodontics of Pontifical Catholic University of Rio Grande do Sul in Brazil. These records included pretreatment and posttreatment CBCT scans and laser scans of poured-up casts of 1 patient. These casts were poured with orthodontic stone from alginate impressions. The patient was a 12-year-old boy with a skeletal and dental Class II malocclusion treated by an author (A.W.) with the Haas-type rapid palatal expander followed by combined headgear therapy and...
comprehensive orthodontic treatment with standard edgewise (0.022-in slot) fixed appliances (Fig 1). The patient’s CBCT scans were available from the data sets obtained for clinical purposes with an i-CAT scanner (Imaging Sciences International, Hatfield, Pa) set at 120 kVp, 8 mA, a large field of view, and a scan time of 40 seconds. The images were reconstructed with 0.25-mm slice thickness and exported as DICOM files.

The laser scans of the pretreatment and posttreatment poured-up casts were obtained using an XCAD scanner (São Paulo, SP, Brazil) and exported as stereolithography files.

The pretreatment and posttreatment DICOM files were imported into Mimics software (version 16.0; Materialise, Leuven, Belgium), and threshold segmentation was individually performed on each set of data, creating 3-dimensional (3D) virtual surface models of the teeth (Fig 2, A). The same process was used on both sets of data. An initial threshold of 2224 to 4095 gray levels was applied to the DICOM data and was manually adjusted until all teeth were accurately captured while also minimizing the amount of surrounding bone to individually segment the teeth. Various functions within Mimics were applied, including region growing, cropping, and edit mask in 3 dimensions to isolate each tooth from the remaining bony structures. Wrapping and smoothing functions were also applied to optimize the 3D surface models of the CBCT teeth (Fig 2, B). These teeth were individually imported into the software 3-matic (version 8.0; Materialise), which has the capability to perform superimpositions of the parts.

The “expected root position” (ERP) setup at posttreatment was created by superimposing the individually isolated tooth crowns (Fig 2, B) from the initial CBCT scan (Fig 2, A) onto the crowns of the posttreatment laser scan (Fig 2, D) of the posttreatment cast (Fig 2, C). The superimposition of the CBCT crowns carries the root information with it and forms the ERP setup, which depicts the expected root positions in 3 dimensions at posttreatment (Fig 2, E). A color displacement map between the individually isolated tooth crowns obtained from the pretreatment CBCT teeth and the posttreatment laser scan was generated to validate the accuracy of the superimposition.

To validate the ERP setup, we performed the previously validated indirect superimposition process between the ERP setup and the posttreatment CBCT scan. This was accomplished by superimposing the crowns of the posttreatment CBCT teeth (Fig 3, A) (that were not individually isolated) onto the crowns of the same posttreatment laser scan used to create the ERP setup (Fig 3, B). A color displacement map of the
superimposed posttreatment CBCT teeth and the post- 
treatment laser scan was generated to validate the accu-
rcacy of the alginate impression and the laser scan. At this 
point, the crowns of the posttreatment CBCT teeth and 
the ERP setup should be in the same position in 3 dimen-
sions (Fig 3, C). After removing the posttreatment 
laser scan (Fig 3, D), the ERP setup and the true positions 
of the roots depicted by the posttreatment CBCT 
scan were indirectly superimposed with each other 
(Fig 3, E).

The ERP and the posttreatment CBCT setups were 
cut roughly at the cementoenamel junction, isolating 
the roots and crowns from each other. The closest 
point surface displacements between thousands of sur-
face triangles in the 3D surface models were measured, 
and color displacement maps were generated to allow 
quanti$ation of the registration errors in 2 scenarios: 
(1) the ERP and the posttreatment CBCT crowns, and 
(2) the ERP and the posttreatment CBCT roots. All 
color maps were generated with the same parameters.

The histogram of the color mapping showed a whole 
spectrum of color ranging from blue, indicating 
displacement of 0.5 mm or more, to red, indicating 
outward displacement of 0.5 mm or more, with most 
of the areas in green at and around 0.0 mm of 
displacement.

RESULTS

After direct superimposition between the pretreatment 
CBCT crowns and the posttreatment laser scan crowns, 
color maps were generated to verify accurate superim-
positions. The color maps showed a maxillary displacement 
of $0.140 \pm 0.314$ mm with a maximum of $1.018$ mm, 
and a mandibular displacement of $0.115 \pm 0.448$ mm 
with a maximum of $1.210$ mm (Fig 4, Table).

Direct superimposition between the posttreatment 
CBCT crowns and the posttreatment laser scan crowns 
was also verified to be accurate through the color 
maps. The color maps showed maxillary displacement
of 0.048 ± 0.317 mm with a maximum of 1.453 mm, and a mandibular displacement of 0.050 ± 0.306 mm with a maximum of 1.537 mm (Fig 5, Table).

After indirect superimposition, the ERP setup was qualitatively compared with the posttreatment CBCT setup through different viewpoints and by making the posttreatment CBCT virtual model semitransparent (Fig 6). Whereas the crowns of the 2 setups were held at best fit, qualitatively, the root positions depicted by the ERP setup showed minimal differences to the true root positions represented by the posttreatment CBCT roots.

Color mapping from indirect superimposition of the ERP setup crowns with the posttreatment CBCT crowns through laser scanned crowns showed a maxillary displacement of 0.048 ± 0.339 mm with a maximum of 1.474 mm, and a mandibular displacement of 0.084 ± 0.274 mm with a maximum of 1.404 mm (Fig 7, Table). Color mapping of the roots showed a maxillary displacement of 0.148 ± 0.411 mm with a maximum of 2.155 mm, and a mandibular displacement of 0.065 ± 0.364 mm with a maximum of 1.978 mm (Fig 8, Table).

**DISCUSSION**

Proper placement of roots is required for successful orthodontic treatment that is stable, functional, and esthetic. However, the majority of the focus in orthodontics is on crown position rather than root position because roots are usually not directly involved with esthetics and occlusal contacts. Although current research has found that proper placement of roots after orthodontic treatment cannot completely eliminate relapse and that even a naturally occurring normal occlusion may not stay normal for life, it is still reasonable to postulate that positioning the roots in their proper places in the basal bone could reduce the extent of relapse after orthodontic treatment. Many orthodontists also notice problems in crown alignment only after observing improper root angulations through radiographs. In addition, the
American Board of Orthodontics recommends assessing root angulations. This assessment requires general root parallelism and deducts points if the roots of adjacent teeth are not parallel with each other or come in contact with each other. The current standard of care suggests the use of panoramic x-rays to monitor root alignment, even though many studies have shown that panoramic x-rays do not accurately depict root positions.

**Table.** Color displacement map analysis

<table>
<thead>
<tr>
<th>Analysis type</th>
<th>Mean displacement (mm)</th>
<th>SD (mm)</th>
<th>Minimum displacement (mm)</th>
<th>Maximum displacement (mm)</th>
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<tbody>
<tr>
<td>Pretreatment CBCT crowns vs posttreatment laser scan crowns</td>
<td>Maxillary crowns 0.140</td>
<td>0.314</td>
<td>0.000</td>
<td>1.018</td>
</tr>
<tr>
<td></td>
<td>Mandibular crowns 0.115</td>
<td>0.448</td>
<td>0.000</td>
<td>1.210</td>
</tr>
<tr>
<td>Posttreatment CBCT crowns vs posttreatment laser scan crowns</td>
<td>Maxillary crowns 0.048</td>
<td>0.317</td>
<td>0.000</td>
<td>1.453</td>
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<tr>
<td></td>
<td>Mandibular crowns 0.050</td>
<td>0.306</td>
<td>0.000</td>
<td>1.517</td>
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<tr>
<td>ERP crowns vs posttreatment CBCT crowns</td>
<td>Maxillary crowns 0.048</td>
<td>0.339</td>
<td>0.000</td>
<td>1.474</td>
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<tr>
<td></td>
<td>Mandibular crowns 0.084</td>
<td>0.274</td>
<td>0.000</td>
<td>1.404</td>
</tr>
<tr>
<td>ERP roots vs posttreatment CBCT roots</td>
<td>Maxillary roots 0.148</td>
<td>0.411</td>
<td>0.000</td>
<td>2.155</td>
</tr>
<tr>
<td></td>
<td>Mandibular roots 0.065</td>
<td>0.364</td>
<td>0.000</td>
<td>1.978</td>
</tr>
</tbody>
</table>

*ERP*, Expected root position.

**Fig 5.** Verification of accurate crown superimposition after direct superimposition between the post-treatment CBCT crowns and posttreatment laser scan crowns: A, color displacement maps comparing the crown positions of the posttreatment CBCT crowns and posttreatment laser scan crowns. *Green areas* indicate 0.0-mm displacement; *blue and red areas* indicate differences equal to or greater than 0.5 mm. B and C, Histograms showing the distribution of displacements between the crowns of the posttreatment CBCT and posttreatment laser scan in the maxillary arch and the mandibular arch. The *blue and red lines* indicate the 0.5-mm limits.
and angulations.\textsuperscript{12-14} Thus, it is necessary to develop a new approach that can accurately monitor root position and angulation.

Previously, a methodology was reported that has the potential to accomplish this; however, this approach was demonstrated only in an ex-vivo typodont model.\textsuperscript{23} Unlike the previous study that used intraoral scans, in this study, we used extraoral laser scans of poured-up study models at posttreatment. Many studies have shown that extraoral scans of poured-up casts are either comparable with or more accurate than intraoral scans.\textsuperscript{31-35} However, the accuracy of the extraoral laser scan depends on an accurate impression and model-pouring process. Thus, to verify the accuracy of the extraoral laser scan used in this study, direct superimposition and color maps were performed comparing both the pretreatment and posttreatment CBCT scan crowns with the posttreatment laser scan crowns in which minimal differences were found.

Impressions are difficult to take during treatment when brackets are still bonded, so no progress casts and laser scans were obtained in this study. Hence, it was not possible to determine whether the presence of brackets would affect the methodology. However, in a previous study, it was demonstrated with intraoral scans that the brackets do not affect the methodology in an ex-vivo typodont model.\textsuperscript{23} Therefore, it is reasonable to postulate that the presence of brackets would not affect this methodology in patients as well. Using intraoral scans to monitor root movements during treatment clearly has a significant advantage.

To validate the ERP against the true root position, depicted by the posttreatment CBCT teeth, an indirect superimposition process was used. In this process, the ERP and CBCT setups were not directly superimposed onto each other. Rather, both setups were superimposed onto the same posttreatment intraoral scan. Thereafter, the extraoral scan was removed, leaving just the ERP and CBCT setups to compare with each other. Direct superimposition between the ERP and CBCT setups was not performed because superimposition of these 2 setups would cause the whole tooth, including the roots, to be in the best fit position, rather than validating the ERP setup that was constructed previously. After accurate indirect superimposition, the crowns from the ERP and CBCT models were separated from the roots, allowing for comparison of solely the crowns or roots with color-map analysis.

The accuracies of the direct and indirect superimposition processes were verified through color-map analysis of the superimposed crowns. Minimal differences were found in the direct superimposition between isolated pretreatment CBCT crowns and the posttreatment laser scan crowns. This accuracy is imperative because

\begin{figure}
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\includegraphics[width=\textwidth]{fig6.png}
\caption{Qualitative comparison of the ERP setup (\textit{multicolored teeth}) and the posttreatment CBCT teeth (\textit{transparent gray}) after indirect superimposition.}
\end{figure}
this process is conducted clinically. The indirect superimposition process was applied for this study because a posttreatment CBCT scan was used to validate the accuracy of the ERP setup, but clinically a posttreatment CBCT scan would not be necessary. No significant differences were found between the ERP setup crowns and the posttreatment CBCT crowns, indicating accurate indirect superimpositions. Some blue and red spots on all color maps were noted, indicating regions of displacement equal to or greater than 0.5 mm. However, we found that most of these spots were localized on the occlusal surface, which has significantly more complex anatomy than the other tooth surfaces. This complex occlusal surface anatomy is difficult to capture on the low-resolution CBCT scan, which results in either missing or added tooth structure and leads to some of the discrepancy between the crown superimpositions. In addition, the quality of the threshold segmentation depends on the CBCT image quality and the software’s algorithms used for segmentation. Although we used Mimics software, considered one of the most accurate and reliable softwares for threshold segmentation and construction of 3D virtual surface models, some areas with complex anatomy were still difficult to segment. This can lead the operator to add or subtract tooth structure and cause these discrepancies, especially on the occlusal surface. The operator also may cause further errors during manual adjustment of segmentation because the operator’s human vision and visual discrimination of crown, root, bone, and air are subject to a host of factors, such as lighting conditions, fatigue, gray-scale ability, and visual acuity. Wrapping and smoothing functions were also applied to optimize the 3D surface models of the CBCT teeth. Smoothing is a function that works like a filter for noise reduction, making rough surfaces smoother. Wrapping is a function used to filter small inclusions or close small holes on the surface of the 3D models of the tooth or root by creating a wrapping surface over the 3D surface models. Although we used low smoothing factor, interaction parameter, and gap-closing distance to limit the smoothing and wrapping,

Fig 7. Verification of accurate crown superimposition after indirect superimposition with posttreatment laser scanned model: A, color displacement maps comparing the crown positions of the ERP and posttreatment CBCT setups. Green areas indicate 0.0-mm displacement; blue and red areas indicate differences equal to or greater than 0.5 mm. B and C, Histograms showing the distribution of displacements between the crowns of the ERP and CBCT setups in the maxillary arch and the mandibular arch. The blue and red lines indicate the 0.5-mm limits.
some small changes on tooth morphology may have been introduced. Additionally, during DICOM acquisition, the CBCT image quality depends on several factors, such as the CBCT machine settings, volume reconstruction, and DICOM export. When scanning is performed with high settings (small voxel size and longer scan time), as in this study, the CBCT images are obtained with better spatial resolution, allowing the construction of more accurate 3D crown and root surface models. However, even with these high settings, the patient’s movement during the scan process (40 seconds) may have produced motion-related artifacts that influenced the contrast of the images and could affect the discrimination between densities while performing threshold segmentation, and, consequently, the construction of the 3D virtual models of the teeth. Furthermore, for the crown superimpositions, the crowns needed to be separated at the cementoenamel junction, but there were some inconsistencies in the cuts made between the different models leading to errors at the cementoenamel junction. All of these factors play a role in the small superimposition errors shown in the color maps.

The color displacement maps also showed minimal differences between the root positions of the ERP and CBCT setups. Therefore, the ERP setup was validated. Qualitatively, we noted many red and blue spots in the color maps, indicating regions of displacement that were equal to or greater than 0.5 mm. Some of these red regions were located at the root apices; we believe these are a result of root resorption caused by orthodontic treatment with rapid palatal expansion, headgear therapy, and fixed appliances. This root resorption slightly reduced the accuracy of our quantitative measurements by increasing the mean displacements and standard deviations between the 2 compared parts. Although the root resorption was not a large source of error for this patient, it could be a large source of error in the quantitative measurements of patients who experience significant root resorption. However, root resorption would not interfere with the qualitative analysis of root alignment. The second molars of this patient were also unerupted at pretreatment, with roots that were not fully developed. When the second molars were captured by the pretreatment CBCT scan, the roots were much shorter than the roots of the fully formed second molars at posttreatment; this also contributed to the superimposition changes in the color maps. Furthermore, similar to the error with the crown anatomy, root anatomy is also greatly influenced by the quality of the CBCT image acquisition and the subsequent threshold segmentation. It is especially difficult to separate the root from the surrounding bone in the threshold segmentation process, so it is

Fig 8. Measurement of displacements between the roots of the ERP setup and the posttreatment CBCT model after indirect superimposition with the laser scanned model: A, color displacement maps comparing the root positions of the ERP and CBCT setups. Green areas indicate 0.0-mm displacement; blue and red areas indicate differences equal to or greater than 0.5 mm. B and C, Histograms showing the distribution of displacements between the roots of the ERP and the posttreatment CBCT setups in the maxillary arch and the mandibular arch. The blue and red lines indicate the 0.5-mm limits.
likely that root structure was either added or missed during threshold segmentation. All of these factors help to explain the quantitative and qualitative differences between the ERP and posttreatment CBCT setups. However, the histograms show that most of these points were within 1 mm, which is still significantly more accurate than panoramic radiographs. Furthermore, this methodology allows the orthodontist to see true 3D discrepancies in root positions, unlike panoramic radiographs, which give false information of reduced discrepancies, since a 3D relationship is projected onto a 2-dimensional image. Therefore, even with the minor quantitative and qualitative discrepancies noted, this methodology is still an improvement over the current standard of using panoramic radiographs to measure root positions.

The main limitation of this methodology was that it is currently too time-consuming for use in a clinical setting. Considerable amounts of time and effort were necessary to perform threshold segmentations of the teeth in complex craniofacial bony structures compared with the previous study of an ex-vivo typodont model. In addition, creating the many superimpositions that are needed is also a time-consuming process. To shorten the overall time of this methodology, the process of creating composite teeth that was used in the ex-vivo typodont methodology was not used in this study. The process of creating composite teeth requires significantly more time for the additional step of cutting out the crowns of the high-resolution intraoral or laser scans, individually superimposing all of these crowns onto the pretreatment CBCT crowns, and suturing them together. Although this process may help with the accuracy of the methodology, it significantly increases the time required to complete it. Additionally, because we were able to demonstrate that this methodology is accurate and reliable when directly using the pretreatment CBCT teeth, the process of creating composite teeth is unnecessary. In the future, it should be possible to automate this entire process, which could then make this methodology clinically useful. Furthermore, technology is constantly improving, so we hope that newer generations of 3D scanners and image-processing software will make this methodology significantly easier and faster.

CONCLUSIONS

1. We have validated the potential clinical use of the ERP method through indirect superimposition of isolated pretreatment CBCT teeth with posttreatment CBCT teeth through direct superimposition of these 2 models onto the posttreatment extraoral scan.
2. We have proved that the root position can be identified using 1 pretreatment CBCT scan and the surface crown scan images taken at any stage of the orthodontic treatment. However, further advancements in software and technology are still needed for the clinical use of this methodology.

REFERENCES

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