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Factors Associated with Orthodontically Induced Apical Root Resorption of Maxillary Incisors

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Factors Associated with Orthodontically Induced Apical Root Resorption of Maxillary Incisors

by

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A Thesis submitted in partial satisfaction of
the requirements for the degree
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Each person whose signature appears below certifies that this thesis in his opinion is adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABBREVIATIONS

A	Apex of root (dental landmark)
ANB	Angle formed by A point, Nasion and B point
ANS	Anterior nasal spine
C	Center of resistance (dental landmark)
CBCT	Cone beam computed tomography
DICOM	Digital imaging and communications in medicine
I	Incisal edge (dental landmark)
MD	Mesio-distal (direction of movement)
MPR (view)	Multi-planar reconstruction view
Na	Nasion
PDL	Periodontal ligament
PNS	Posterior nasal spine
RME	Rapid maxillary expansion
RR	Root resorption
T1	Pre-orthodontic treatment
T2	Post-orthodontic treatment
WO	Working orientation

ABSTRACT OF THE THESIS

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by

Brandon Malan

Master of Science, Graduate Program in Orthodontics and Dentofacial Orthopedics
Loma Linda University, September 2017
Dr. Kitichai Rungcharassaeng, Chairperson

Introduction: Resorption of root apices is a ubiquitous occurrence in orthodontic treatment. Although most occurrence of resorption during orthodontic treatment is clinically inconsequential, a small percentage of patients have a severe amount of root structure that is lost. There are factors that are widely accepted as responsible for apical root resorption (RR), such as heavy compressive forces on the periodontal ligament (PDL). Unfortunately, it is still largely unpredictable if one patient will experience more root loss than what is considered normal. Thus, it is of clinical interest to further study what factors play a role in RR.

Purpose: The purpose of this study was to utilize Cone Beam Computed Tomography (CBCT) to evaluate whether certain treatment-related and patient-related factors are associated with increased severity of orthodontically induced apical root resorption.

Methods: Initial (T1) and final (T2) Digital Imaging and Communications in Medicine (DICOM) CBCT images of patients orthodontically treated at Loma Linda University were imported into OsiriX MD software (version 7.5.1, Pimeo, Bernex, Switzerland) for measuring RR of right and left maxillary central incisors. Using fiduciary markers at the anterior nasal spine (ANS), posterior nasal spine (PNS), and nasion (Na), movement of the incisors were assessed at three dental landmarks, the incisal edge (I), the center of resistance (C), and the apex (A). Patient treatment records were reviewed for information regarding patient age, gender, ethnicity, medical history, expander appliances used, whether teeth were extracted, and time in treatment. Non-parametric Spearman-Rho correlation tests were performed to determine whether correlations existed between specific directions of tooth movement, time in treatment, or age of the patient and the severity of RR. Kruskal-Wallis and Mann-Whitney U tests were also used to determine differences in RR among groups of ethnicity, gender, expansion treatment, extraction treatment and asthmatics.

Results: A total of 291 patients (582 teeth) were included in this study. Total movement at A, intrusion at A and retraction at I were directions of movement that had the highest correlations with RR at 0.344, 0.343, and 0.328 respectively. Time in treatment had a significant but weak correlation with RR of 0.213. There was no correlation with the patient age and amount of resorption. Males had statistically more RR than females. However, males also had statistically more total movement of the root apex. Incisors treated with extraction of two premolars also had more RR but also more total movement at the apex compared to non-extraction treatment. Patients treated with a rapid maxillary expansion appliance or a quad helix had more RR than those treated non-expansion. There were no differences in RR among ethnicities or between asthmatics and non-asthmatics.

Conclusions: In our sample, total movement at the apex, intrusion at the apex, and retraction at the incisal edge had the highest correlation with root resorption. Treatment

involving rapid palatal expansion and extractions had higher means of resorption. Additionally, there were no differences in severity of resorption among ethnicities or asthmatics and non-asthmatics.

CHAPTER ONE

LITERATURE REVIEW

Apical root resorption is a common iatrogenic effect from orthodontic tooth movement.[1] Histological studies have shown that 90% of teeth that have had orthodontic forces applied to them have apical root resorption (RR).[12] When evaluated from radiographs, approximately 73% of teeth treated orthodontically show signs of RR.[12] Fortunately, most resorption caused by orthodontic treatment will have little clinical significance on the health of the tooth, however this may not be the case if resorption is severe.[4,5]

The literature defines apical root resorption as severe once the root has lost more than 4 mm or 1/3 of the original root length.[12] This severity of RR has been reported to occur to between 1-5% of treated teeth.[12,15] Maxillary incisors have consistently been identified as the teeth at highest risk of severe RR with 25% of them having greater than 2 mm of resorption.[6]

Prognosis of teeth that have undergone severe RR is questionable. Optimistic results from long term studies have found that even when significant root loss has occurred it is likely that the tooth will not be lost.[4,5] Loss of a tooth as a direct outcome of severe root resorption is considered uncommon.[3] Stability may be maintained since root structure lost at the apical portion of the root is more narrow and contributes less to the overall periodontal ligament (PDL) surface area. An average root that is shortened 5 mm will still retain 75% of its original periodontal attachment.[12] Another comparison to periodontal support is that 3 mm of RR is equivalent to 1 mm of crestal bone loss.[12]

The periodontal support that remains is more critical to the prognosis of the tooth than simply how many millimeters of the apex was lost from RR. However, RR does contribute to periodontal loss and leaves the tooth more vulnerable to the effects of periodontal disease. Maxillary incisors are at considerable risk of hypermobility when less than 9 mm of periodontal support is remaining.[3,4]

Apical resorption from orthodontic treatment is largely unavoidable. Orthodontic forces placed on teeth produce local areas of hyalinization along the PDL space which are attributed to the pathway of root resorption.[35] The osteoclasts and macrophages that remove the necrotic tissues in those areas also are capable of removing the protective cementum; which leaves the tooth vulnerable to be further attacked in the resorptive processes.[17] Resorption craters on the lateral root surfaces are usually filled in and repaired by cementoblasts, but when the apical surfaces are involved, cratering results in permanent loss to root length.[33]

Although the biological process by which root resorption occurs is generally understood, there are still many controversies surrounding what factors exacerbate this process. Generally, these risk factors can be separated into two categories: patient-related (biological factors) and treatment-related (mechanical factors).[33]

In terms of RR, some patients may have a heightened negative response to orthodontic force. Evidence suggests that each patient's risk for RR is dictated by intrinsic patient characteristics or a genetic profile which the orthodontist has no control over. Factors such as root shape, genetics, hormone deficiencies such as hypothyroidism or hypopituitarism, asthma, bone density, allergies, chronic alcoholism, age, and gender have been investigated.[1,12] However, it is disputable whether certain of these factors actually play a significant role in determining individual risk for RR.

Whether treatment at a younger age avoids more RR is debatable. Linge and Linge[36] reported less RR occurred if orthodontic treatment was performed before the age of 11 years-old. By the time a child reaches 11 years-old the roots of the maxillary incisors reach completion. At completion of the root apex, the apex is more prone to resorption than a developing root.[26] However, it is unclear how one can verify how much root loss could be avoided if the original root length was not completely formed before orthodontic treatment. Additionally, comprehensive orthodontic treatment before this stage is not practical since it often precedes the permanent dentition stage. In other studies, age has not been shown to have any significant impact on RR for patients receiving comprehensive orthodontic treatment.[9,16,27]

Some studies have reported differences in severity of RR between males and females. Braumind et al[22] found that in their adult sample, males had an average of 1.2 mm more resorption than females. This is a significant difference compared to other studies which found no difference between genders.[14,16,26-28] Since most studies regarding root resorption have a large adolescent sample size there could be differences between male and female at later ages. However, there may also be confounding factors such as the possibility that the adult male-seeking-orthodontic-patient may have greater corrective needs than the adult female-seeking-patient. Other studies have reported a difference in root resorption between male and female but those differences are not statistically significant.[6,9]

Patients who have asthma or allergies have also been reported as being at greater risk for RR. The systemic inflammatory processes in these patients could intensify the inflammatory process involved in tooth movement.[1,32] McNab et al[31] found that asthmatics had a higher overall incidence of root resorption to the maxillary posterior dentition. However, it is important to note that there was no significant difference in the incidence of moderate or severe root resorption between asthmatics and healthy patients. Thus, clinical significance of asthmatics being more prone to root resorption may be weak.

Dilacerated or pipette shaped roots have been reported to be at greater risk of resorption.[6,10,37] However, others have judged root shape to have no impact on the amount of RR that occurs.[26,38] In addition to the shape of the root, longer root lengths have been found to have a weak but positive correlation to RR.[6,10] A possible reason for this is that longer roots require greater distances for the apex to travel in torqueing and angulation correction. Additionally, it would be expected that orthodontists are generally more cautious with their mechanics and forces when the roots start off stubby or short compared to when the roots are long.

Genetic implications and the role it plays in RR are being further investigated. Sameshima[6] reported that Asians had significantly lower average root resorption than Caucasians or Hispanics. Hispanics, with the highest mean root resorption among the three ethnicities had a mean of 0.7 to 0.8 mm more resorption than the Asian sample. Further evidence suggests a strong familial association with RR.[32]

Efforts have been made to determine specific genes that can be used as markers of increased risk of severe RR. Patients who were homozygous with the IL-1beta allele 1 polymorphism were reported to have a 5.6 fold increased risk of having more than 2 mm of resorption.[8] Additionally, another study found that those who had the IL-6 SNP rs1800796 GC genotype had greater resorption.[9]

Besides patient-related factors, many have investigated clinical variables that can be controlled by the orthodontist to minimize the severity of resorption. Extraction patterns, transverse expansion, surgical treatment, time in treatment, specific directions of tooth movement, and proximity to the lingual cortical plate are typical factors explored in such studies.[12] Again, uncertainty exists on which of these factors have strong associations with increased RR.[11]

Considerable evidence shows that heavy compressive forces on the PDL cause more resorption than light forces or areas with tensile forces.[17] Nevertheless, in clinical practice a variety of force applications and conditions are introduced to the teeth in which the clinician has limited knowledge of the magnitude of forces being applied. In an attempt to evaluate whether there are directions of movement that pose greater risk of RR than others, many investigators have tested for correlation between root resorption and specific directions of tooth movement; such as buccal root torque versus lingual root torque, intrusion versus extrusion, etc. Parker and Harris reported that incisor intrusion and lingual root torque were the strongest predictors for resorption but that bodily retraction, extrusion and buccal root torque had no significant relationship.[14] Intrusion had a correlation of 0.77 and resulted in 4x more root resorption than extrusive movements.[12] Intrusion in another study was not a significant factor in RR but rather lingual root torque and retraction did have a significant relationship on RR.[22,23] Sameshima found that anterior-posterior movement of the apex was significantly associated with root resorption but not vertical movement.[7] Braumind et al reported that for every 1 mm of retraction there was on average approximately 0.3 mm of resorption.[22] Kaley and Phillips[23] reported that maxillary surgery, root torque and lingual cortical plate approximation significantly increased the risk of resorption. Horiuchi[13] found that approximation of the lingual cortical plate explained 12% of the variation of the root resorption they measured in their sample. However, lingual cortical plate approximation may be more related to confounding variables such as retraction of incisors, extraction treatment, and lingual root torque which as previously stated have been identified as having a positive correlation with RR[7,25,26,30].

In contrast to these findings, Simplicio et al reported that when incisors were retracted with extraction of premolars, there were no significant correlations between vertical, horizontal, or total apical movement of the maxillary incisors with severity of RR.[24] Mirabella et al[37] found no correlation between RR and proximity to the lingual cortical plate, rather they concluded that root resorption is more closely related to the total root movement.

As evident in the literature, there remains a lack of consensus regarding which treatment or patient related variables are most related to the severity of apical root resorption that occurs. Thus, severity of RR as a consequence of treatment remains highly unpredictable from patient to patient.

Lack of agreement between studies could be due to the use of conventional radiographs to make measurements. Periapical and panoramic radiographs are vulnerable to distortion and measurements of root changes may not be accurate.[18] Lateral cephalograms provide poor visualization of the location of root apices due to superimposition of overlapping structures. The majority of past studies utilized periapical or panoramic radiographs to determine incidence and severity of resorption. Many of these studies could not objectively measure the root length before and after treatment because of these limitations.[39] Instead, studies sometimes classify RR into broad categories of severity based on the general impression of RR shown in the radiograph. Although this method aims to highlight the RR of clinical significance, this type of classification and the radiographs used for it can be unreliable.[39,40]

Cone-beam computed tomography (CBCT) allows an examiner to avoid errors related to projection geometry and structure superimposition.[27,28] Dudic[19] reported that incidence of root resorption is underdiagnosed in panoramic radiographs (44% incidence) compared to CBCT (69% incidence). Ponder[20] showed that both high and low resolution CBCT images had good agreement with microCT volumetric quantification of external root resorption defects and can more accurately measure resorption defects than periapical radiographs. Although their use for diagnosing root resorption is superior to panoramic and periapical radiographs, there is not widespread prescription for CBCT records since the effective dose for a CBCT image is much higher than that for conventional radiographs.[19,27] Utilizing CBCT technology in future RR studies however will allow for more accurate measurements.

Limitations to previous clinical trials investigating RR risk factors include small sample sizes and short evaluation periods which complicate the ability to come to any certain conclusions.[12] Retrospective studies allow for larger sample sizes and an evaluation period that spans the entire treatment time, but they lack the ability to evaluate precise forces applied and intermediate tooth movements that occurred. These limitations and differences in study design lead to the lack of consensus on the role that risk factors play in the severity of apical root resorption.[12]

Many controversies still exist regarding factors that increase the risk of RR. However, as future research explores why some patients experience more RR than others, orthodontists will be able to have a stronger evidenced-based approach to minimize RR for those they treat.

CHAPTER TWO

FACTORS ASSOCIATED WITH ORTHODONTICALLY INDUCED APICAL ROOT RESORPTION OF MAXILLARY INCISORS

Abstract

Introduction: Resorption of root apices is a ubiquitous occurrence in orthodontic treatment. Although most occurrence of resorption during orthodontic treatment is clinically inconsequential, a small percentage of patients have a severe amount of root structure that is lost. There are factors that are widely accepted as responsible for root resorption (RR), such as heavy compressive forces on the periodontal ligament (PDL). Unfortunately, it is still largely unpredictable if one patient will experience more root loss than what is considered normal. Thus, it is of clinical interest to further study what factors play a role in RR.

Purpose: The purpose of this study was to utilize Cone Beam Computed Tomography (CBCT) to evaluate whether certain treatment-related and patient-related factors are associated with increased severity of orthodontically induced apical root resorption.

Methods: Initial (T1) and final (T2) Digital Imaging and Communications in Medicine (DICOM) CBCT images of patients orthodontically treated at Loma Linda University were imported into OsiriX MD software (version 7.5.1, Pimeo, Bernex, Switzerland) for measuring RR of right and left maxillary central incisors. Using fiduciary markers at the anterior nasal spine (ANS), posterior nasal spine (PNS), and nasion (Na), movement of the incisors were assessed at three dental landmarks, the incisal edge (I), the center of resistance (C), and the apex (A). Patient treatment records were reviewed for information regarding patient age, gender, ethnicity, medical history, expander appliances used, whether teeth were extracted, and time in treatment. Non-parametric Spearman-Rho correlation tests were performed to determine whether correlations existed between specific directions of tooth movement, time in treatment, or age of the patient and the severity of RR. Kruskal-Wallis and Mann-Whitney U tests were also used to determine differences in RR among groups of ethnicity, gender, expansion treatment, extraction treatment and asthmatics.

Results: A total of 291 patients (582 teeth) were included in the study. Total movement at A, intrusion at A and retraction at I were directions of movement that had the highest correlations with RR at 0.344, 0.343, and 0.328 respectively. Time in treatment had a significant but weak correlation with RR of 0.213. There was no correlation between the patient age and amount of resorption. Males had statistically more RR than females. However, males also had statistically more total movement of the root apex. Incisors treated with extraction of two premolars also had more RR but also more total movement at the apex compared to non-extraction treatment. Patients treated with a rapid maxillary expansion appliance or a quad helix had more RR than those treated non-expansion. There were no differences in RR among ethnicities or between asthmatics and non-asthmatics.

Conclusions: In our sample, total movement at the apex, intrusion at the apex, and retraction at the incisal edge had the highest correlation with root resorption. Treatment involving rapid palatal expansion and extractions did have a higher mean resorption. Additionally, there were no differences in severity of resorption among ethnicities or asthmatics and non-asthmatics.

Introduction

Statement of the Problem

Apical root resorption (RR) is an irreversible iatrogenic effect that can occur with orthodontic treatment.[1] Although most RR during orthodontic treatment is clinically inconsequential, severe RR, although rare, is problematic. For those with severe RR, avoidance of further root loss becomes a primary objective, leading to limitations of treatment and possibly an esthetic compromise. After treatment the patient remains at risk for tooth loss for those teeth affected.[2-5]

Maxillary incisors have consistently been reported as being most vulnerable to severe RR.[6] However, severity of resorption varies between individuals and it is difficult to predict who is at highest risk.[6,7] Factors that predispose a patient to severe RR may be related to specific patient characteristics; such as genetics or root shape.[8-12] Other factors may be related to mechanical control or how the orthodontist moves the tooth during treatment.[1,7,10-15]

It is widely accepted that heavy compressive forces on the periodontal ligament (PDL) create hyalinized zones which lead to the destruction of the protective cementum layer covering the root.[15-17] However, magnitudes of force that the clinician delivers are often unknown and certain directions of tooth movement may increase the incidence of root resorption. However, there are areas of controversy regarding which directions of tooth movement or orthodontic appliances are associated with more resorption.[11]

Most previous studies regarding RR have been limited to the use of periapical films, panoramic radiographs, and lateral cephalograms to measure root length and tooth position changes. Image distortion and image superimposition make these radiographic images unreliable for measuring root resorption.[18] Conversely, cone-beam computed tomography (CBCT) has been shown to be superior for diagnosing and measuring RR.[19,20]

The purpose of this study was to determine whether a relationship exists among root resorption of the maxillary central incisors and treatment or patient related factors; such as direction and magnitude of linear and angular tooth movement, time in treatment, age of the patient, extraction of premolars, palatal expansion, gender, ethnicity and history of asthma.

Hypothesis

The null hypothesis stated that there were no correlations between the amount of root resorption and the direction and magnitude of linear and angular tooth movement. Additionally, the null hypothesis stated that there were no differences in the amount of root resorption when comparing different ethnicities, genders, presence and absence of palatal expanders, extraction and non-extraction treatment, and presence and absence of an asthmatic condition.

Materials and Methods

Patient Selection

This study was approved by the Institutional Review Board (IRB) of Loma Linda University (LLU), Loma Linda, CA. Records were obtained of patients treated at Loma Linda University Orthodontic Graduate clinic with pre-treatment (T1) and post-treatment

(T2) CBCT radiographs. One examiner (BM) performed all measurements and data collection. Cases were selected based on the following inclusion/exclusion criteria:

Table 1. Inclusion and exclusion criteria used in patient selection

Inclusion Criteria
1. Full treatment case with T1 and T2 CBCT scans 2. Both T1 and T2 scans taken from NewTom 5G
Exclusion Criteria
3. Missing or not fully formed maxillary central incisor 1. Phase 1 treatment 2. Maxillary surgical cases 3. Changes in incisal contour to central incisor crowns

Data Collection

Records from patients who met the selection criteria were reviewed and the following data recorded:

- Chart number
- Gender
- Age at beginning of comprehensive of treatment
- Ethnicity (Asian, Black, Caucasian, Hispanic)
- Time in treatment
- Orthodontic expanders used
- Teeth that were extracted for treatment
- Medical History

Central Incisor Landmarks

CBCT records of patients who met the criteria were anonymized and imported into OsiriX MD (version 7.5.1, Pimeo, Bernex, Switzerland) as Digital Imaging and Communication in Medicine (DICOM) files. In the multi-planar reconstruction (MPR) view, a 0.15 mm sagittal slice was made through the middle of each maxillary central incisor. In this sagittal view the incisal edge (I), center of resistance (C), and root apex (A) were identified. The center of resistance was approximated as the bucco-lingual center of the root at 1/3 of the length from the crestal bone to the root apex.[21] The measurement between I-A was recorded as tooth length. Additionally, the I-C length and the CIA angle were recorded from T1 images in order to duplicate the I, C, and A points on to the same tooth at T2 (Figure1).

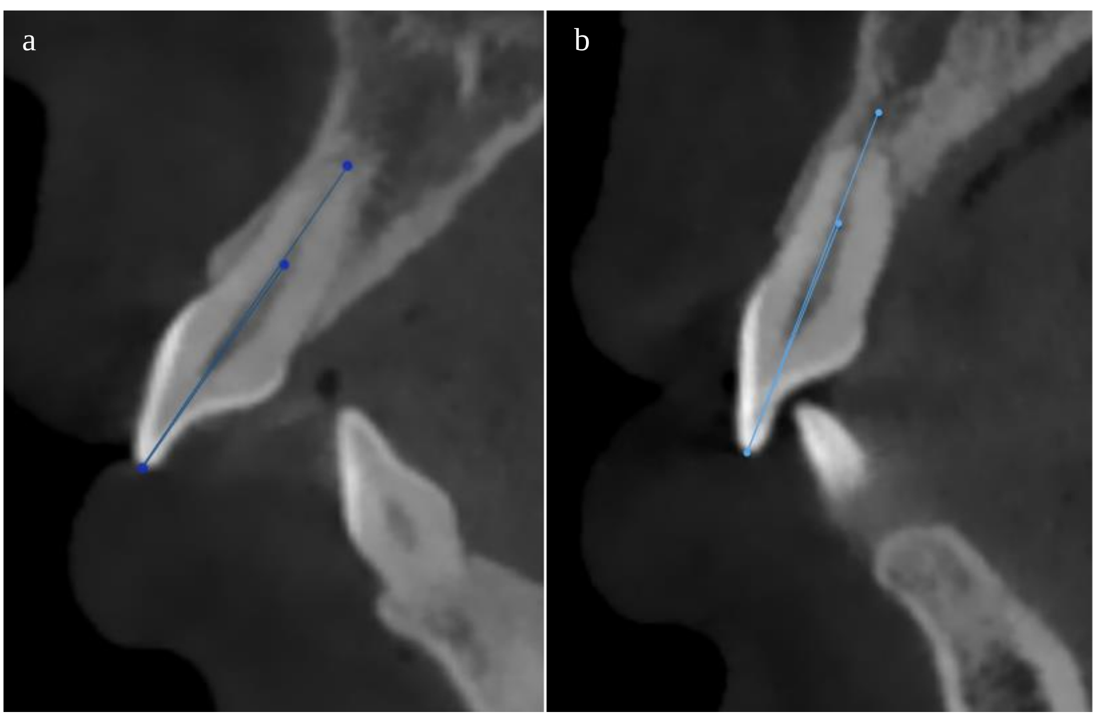

Figure 1. 0.15 mm sagittal slice through the central incisor at T1 (a) and T2 (b). Markers were placed at I, C, A on T1 (a). Distance and angle relationships between those markers were duplicated on T2 (b).

Volume Orientation

In MPR, a working orientation (WO) of the head was then constructed using fiduciary markers at anterior nasal spine (ANS), posterior nasal spine (PNS), and nasion (Na). The head was positioned so that the ANS-PNS line (palatal plane) aligned completely horizontal in a sagittal view and vertical in the transverse view. In the coronal view the Na-ANS line was orientated completely vertical. Once the head was in WO (Figure 2), measurements of tooth positions were performed.

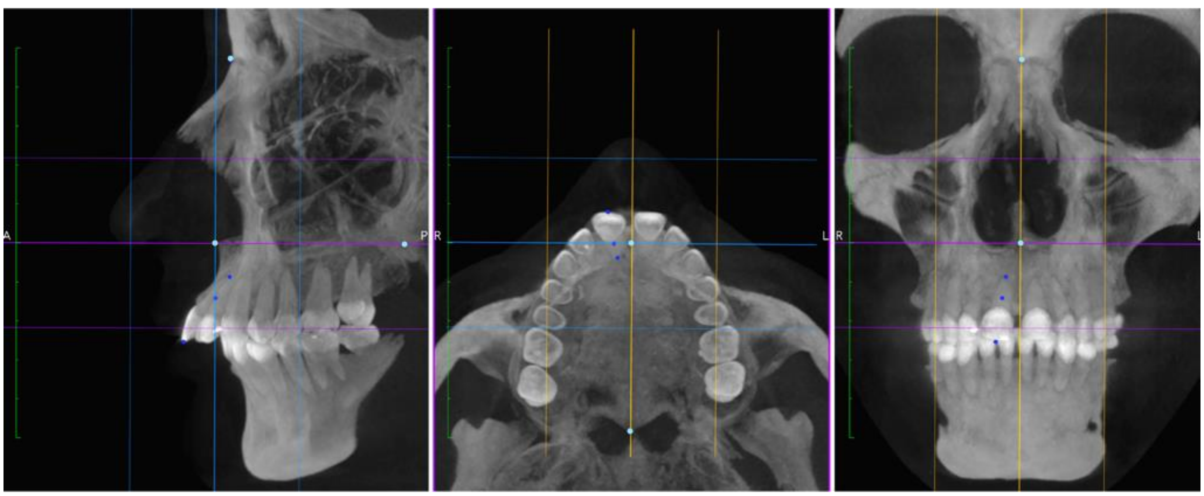

Figure 2. The head was orientated in all 3 planes in MPR utilizing cephalometric landmarks, Na, ANS, and PNS. WO was established before measurements of tooth position were made.

CBCT Tooth Position Measurements

Vertical, mesio-distal, and angulation measurements of tooth position were performed in the coronal view (Figure 3). Mesio-distal positions of the landmarks were determined using the horizontal distance away from the Na-ANS line. Vertical position of the dental landmarks I, C, and A were measured as the vertical distance away from ANS in WO. Angulation of the tooth was measured as the angle formed by I-A and the vertical reference line.

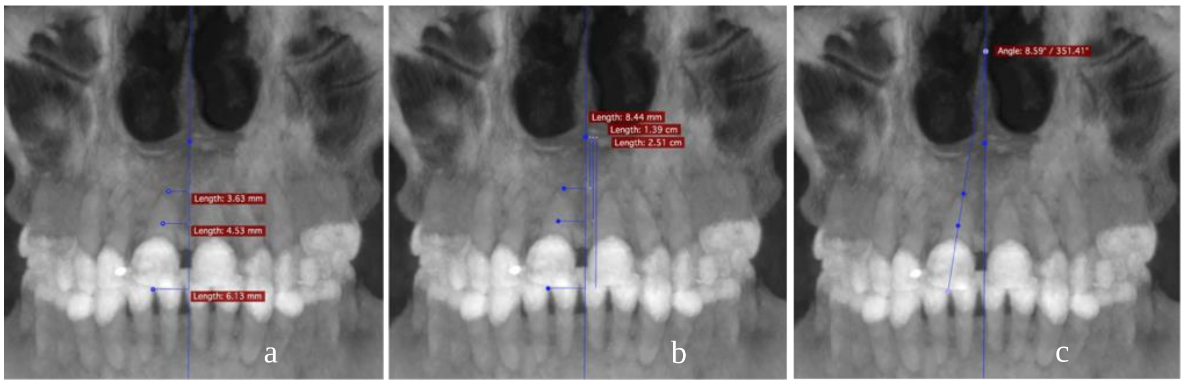

Figure 3. Horizontal distances from a vertical line through ANS to I, C, A landmarks defined the mesial/distal position of the tooth (a). Vertical distances of the I, C, A landmarks from ANS were then recorded (b). Angulation was measured as the angle between I-A and the vertical line (c).

The anterior-posterior positions of I, C, and A were determined as the distance away from the perpendicular of ANS-PNS at ANS in the transverse view (Figure 4). If any dental landmark was anterior to ANS the linear distance to that landmark was given a negative value. While in this view, rotation was also measured as the angle formed from the incisal edge and the ANS-PNS line (Figure 4).

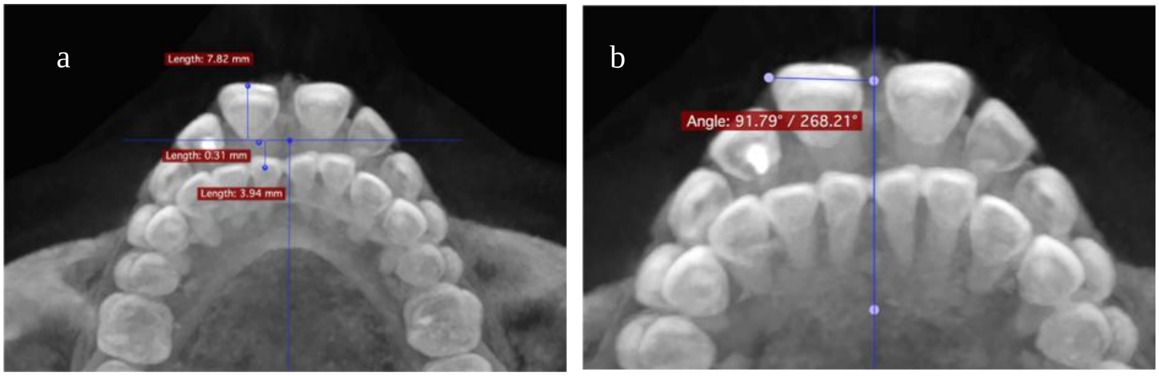

Figure 4. Anterior posterior position of I, C, A were determined as vertical distances away from the horizontal line through ANS in a WO transverse view (a). Rotation of the incisor measured as an angle between the incisal edge and the vertical line in the transverse view (b).

In the sagittal view, inclination was measured as the angle formed from the I-A and ANS-PNS lines (Figure 5). The ANB angle was measured as well. Changes in the inclination angle from T1 to T2 would denote either lingual or buccal root torque.

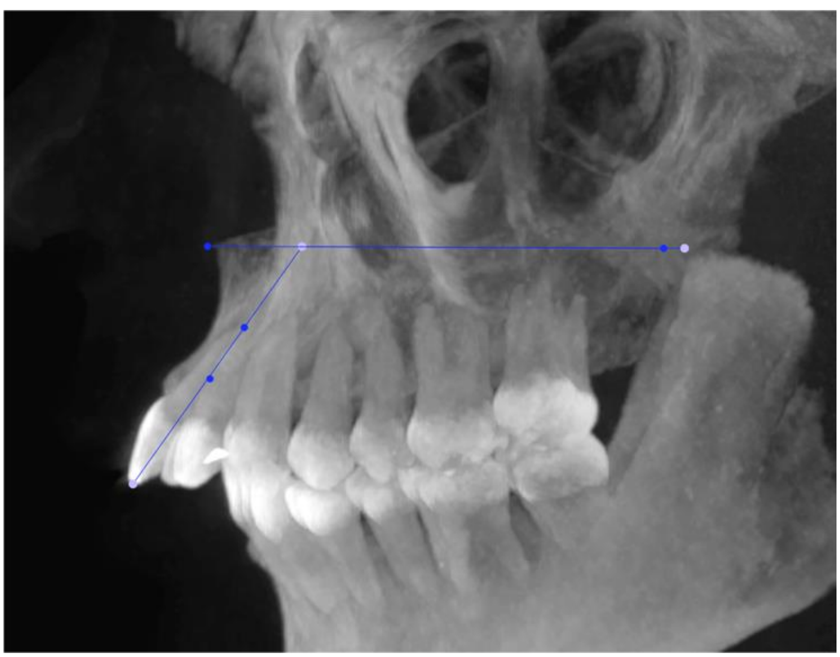

Figure 5. Tooth inclination measured as the angle of I-A to ANS-PNS.

Tooth length was measured from the incisal edge to the root apex on T2 CBCT images. The difference in tooth length between T1 and T2 was recorded as the amount of root resorption. However, the C and A landmarks were placed according to the I-C length, I-A length and CIA angle measurements from T1 in order to duplicate the length of the original root and position of the center of resistance. All measurements previously explained were then performed on the T2 image. All linear and angular measurements were recorded to the nearest 0.1 mm and 0.1° respectively.

Orthodontic movement of the dental landmarks were determined by calculating the difference of the T1 and T2 positions. Negative numerical differences indicated that the direction of movement was extrusion, retraction, or lingual root torque. Differences with a positive value indicated the direction was intrusion, protraction, or buccal root torque. Mesio-distal movements, rotation, and angulation changes were all treated as absolute values with no respect to direction. The total absolute distances, irrespective of direction, that each dental landmark moved from the T1 position was determined by taking the square root of the sum of squares of the vertical, mesio-distal, and anterior-posterior distances for each respective landmark.

Statistical Analysis

Each measured direction of tooth movement for each dental landmark was treated as an independent variable. Non-parametric Spearman-Rho correlation analyses were performed to determine the possible correlations with directions of tooth movement to root resorption. Kruskal-Wallis and Mann-Whitney U tests were performed to determine differences in root resorption between ethnicities, gender, asthmatics, extraction treatment and use of expanders. The data regarding tooth movement was also stratified according to the magnitude of movement in each direction and Kruskal-Wallis and post hoc tests were used to determine differences of root resorption experienced at increasing ranges of tooth movement. Reliability of the measurements was assessed using intra-class correlation tests. For all statistical analyses the significance level was set at alpha ≤ 0.05.

Results

Two hundred ninety-one patients met the selection criteria for this study. One hundred seventy-one were female and one hundred twenty were male. The mean age of the patients was 17.0 ± 9.5 years with a range of 10 to 66 years. The average time in treatment for the sample was 26.6 ± 8.3 months with a range of 9 to 60 months. The mean root resorption in the entire sample was 1.08 ± 1.04 mm with a range of 0.0 to 7.0 mm. Fourteen teeth, or 2.4 %, of all incisors in the sample had 4 mm or more RR.

Both right and left incisors were grouped together for a total of 582 teeth for statistical analysis. Most variables did not display normality; thus non-parametric statistical testing was performed for all analyses.

Table 2. Root Resorption (RR) Severity Distribution

RR (mm)	N	% of total sample
0.0 - 0.4	183	31.4
0.5 - 0.9	141	24.2
1.0 - 1.4	110	18.9
1.5 - 1.9	55	9.5
2.0 - 2.4	38	6.5
2.5 - 2.9	22	3.8
3.0 - 3.4	10	1.7
3.5 - 3.9	9	1.5
≥ 4.0	14	2.4

All measurements were repeated on 30 patients and intra-class correlation tests showed good agreement between original and repeated measurements with most correlation coefficients above 0.85 (Table 3). Mesio-distal movement measurements at I and C were the only measurements with lower coefficients at 0.78 and 0.77 respectively.

Table 3. Intra-Class Correlation on Repeated Measurements

Variable	Intra-Class Correlation	Variable	Intra-Class Correlation
AP I	0.99	Angulation	0.87
AP C	0.91	Rotation	0.93
AP A	0.96	Inclination	0.99
Vertical A	0.94	ANB	0.99
Vertical C	0.92		
Vertical I	0.92	Tooth length	0.97
MD I	0.78		
MD C	0.77		
MD A	0.89		

Correlation Between the Amount of RR and Tooth Movement

Spearman-Rho correlation tests were performed for all directions of tooth movement (Table 4). Weak but statistically significant correlations were found for all linear directions of movement at landmarks A and C except for protraction. For linear directions at landmark I, weak but statistically significant correlations were found only for intrusion, retraction and total movement. For angular measurements, weak but statistically significant correlations were found for all directions of movement.

Table 4. Correlation of Amount of Movement to RR

Direction	Landmark	Correlation	p-value
Intrusion			
	A	0.343	< 0.001*
	C	0.274	0.001*
	I	0.147	0.037*
Extrusion			
	A	0.184	< 0.001*
	C	0.142	0.003*
	I	-0.080	0.120
Retraction			
	A	0.268	< 0.001*
	C	0.283	< 0.001*
	I	0.328	< 0.001*
Protraction			
	A	-0.103	0.176
	C	-0.054	0.483
	I	0.064	0.264
Mesio-distal			
	A	0.165	< 0.001*
	C	0.112	0.007*
	I	0.050	0.230
Lingual Root Torque	-	0.227	< 0.001*
Buccal Root Torque	-	0.162	0.017*
Angulation	-	0.092	0.026*
Rotation	-	0.087	0.036*
Total Movement			
	A	0.344	< .001*
	C	0.303	< .001*
	I	0.181	< .001*

* Statistically significant

Comparisons of mean RR according to the magnitude of tooth movement was made for each linear and angular direction using Kruskal-Wallis and post hoc tests. Intrusion at A showed significantly more RR occurred after only 0.5 to 0.9 mm of intrusion (Table 5). The means of RR associated with 0.5 to 0.9 mm of intrusion at A and

C were comparable to the RR associated with 2.0 to 2.9 mm of extrusion at A and C. There were no significant differences among the RR associated with increasing magnitudes of movement at I in either vertical dimension.

Table 5. Comparison of the amount of RR according to the amount of tooth movement in the vertical dimension

		Root Resorption (mm)		
Movement (mm)	N	Mean ± SD	Range	p-value
Intrusion A				0.002*
0.0 -0.4	51	0.79 ± 0.83^{a}	0.0 - 3.5	
0.5- 0.9	34	1.33 ± 1.00^{b}	0.0 - 3.9	
1.0- 1.4	20	$1.44 \pm 1.15^{a,b}$	0.0 -4.0	
>1.5	25	1.68 ± 1.17^{b}	0.0 - 4.1	
Intrusion C				< .001*
0.0 -0.4	74	0.88 ± 0.79^{a}	0.0 - 3.5	
0.5- 0.9	52	$1.33 \pm 0.99^{a,b}$	0.0 - 3.9	
1.0- 1.4	19	2.06 ± 1.18^{b}	0.2 - 4.1	
>1.5	8	$1.11 \pm 0.94^{a,b}$	0.0 - 2.6	
Intrusion I				0.292
0.0 -0.4	95	1.01 ± 1.07	0.0 - 6.0	
0.5- 0.9	48	1.02 ± 0.94	0.0 - 3.9	
1.0- 1.4	31	1.12 ± 0.72	0.0 - 2.7	
>1.5	26	1.14 ± 0.82	0.2 - 3.3	
Extrusion A				< .001*
0.0 - 0.9	193	0.85 ± 0.82^{a}	0.0 - 4.6	
1.0 - 1.9	140	0.88 ± 0.89^{a}	0.0 - 7.0	
2.0 - 2.9	80	1.32 ± 1.11^{b}	0.0 - 5.3	
≥ 3.0	39	1.88 ± 1.64^{b}	0.0 - 6.0	
Extrusion C				0.005*
0.0 - 0.9	203	0.87 ± 0.80^{a}	0.0 - 4.6	
1.0 - 1.9	145	$1.01 \pm 1.11^{a,b}$	0.0 -7.0	
2.0 - 2.9	55	1.32 ± 1.18^{b}	0.0 - 5.3	
≥ 3.0	26	$1.75 \pm 1.68^{a,b}$	0.0 - 6.0	
Extrusion I				0.246
0.0 - 0.9	194	1.13 ± 1.07	0.0 - 5.7	
1.0 - 1.9	113	1.07 ± 1.01	0.0 - 5.3	
2.0 - 2.9	49	0.88 ± 1.23	0.0 – 7.0	
≥ 3.0	26	1.19 ± 1.22	0.0 - 4.2	

* Statistically significant

The mean RR increased with the magnitude of retraction at A and C but not with protraction (Table 6). Each millimeter of retraction at C appeared to have greater impact on the amount of resorption that occurred compared to retraction at A. The same magnitudes of retraction at A and I were associated with similar resorption values. Protraction at I showed significantly more RR once I was retracted 4 mm or more.

Table 6. Comparison of the amount of RR according to the amount of tooth movement in the anterior-posterior dimension

		Root Resorption (mm)		
Movement (mm)	N	Mean ± SD	Range	p-value
Retraction A				< .001*
0.0 - 0.9	128	0.86 ± 0.86[a]	0.0 - 3.9	
1.0 - 1.9	128	1.15 ± 1.00[a,b]	0.0 - 6.0	
2.0 - 2.9	83	1.24 ± 1.04[b,c]	0.0 - 5.7	
3.0 - 3.9	27	1.38 ± 0.80[b,c]	0.3 - 3.0	
≥ 4.0	43	1.89 ± 1.33[c]	0.0 - 5.3	
Retraction C				< .001*
0.0 – 0.9	164	0.94 ± 0.92[a]	0.0 – 7.0	
1.0 – 1.9	146	1.26 ± 1.01[b]	0.0 – 5.3	
2.0 – 2.9	75	1.33 ± 0.92[b]	0.0 – 4.3	
3.0 – 3.9	20	2.06 ± 1.33[b,c]	0.2 – 5.3	
≥ 4.0	7	3.20 ± 1.36[c]	1.6 – 5.3	
Retraction I				< .001*
0.0 – 0.9	69	0.78 ± 0.79[a]	0.0 – 3.9	
1.0 – 1.9	68	0.92 ± 0.99[a]	0.0 – 5.3	
2.0 – 2.9	65	1.20 ± 1.14[a,b]	0.0 – 5.3	
3.0 – 3.9	25	1.77 ± 1.43[b,c]	0.0 – 4.3	
≥ 4.0	47	1.78 ± 1.25[c]	0.0 – 7.0	
Protraction A				0.500
0.0 – 0.4	61	0.92 ± 0.96	0.0 – 4.2	
0.5 – 0.9	45	0.76 ± 0.93	0.0 – 4.6	
1.0 – 1.4	34	0.57 ± 0.62	0.0 – 2.7	
1.5 – 1.9	17	1.12 ± 1.70	0.0 – 7.0	
≥ 2.0	16	0.91 ± 1.18	0.0 – 4.0	
Protraction C				0.870
0.0 – 0.4	83	0.72 ± 0.91	0.0 – 5.7	
0.5 – 0.9	35	0.81 ± 1.12	0.0 – 6.0	

1.0 – 1.4	25	0.64 ± 0.91	0.0 – 4.6	
1.5 – 1.9	14	0.84 ± 1.00	0.0 – 3.5	
≥ 2.0	13	0.53 ± 0.64	0.0 – 1.3	
Protraction I				0.014*
0.0 – 0.9	116	0.91 ± 0.89[a]	0.0 - 4.4	
1.0 – 1.9	91	0.98 ± 0.87[a, b]	0.0 – 4.6	
2.0 – 2.9	51	0.81 ± 0.62[a]	0.0 – 5.3	
3.0 – 3.9	25	0.74 ± 0.69[a]	0.0 – 3.4	
≥ 4.0	25	1.81 ± 1.56[b]	0.0 – 6.0	

* Statistically significant

In the mesio-distal dimension, mean RR was significantly higher with more than 2 mm of mesio-distal movement at A and C (Table 7). There were no differences in RR among the magnitudes of mesio-distal movement at I.

Table 7. Comparison of the amount of RR according to amount of Mesial-Distal Movement

		Root Resorption (mm)		
Movement (mm)	N	Mean ± SD	Range	p-value
Mesio-distal A				
0.0 - 0.9	346	0.96 ± 0.96[a]	0.0 - 5.3	< 0.001*
1.0 - 1.9	173	1.09 ± 1.04[a,b]	0.0 - 7.0	
2.0 - 2.9	52	1.67 ± 1.30[c]	0.0 - 6.0	
≥ 3.0	11	1.50 ± 1.03[a,b,c]	0.0 - 3.0	
Mesio-distal C				0.004*
0.0 - 0.9	407	1.02 ± 1.04[a]	0.0 - 7.0	
1.0 - 1.9	154	1.14 ± 0.98[a,b]	0.0 – 5.3	
≥ 2.0	21	1.62 ± 1.31[b]	0.0 – 6.0	
Mesio-distal I				0.449
0.0 – 0.9	340	1.04 ± 1.04	0.0 – 7.0	
1.0 – 1.9	182	1.11 ± 1.06	0.0 – 6.0	
2.0 – 2.9	43	1.13 ± 1.04	0.0 – 5.7	
≥ 3.0	17	1.28 ± 1.07	0.0 – 3.9	

* Statistically significant

There appeared to be statistically significant differences in RR with increased buccal root torque; however, no differences were actually found when the significant values were adjusted by the Bonferroni correction for multiple comparisons in the post hoc tests. Still there appears to be a clinical trend of increasing RR with increased buccal root torque. A statistically significant increase in RR occurred with 10.0 to 14.9° of lingual root torque and then another increase of RR with 20° or more (Table 8).

Table 8. Comparison of the amount of RR according to the amount torque

		Root Resorption (mm)		
Movement (°)	N	Mean ± SD	Range	p-value
Buccal Root Torque				0.014*
0.0 - 4.9	104	0.97 ± .98	0.0 - 4.6	
5.0 - 9.9	64	0.99 ± 1.13	0.0 - 4.3	
10.0 - 14.9	21	1.11 ± 0.94	0.0 - 3.6	
15.0 - 19.9	17	1.60 ± 1.24	0.0 - 4.1	
≥20.0	11	2.20 ± 1.89	0.0 - 7.0	
Lingual Root Torque				< .001*
0.0 - 4.9	148	0.81 ± 0.65[a]	0.0 - 3.6	
5.0 - 9.9	117	1.05 ± 1.12[a, b]	0.0 - 5.3	
10.0 - 14.9	58	1.30 ± 0.95[b, c]	0.0 - 4.4	
15.0 - 19.9	22	1.24 ± 0.85[a,b,c]	0.0 – 3.5	
≥ 20	20	2.00 ± 1.58[c]	0.0 – 6.0	

* Statistically significant

The Kruskal-Wallis test showed that a statistically significant difference in RR existed with increased angulation changes (Table 9); however, again there were no statistical differences found when adjusted by the Bonferroni correction for multiple comparisons.

Rotation of 10 to 14.9° was associated with statistically more RR but no increase of RR occurred with more rotation (Table 10).

Table 9. Comparison of the amount of RR according to the amount of angulation change

		Root Resorption (mm)		
Movement (°)	N	Mean ± SD	Range	p-value
Angulation				0.012*
0.0 - 4.9	425	0.98 ± 0.95	0.0 - 5.3	
5.0 - 9.9	134	1.25 ± 1.17	0.0 - 7.0	
≥10.0	23	1.70 ± 1.41	0.0 -5.7	

* Statistically significant

Table 10. Comparison of the amount of RR according to the amount of rotation

		Root Resorption (mm)		
Movement (°)	N	Mean ± SD	Range	p-value
Rotation				0.044*
0.0 - 4.9	208	0.99 ± 1.03[a]	0.0 - 5.7	
5.0 - 9.9	168	1.02 ± 0.92[a,b]	0.0 -4.3	
10.0 - 14.9	122	1.32 ± 1.27[b]	0.0 - 7.0	
15.0- 19.9	42	1.11 ± 0.82[a,b]	0.0 - 3.4	
≥ 20.0	42	0.95 ± 0.94[a,b]	0.0 - 3.9	

* Statistically significant

Root resorption significantly increased as total linear movement, irrespective of direction, increased at all the dental landmarks (Table 11). It appeared that A and C had more impact on root resorption for every millimeter of movement than at I.

Table 11. Comparison of the amount of RR according to the amount of total tooth movement

		Root Resorption (mm)		
Movement (mm)	N	Mean ± SD	Range	p-value
Total A				< .001*
0.0 - 1.4	119	0.66 ± 0.69[a]	0.0 - 3.9	
1.5 - 2.9	281	1.00 ± 0.97[b]	0.0 - 7.0	
3.0 - 4.4	124	1.21 ± 1.00[b]	0.0 - 5.3	
≥ 4.5	58	1.98 ± 1.41[c]	0.0 - 6.0	
Total C				< .001*
0 - 0.9	76	0.58 ± 0.57[a]	0.0 - 2.7	
1 - 1.9	239	0.91 ± 0.87[b]	0.0 - 7.0	
2.0 - 2.9	160	1.19 ± 1.08[b]	0.0 - 5.3	
≥ 3.0	107	1.61 ± 1.31[c]	0.0 - 6.0	
Total I				< .001*
0.0 - 1.9	208	0.94 ± 0.98[a]	0.0 - 5.3	
2.0- 3.9	268	0.94 ± 0.87[a]	0.0 - 5.3	
4.0 - 5.9	63	1.50 ± 1.28[b]	0.0 - 7.0	
≥ 6.0	43	1.92 ± 1.38[b]	0.0 - 6.0	

* Statistically significant

Relationship of RR with Other Factors

There was a statistically significant but weak correlation with root resorption and time in treatment ($r = 0.213$, $p < 0.001$; Table 12).

No correlation was found between root resorption and the age of patient. There was also no correlation with root resorption and the patient’s ANB angle when the patient had a Class III skeletal relationship. However, there was a weak but significant correlation ($r = 0.200$, $p < 0.001$; Table 12) with RR and positive ANB angles.

Table 12. Correlation of other variables to RR

Variable	Correlation	p-value
Treatment Time	0.213	< .001*
Age	-0.003	0.952
Positive ANB	0.200	< .001*
Negative ANB	-0.083	0.673

* Statistically significant

Ethnicity was divided into 4 categories, Asian, Black, Caucasian and Hispanic. 14 patients' ethnicity was unknown and were not included for comparison. There were no significant differences in root resorption among them ($p = 0.100$; Table 13). Total movement at the apex was also compared among groups to control for a confounding variable. The Kruskal-Wallis test showed that there were no differences in total movement at the apex among ethnicities.

Table 13. Comparison of RR Based on Ethnicity

		Root Resorption (mm)		
Ethnicity	N	Mean	SD	p-value
Asian	16	0.57	0.67	0.100
Black	44	1.21	1.02	
Caucasian	284	1.10	1.09	
Hispanic	210	1.06	1.02	

Mean root resorption for males was 0.25 mm more than for females ($p = 0.008$; Table 14). However, the mean total movement at the apex was higher for males (2.90 ± 1.55 mm) than females (2.27 ± 1.11 mm; $p < 0.001$).

Table 14. Comparison of RR Based on Gender

Gender	N	Root Resorption (mm) Mean	SD	p-value
Female	342	0.97	0.96	0.008*
Male	240	1.22	1.13	

Mean root resorption was significantly higher for patients who had rapid maxillary expansion (RME) or expansion with a quad helix ($p < 0.001$; Table 15) while at the same time there were no differences in the total movement at the apex among groups. Treatment involving extraction of two upper premolars had higher mean RR than incisors treated in non-extraction ($p < 0.001$; Table 16). Expectedly, the extraction group also had more movement at the apex (2.75 ± 1.45 mm) compared to the non-extraction group (2.49 ± 1.31 mm; $p = 0.015$).

Table 15. Comparison of RR Based on Use of RME appliance

Expander	N	Root Resorption (mm) Mean	SD	p-value
Non expansion	420	0.95[a]	0.96	<0.001*
RME	82	1.58[b]	1.34	
Quad Helix	80	1.20[b]	0.96	

Table 16. Comparison of RR Based on Extractions

Extraction	N	Root Resorption (mm) Mean	SD	p-value
Non-EXT	462	0.99[a]	0.99	<0.001*
1 Tooth	14	0.94[a, b]	0.73	
2 Teeth	106	1.43[b]	1.19	

Root resorption was not different between asthmatics and non-asthmatics (p = 0.954; Table 17). Additionally, there was no difference in amount of total movement at the apex between the two groups.

Table 17. Comparison of Root Resorption between Non-Asthmatic and Asthmatic

		Root Resorption (mm)		
Asthma	N	Mean	SD	p-value
Non-Asthmatic	516	1.05	0.98	0.962
Asthmatic	66	1.20	1.43	

Discussion

Patients receiving orthodontic treatment need to be well informed about the risk of apical root resorption. However, since the occurrence of severe resorption of roots is uncommon, the benefits of orthodontic treatment most likely outweigh the risks. To demonstrate the low risk, we found that approximately 31.4% of incisors in our sample had less than 0.5 mm of resorption (Table 2). Additionally, only 2% of the teeth in our sample had 4 mm or more apical resorption. Our findings are consistent with previous studies that report a range between 1-5% of teeth having severe root resorption.[12,15]

We found that some directions of tooth movement were more associated with severity of root resorption than others. Regarding vertical movement at A and C, even though intrusion and extrusion were both significantly correlated, intrusion appeared to have more impact on the severity of root resorption than extrusion (Table 5). Some studies have found no significant relationship between intrusion and resorption[22-24] while others have reported a significant relationship.[12,14] Pressure produced from orthodontic force during intrusion of an incisor can easily become excessive and lead to hyalinized zones in the PDL. One has to be cautious of forces during intrusion since low forces values can still produce high pressure when it is applied to a small root surface area.

Neither intrusion nor extrusion at I showed any trend of higher RR with increasing movement (Table 5). This might be due to the fact that changes in vertical position at the incisal edge of maxillary central incisors in this study could have been a result of relative intrusion and extrusion from tipping of the tooth, rather than true intrusion and extrusion.

In the anterior-posterior direction, there were significant correlations between retraction and RR at all the dental landmarks whereas there were none between RR and protraction (Table 6). Retraction of the incisor would likely bring the root against the denser bone of the palatal cortical plate, which has been regarded as a risk factor of RR.[23] Each millimeter of retraction at C appeared to have greater root resorption than retraction at A and I. Retraction at C would indicate that lingual bodily movement (translation) of the tooth occurred; and in the process the root apex could have cycled through many redundant tipping and uprighting movements, thus exposing the root to more resorption.

Although protraction at A, C and I did not have any correlations with RR (p = 0.176, 0.483, 0.264; Table 4), when RR was compared according to the magnitude of protraction at I there was significantly more RR once 4 mm or more of protraction occurred (Table 6). Greater protraction at I at this magnitude could be related to uncontrolled tipping which brings the apex of the root into close proximity to the palatal cortical plate. All protraction values at A and C had low mean values of RR. The thin or less dense buccal bone that the tooth moves against in this direction could be a factor as to why values of RR were lower.

Unlike the other dimensions of linear movement, mesio-distal movement was not subdivided into separate mesial and distal categories of movement. This is because unlike the vertical and anterior-posterior movements, in mesial or distal movements the surface area of the PDL being compressed and the density of the surrounding bone is generally the same in either direction. Mesio-distal movements at A and C had significant correlations with RR ($p < 0.001$, $= 0.007$) but not at I ($p = 0.230$; Table 4). This supports the notion that orthodontic movement of the incisal edge alone likely has little association with RR.

All angular measurements had statistically significant correlations although angulation and rotation had very weak correlations with RR. Although buccal root torque had a correlation of 0.162 ($p = 0.017$; Table 4) there were no statistically significant differences of RR found among different magnitudes of buccal root torque (Table 8). However, there still appeared to be a clinically relevant trend of increased RR in the groups of higher buccal root torque, but the sample sizes in those groups were likely too small to determine statistical difference.

Lingual root torque between 10 to 14.9° had significantly higher mean RR compared to incisors with 0.0 to 4.9° lingual root inclination change (1.30 ± 0.95 versus 0.81 ± 0.65 mm, $p <0.001$; Table 8). An even higher and clinically significant mean RR was associated with lingual root torque that exceeded 20° (2.00 ± 1.58 mm). Lingual root torque has previously been reported as an important factor related to root resorption.[12,23] For instance, Parker and Harris reported lingual root torque as one of the strongest predictors for resorption while buccal root torque had no significant relationship.[14] While we did find increases in lingual root torque to be associated with statistically significant increases in mean resorption, we also found increasing buccal root torque to have similar increasing trends of resorption although these were not statistically significant.

Total linear movement at all the dental landmarks had significant but weak correlations with root resorption (Table 4). A meta-analysis performed on treatment related factors found a high correlation of total movement at the apex with root resorption.[11] Total movement at the apex did have the highest correlation of all the movement variables in our sample but the correlation was still weak. Significantly more resorption occurred when the apex was moved 4.5 mm or more compared to when the apex was moved between 0.0 to 1.49 mm (1.98 ± 1.41 versus 0.66 ± 0.69 mm, $p< 0.001$; Table 11). When orthodontic forces are primarily concentrated on the apex it would be expected that more resorption would take place.

Time in treatment also had a significant but weak correlation with root resorption ($p < 0.001$; Table 12). The correlation we found was lower than what has previously been reported.[11] There is some ambiguity on how other studies measure time in treatment. This variable may not be an accurate measurement of active treatment since it does not necessarily indicate how long forces were applied to the incisors. Nevertheless, in our study, time in treatment was initiated when upper incisors were bracketed or a palatal expander was placed and ended when the brackets were removed. Motokowa et al[25] found that RR was higher when treatment lasted longer than 30 months. Maues et al[26] compared time in treatment of more than 3 years to less than 3 years and found that significantly more resorption occurred in the former. Longer time in treatment could be related to longer stimulation of resorptive processes. The accumulation of surface resorption could lead to more severe resorption.

Negative ANB angles were not correlated with root resorption. Patients with negative ANB angles have a Class III tendency and non-surgical orthodontics would likely warrant protraction of the incisors. There was no correlation in protraction of the upper incisors with root resorption which may be the reason that negative ANB angles also did not have a significant correlation. Positive ANB angles did have a significant but weak correlation ($p < 0.001$; Table 12) which is likely related to retraction of the upper incisors, which is often necessary to resolve occlusal discrepancies due to mandibular deficiencies.

There were no differences in the amount of root resorption among the ethnicities identified. A previous study reported that Asians have less root resorption than Caucasians and Hispanics.[6] Asians in this sample did have less root resorption on average, but it was not statistically significant. Our sample size from the Asian group was also considerably smaller than that of Caucasians and Hispanics. However, it would have been beneficial to have more Asian samples in our study for a better comparison. The previously mentioned study also reported that Hispanics had the most resorption with a mean of 0.7 to 0.8 mm more than Asians. Our results also conflict with this finding.

Our sample of male patients had a mean of 0.25 mm more resorption than female patients. Another study reported their adult male patients had 1.2 mm more resorption than their adult female patients.[22] However, our sample of males also had more total linear movement at A (2.90 ± 1.55 mm) compared to females (2.27 ± 1.11 mm, $p < 0.001$; Table 14). Thus the higher resorption in our sample of males may be related to the magnitude of tooth movement more than the characteristic of gender. This may be likely as many previous studies have found no difference of root resorption between genders. [1,6,9,14,16,26-28]

There were two expansion groups in our study, patients treated with a rapid maxillary expansion (RME) appliance, such as a hyrax or haas, and patients treated with a dental expansion appliance, such as a quad helix. Both expansion groups had more root resorption than the non-expansion group ($p < 0.001$; Table 15). The RME group had more root resorption than the quad helix group but it was not statistically significant. Other studies comparing expanders to root loss usually limit their investigation to the premolars and molars since they are under direct force of the appliance. However, the opening of the palatal suture during RME could introduce inflammatory mediators in proximity of the incisor roots and increase the risk of resorption. Quad helixes can also stretch the palatal suture for less dramatic skeletal changes.[29] However, this is usually possible only in younger patients. A previous study found no significant differences of root resorption to the incisors for transverse treatments including rapid palatal expansion, slow expansion or no expansion.[7]

Whether more resorption that occurred in the RME group was due to more tooth movement or due to the rapid bone modeling occurring in close proximity to the roots is difficult to determine. In our study, total movement at A was not statistically different among non-expansion and the expansion groups. Yet, we know that between T1 and T2 the incisors are spaced apart from the expansion and more movement is needed to close the space. The extra distance of root movement could not be recorded by our methods but it may be partially responsible for why more root resorption occurred.

Patients who had two upper premolars extracted had more root resorption than those who had no extraction ($p < 0.001$; Table 16). Usually treatment involving the extraction of two upper premolars requires retraction of the incisors which is a direction of movement that was found to be correlated with root resorption. Sameshima[10] found no differences in RR among different extraction patterns for those patients who had severe resorption. McNab[30] reported that the incidence of resorption of posterior teeth was approximately 3.7 times higher for those who had extractions. Motokawa et al[25] reported their extraction group had a higher prevalence of severe resorption to the maxillary central incisors as well, which supports our findings.

Our findings of root resorption in asthmatics conflicts with previous reports that asthmatics are at greater risk for root resorption.[12,31] It has been supposed that the systemic inflammatory processes in asthmatics or patients with allergies could intensify the inflammatory process involved in tooth movement.[1,32] Our sample of asthmatics had no significant difference of resorption compared to non-asthmatics. However, due to our method of data collection, only the presence of an asthmatic condition, but not the severity, was recorded and evaluated.

Other medical related factors such as medications taken, hormonal deficiencies such as hypothyroidism or hypopituitarism, and chronic alcoholism have possible relationships with root resorption.[12] We attempted to gather as much information from the medical history as possible but unfortunately sample sizes for these and other conditions were too small to make any comparisons.

For all the variables that we examined for this study, no moderate or strong correlations were found. However, based on our results, orthodontists should be more cautious of root resorption in patients that require significant intrusion and retraction, yet we acknowledge that there are likely other factors that have greater impact on the risk for resorption such as force values[12,15,22,33] and genetics.[9,8]

Conclusions

Based on the results from this study, we conclude that:

1. Weak but statistically significant correlations existed between RR and all linear movements of A and C, except for protraction. At I, only retraction and intrusion had significant but weak correlations with RR.
2. Total movement of A, intrusion of A, and retraction of I had the highest correlations with RR (r= 0.344, 0.343, 0.328).
3. Weak but statistically significant correlations existed between all angular measurements and RR.
4. Lingual root torque had the highest correlation of angular measurements with RR (r=0.227).
5. Weak but statistically significant correlations with RR existed for both treatment time and positive ANB angles (r= 0.213 and 0.200). No correlation with RR existed for patient age or negative ANB angles.
6. Treatment with expansion or extraction of two premolars resulted in more RR than non-expansion or non-extraction treatment respectively.
7. There were no differences in RR among different ethnicities nor between asthmatics and non-asthmatics.

CHAPTER THREE

EXTENDED DISCUSSION

Study Limitations

It is difficult to be exact when determining the distance and direction of tooth movement solely from orthodontic force. The direction of tooth movement in this study was defined by the palatal plane as well as the other planes used in WO. The palatal plane at ANS has long been established as a reference for cephalometric measurement of maxillary dental changes during orthodontic treatment.[34] When superimposing T1 and T2 cephalograms on these reference structures there would be minimal change in tooth position in the absence of orthodontic treatment. The minimal change that would be present would be due to post-eruption movement of the dentition if growth was present between T1 and T2.

The upper incisors are expected to erupt downward and forward approximately 0.2 to 0.3 mm per year when superimposed over the palatal plane at ANS.[34] This movement forward and down would affect the ability to accurately measure extrusion and intrusion or protraction and retraction that occurred solely from orthodontic force. However, the effect is small. Additionally, 82% of the patients in the study were under 18 years old, making the effects of eruption present in most of the measurements performed. Therefore, due to the difficultly to control for it and it being most likely inconsequential to the results, natural post-eruption movement from growth was not accounted for.

Regarding the method of measuring root length changes, wear of incisal edges during orthodontic treatment could have affected these measurements. Patients whose treatment charts included notes of enameloplasty to the incisal edges of the maxillary incisors were excluded from this study for this very reason. The measured changes in root length could be more reliable if a more stable point was available for reference. The cemento-enamel junction for example would have been stable. However, even though anatomically the structure is stable, it was judged to be more difficult to replicate the precise location of its position on the radiographic image compared to the incisal edge.

Lastly, while the distance that the tooth moved from T1 to T2 images can be measured, it is uncertain how much the tooth moved between those time points. Often with orthodontic treatment, “round tripping” occurs, in which the tooth is moved in one direction but then is moved back to the other direction. The results in this study assumes that “round tripping” is inconsequential to the movement that was measured.

Future Study Direction

The correlations in this study were determined based on the root resorption that occurred in patients chosen in reverse chronological order from the T2 records date. Only a very small percentage of the patients in the study had root resorption that was severe. When enough data is available, a future study could include only data from patients with severe resorption and analyze the treatment and patient related factors present.

Future studies in root resorption could also investigate genetics. These studies could also be retrospective in design but patients would have to be recalled in order to determine allele types of the specific genes being investigated.

Root shape and proximity to the cortical bone were not measured in this study, but these are factors that should be followed up on with CBCT imaging. Additionally, future studies that use CBCT data can analyze and measure root resorption as a volume instead of a linear measurement. A volumetric measurement would be a more accurate characterization of the destructive changes that occur to the root during treatment.

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