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Validation of two-dimensional measurements of root resorption craters on human premolars after 28 days of force application

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SUMMARY The aims of this study were to develop a three-dimensional (3D) mathematical model of a typical root resorption crater and to correlate two-dimensional (2D) surface area measurements to 3D volumetric measurements of root resorption craters created under light and heavy orthodontic forces. Data were obtained from a previous study of 36 first premolars from 16 subjects requiring extraction of these teeth as part of their orthodontic treatment. Buccal tipping forces of 25 or 225 g were applied for an experimental period of 28 days. After extraction, the samples were prepared for scanning electron microscopy (SEM) imaging, image processing and analysis. Surface area (2D) and volumetric (3D) measurements of all craters were obtained. A mathematical analysis of the 2D/3D relationship enabled the determination of an appropriate digital model for the shape, type and dimensions of resorption craters, which was also able to distinguish between a 'hemispheric' model versus a 'layered' model of craters.

The results demonstrated that 2D and 3D measurements were strongly correlated ($r = 0.991$**). Within the light and heavy force groups, the measurements were also strongly correlated ($r = 0.978$** and $r = 0.994$**, respectively). For a 28 day experimental period, 2D measurements of root resorption craters were found to be as reliable as 3D measurements.

Introduction

Root resorption has been used as a universal term that describes a pathological process for which no single aetiological component is engaged in the expression (Brezniak and Wasserstein, 2002). It has been defined as the active removal of mineralized cementum and dentine (Brudvik and Rygh, 1994). The study of this phenomenon over the years has concluded that root resorption could be an idiopathic and unpredictable adverse effect of orthodontic treatment. The detection of root resorption has been mainly through radiographs (Ketcham, 1929), light microscopy (Reitan, 1974) and scanning electron microscopy (SEM) (Jones and Boyde, 1972; Kvam, 1972a, b). Although the importance of identifying high-risk patients and their various ways of management has been highlighted, quantitative evaluation of root resorption is still relatively poor. There remain several flaws in two-dimensional (2D) surface measurements for this three-dimensional (3D) phenomenon.

It has been previously reported that most external root resorption could be self-limiting. For this reason, approximately 70 per cent of all defects seen in mature teeth are anatomically repaired (Henry and Weinmann, 1951; Andreasen, 1988). However, the mechanism behind this self-limiting phenomenon has not been fully explored.

The aims of this study were to develop a 3D mathematical model of a typical root resorption crater created under both light and heavy orthodontic forces and to correlate accurate 2D surface area measurements to 3D volumetric measurements of root resorption craters.

Materials and method

A sample of 36 teeth from 16 patients (10 males, six females, mean age 13.9 years, range 11.7–16.1 years) requiring at least bilateral maxillary or mandibular first premolar extraction for orthodontic treatment was collected. Ethical approval and informed consent from all patients were obtained. They also complied with a strict selection criterion excluding any local or systemic conditions that may predispose to root resorption (Srivicharnkul *et al.*, 2005). The clinical set-up for the application of forces has been previously described (Srivicharnkul *et al.*, 2005).

The patients were allocated equally into a light or heavy force group with a buccal tipping force of 25 or 225 g applied to the first premolars using a cantilever spring from the ipsilateral first molar. Within the same patients, the contralateral sides served as the control (0 g). After an experimental period of 28 days, the premolars were extracted, disinfected and cleaned (Malek *et al.*, 2001). The samples were then bench dried and carbon coated for SEM imaging with a XL30 SEM (Phillips, Eindhoven, The Netherlands). A motorized jig (Figure 1) was designed so that all surfaces of the root could be studied without constant pumping and venting of the vacuum chamber. Using stereo imaging, all craters detected on the buccal and lingual surfaces of the samples were digitally obtained and stored as TIFF images. The imaging surface of the root was positioned to line up parallel to the horizontal during imaging to minimize parallax errors. A further shading correction (Chan *et al.*, 2004) also eliminated the innate

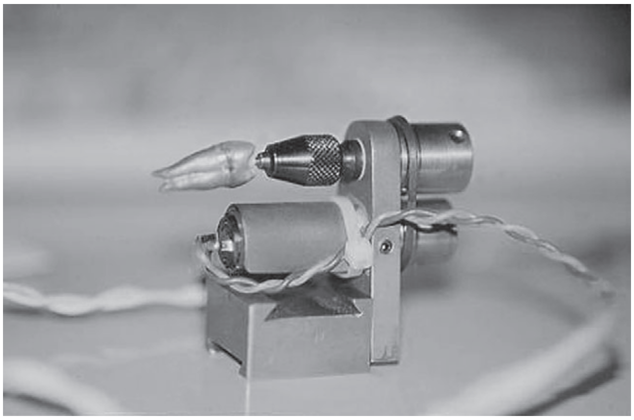

Figure 1 The 360 degree motorized rotating jig that was installed in the scanning electron microscope (SEM) chamber enabled the viewing and imaging of all surfaces of the root in the SEM chamber without time-consuming and constant pumping and venting.

curvature present, which could induce errors in quantitative measurements. Surface area and volumetric recordings of these craters were obtained using a modification of a commercial computer software (Analysis Pro 3.1 Soft Image System, SIS, Münster, Germany). For surface area (2D) measurements, absolute straight-on images were captured, whereas for volumetric (3D) measurements, stereo pairs of images at 6 degree angulations were taken. This methodology has been described previously (Chan *et al*., 2004). The analysis software was previously calibrated with a Vickers hardness tester using four different metallic rods and has proven its accuracy and reproducibility (Chan *et al*., 2005). The profiles for surface area and volumetric measurements were compared and correlated. A digital model of a typical crater was mathematically derived.

Statistical analysis

Univariate analysis of variance (one-way ANOVA) was performed using the Statistical Package for Social Sciences (SPSS for Windows, version 11, SPSS Inc, Chicago, Illinois, USA). During statistical evaluation, the raw data were transformed for the residual plots to conform to normality. The square root of the surface area (srtarea) and cube root of the volumetric readings (crtvol) were used to create the full model for statistical analysis. This allowed correlation of the quantitative data between 2D and 3D measurements.

Results

Comparing the area and volumetric measurements

The profiles of the surface area (2D) measurements demonstrated very similar results to the volumetric (3D) measurements (Table 1). The 2D measurements were strongly correlated to the 3D measurements ($r = 0.991$**) (Table 2). Within the light and heavy force groups, the measurements were also strongly correlated ($r = 0.978$** and $r = 0.994$**, respectively) (Table 3).

Digital model of a resorption crater

The values obtained for the area and volumetric measurements were analysed mathematically to test for either a layered or hemispheric model. If a layered model of craters is appropriate, then a graph of volume against area should be linear. On the other hand, if a hemispheric model is appropriate, then a graph of volume against area should show a curvature, while a graph of cube root volume against square root area should be linear. The appropriate graphs are shown in Figure 2. Figure 2a does in fact show a curved relationship between volume and area (even more pronounced if the 'outlier', the largest crater, is ignored), whereas Figure 2b shows a relationship that is essentially linear. These observations are supported by the correlations obtained between the sets of measurements: the correlation between volume and area was 0.97 (0.96 with the outlier removed), whereas the correlation between cube root volume and square root area was 0.99. These results indicate that the craters tend to conform to a hemispheric model rather than a layered model, although the very largest craters may not conform. This demonstrates that typical craters tend to be hemispheric models (area less than 2×10^6 μm^2 and volume less than 300×10^6 μm^3) (Figure 3a), whereas very large craters tend to be layered (Figure 3b).

Discussion

Previous studies investigating the quantitative value of root resorption utilized 2D measurements. A series of studies by Owman-Moll (1995) and Owman-Moll *et al.* (1995, 1996a, b) performed on 144 adolescents and 200 premolar teeth reported that tooth movements and severity of root resorption were not significantly affected by doubling the force magnitude from 50 to 100 g. It was also noted that the amount of root resorption was greater after 7 weeks with a force magnitude of 50 g compared with 100 g. Although the authors could not explain this phenomenon, their results were in agreement with Stenvik and Mjör (1970), who reported that an increased force caused a decrease in the frequency of root resorption when premolars were intruded. They observed that root resorption increased after the application of light forces of 35 g when compared with heavy forces of 250 g. They all contributed this phenomenon to other idiopathic individual variations, e.g. the metabolic responses of the subjects. They then concluded that root resorption does not seem to be very force sensitive. Despite these observations, they still cautioned that their results should not mislead clinicians into using heavy forces.

However, in a recent study measuring the volume of resorption craters (Chan and Darendeliler, 2005) it was demonstrated that the mean volume of resorption in the light force group was 3.49-fold more than in the control

Table 1 Descriptive statistics (a) and one-way ANOVA (b) for raw and transformed volume and area measurements by force group.

	n	Mean	Standard deviation
(a) Descriptive statistics			
Volume total			
0 control	108	2.796	21.081
1 light	54	9.781	33.098
2 heavy	54	32.428	84.085
Total	216	11.950	48.813
Surface area			
0 control	108	0.025	0.163
1 light	54	0.090	0.293
2 heavy	54	0.270	0.596
Total	216	0.102	0.363
Cube root volume			
0 control	108	0.174	0.768
1 light	54	0.591	1.394
2 heavy	54	1.220	2.124
Total	216	0.540	1.438
Square root area			
0 control	108	0.033	0.155
1 light	54	0.113	0.280
2 heavy	54	0.258	0.455
Total	216	0.109	0.301

	Sum of squares	df	Mean square	*F*	Significance
(b) ANOVA					
Volume total					
Between groups	31949.468	2	15974.734	7.084	0.001
Within groups	480334.235	213	2255.090		
Total	512283.703	215			
Surface area					
Between groups	2.171	2	1.086	8.821	0.000
Within groups	26.216	213	0.123		
Total	28.388	215			
Cube root volume					
Between groups	39.546	2	19.773	10.398	0.000
Within groups	405.053	213	1.902		
Total	444.600	215			
Square root area					
Between groups	1.812	2	0.906	10.884	0.000
Within groups	17.730	213	0.083		
Total	19.542	215			

group, and in the heavy force group was 11.59-fold more than in the control group. The heavy force group had a 3.31-fold more total resorption volume than the light force group. The buccal cervical and lingual apical regions demonstrated significantly more resorption craters than the other regions. Although there was more resorption recorded in the light group, the difference in the amount of resorption between the light and control groups was not significantly different.

The method of quantitative analysis of craters described in earlier studies may not be sufficiently adequate to truly reflect the amount of resorption that occurred. Serial sectioning and selective sampling of the resorbed area may have caused resorption regions to be missed. Parallax error was not taken into consideration and could have markedly distorted the data. The selection criteria for the premolars were not strict and external factors that may predispose to root resorption did not seem to be excluded. Ligature wires used to engage the wires into the bracket could have distorted the force system by introducing undesired moments (Chan and Darendeliler, 2004).

On the other hand, Reitan (1964, 1974, 1985) has always advocated the use of light orthodontic forces during treatment in order to increase cellular activity in the surrounding tissues and to reduce the risk of root resorption. This was later confirmed by King and Fischlschweiger (1982). They found in an investigation in rats that light forces produced

Table 2 Correlations between raw and transformed volume and area measurements.

	Volume total	Surface area	Cube root volume	Square root area
Volume total				
Pearson correlation	1.000	0.971**	0.868**	0.879**
Significance (two-tailed)		0.000	0.000	0.000
n	216	216	216	216
Surface area				
Pearson correlation	0.971**	1.000	0.916**	0.945**
Significance (two-tailed)	0.000		0.000	0.000
n	216	216	216	216
Cube root volume				
Pearson correlation	0.868**	0.916**	1.000	0.991**
Significance (two-tailed)	0.000	0.000		0.000
n	216	216	216	216
Square root area				
Pearson correlation	0.879**	0.945**	0.991**	1.000
Significance (two-tailed)	0.000	0.000	0.000	
n	216	216	216	216

**Correlation is significant at the 0.01 level (two-tailed).

Table 3 Correlations between raw and transformed volume and area measurements in (a) the light force and (b) the heavy force groups.

	Volume total	Surface area	Cube root volume	Square root area
(a) Light force group				
Volume total				
Pearson correlation	1.000	0.947**	0.889**	0.902**
Significance (two-tailed)		0.000	0.000	0.000
n	54	54	54	54
Surface area				
Pearson correlation	0.947**	1.000	0.874**	0.941**
Significance (two-tailed)	0.000		0.000	0.000
n	54	54	54	54
Cube root volume				
Pearson correlation	0.889**	0.874**	1.000	0.978**
Significance (two-tailed)	0.000	0.000		0.000
n	54	54	54	54
Square root area				
Pearson correlation	0.902**	0.941**	0.978**	1.000
Significance (two-tailed)	0.000	0.000	0.000	
n	54	54	54	54

	Volume total	Surface area	Cube root volume	Square root area
(b) Heavy force group				
Volume total				
Pearson correlation	1.000	0.974**	0.878**	0.880**
Significance (two-tailed)		0.000	0.000	0.000
n	54	54	54	54
Surface area				
Pearson correlation	0.974**	1.000	0.933**	0.949**
Significance (two-tailed)	0.000		0.000	0.000
n	54	54	54	54
Cube root volume				
Pearson correlation	0.878**	0.933**	1.000	0.994**
Significance (two-tailed)	0.000	0.000		0.000
n	54	54	54	54
Square root area				
Pearson correlation	0.880**	0.949**	0.994**	1.000
Significance (two-tailed)	0.000	0.000	0.000	
n	54	54	54	54

**Correlation is significant at the 0.01 level (two-tailed).

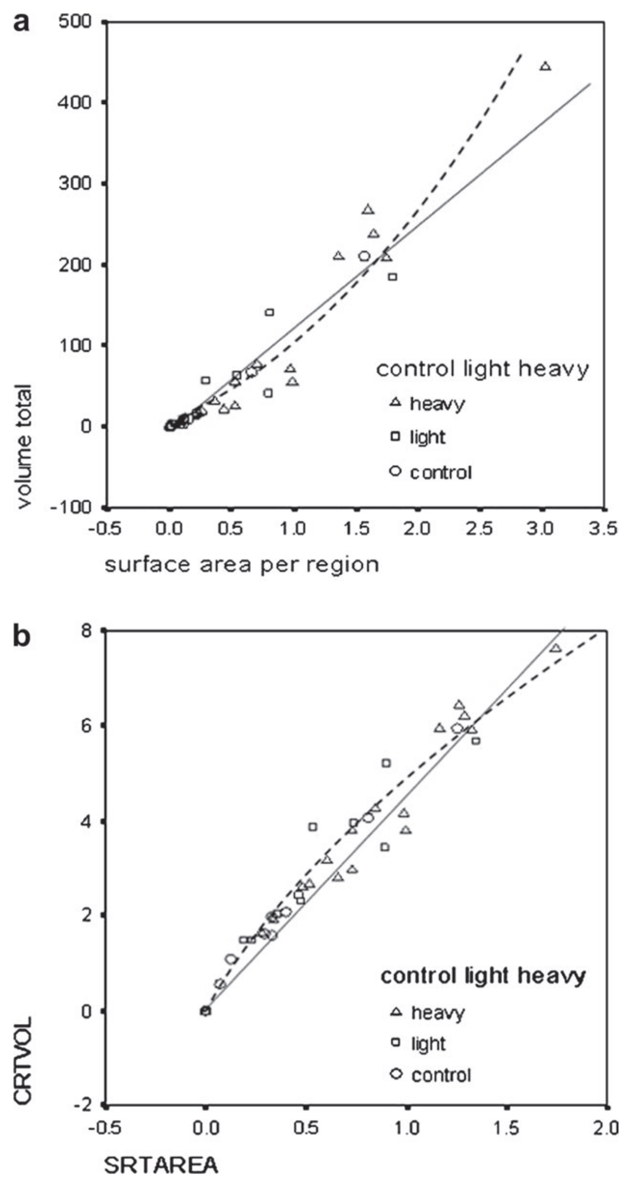

Figure 2 Graphs of (a) volume plotted against area for control, light and heavy groups testing for a layered model and (b) cube root volume plotted against square root area for control, light and heavy groups testing for a hemispheric model.

insignificant root resorption, whereas intermediate or heavy forces resulted in substantial crater formation. This result was in agreement with earlier findings, both in animals (Dellinger, 1967; Kvam, 1972a) and in humans (Harry and Sims, 1982), as well as the findings of the present study.

However, it should be borne in mind that in the present study, the force was only applied for a period of 28 days. A longer period of force application may result in the formation of deeper craters. In that case, 2D measurements may not be sufficiently accurate to evaluate the extent of the resorption. This present investigation correlated accurate 2D versus 3D measurements of root resorption. With the elimination of parallax errors, missed or distorted craters and other confounding factors, it has been demonstrated that if 2D measurements are conducted adequately, they could be as reliable as 3D measurements in a 28 day force application study. The mathematical model derived for resorption craters also allows understanding of the morphology of resorption craters of differing sizes.

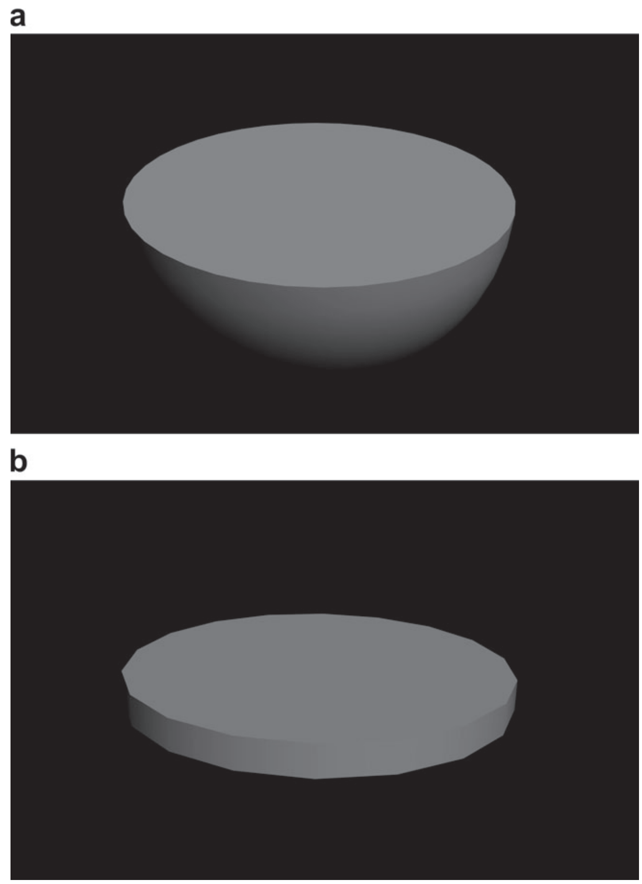

Figure 3 (a) A digital hemispheric model. (b) A digital layered model.

The present research has attempted to shed some light on the effect of 2D versus 3D measurements and force magnitude on root resorption. After a 28 day experimental period, the typical root resorption crater conformed more to a hemispheric model, whereas if the craters were larger they conformed more to a layered model. Does the thickness of cementum and dentine at various levels of the root play a role in self-limiting the depth of these craters? Is there an inner dentine layer that is ‘hard’ enough to resist resorption? Is the mechanism behind root resorption different between a light and heavy force group? What happens after 28 days? These questions remain to be addressed in future studies and investigations.

Conclusions

In this study, when light (25 g) and heavy (225 g) forces were applied for 28 days, 2D measurements of root resorption craters were as reliable as 3D measurements. A typical crater (area less than 2×10^6 μm^2 and volume less than 300×10^6 μm^3) in this study conformed more to a hemispheric model; larger craters tended to be layered.

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References

Andreasen J 1988 Review of root resorption systems and models. Etiology of root resorption and the homeostatic mechanisms of the PDL. In: Davidovitch Z (ed.) Biological mechanisms of tooth eruption and root resorption. Ebsco Media, Birmingham, Alabama, pp. 9–21

Brezniak N, Wasserstein A 2002 Orthodontically induced inflammatory root resorption. Part II: The clinical aspect. Angle Orthodontist 72: 180–184

Brudvik P, Rygh P 1994 Root resorption associated with orthodontic/experimental tooth movement: the initial attack and the resorption–repair sequence on tooth surfaces exposed to compression. In: Davidovitch Z (ed.) The biological mechanisms of tooth eruption, resorption and replacement by implants. Harvard Society for the Advancement of Orthodontics, Boston, pp. 557–575

Chan E K M, Darendeliler M A 2004 Exploring the third dimension in root resorption. Orthodontics and Craniofacial Research 7: 1–18

Chan E K M, Darendeliler M A 2005 Physical properties of root cementum: Part 5. Volumetric analysis of root resorption craters after application of light and heavy orthodontic forces. American Journal of Orthodontics and Dentofacial Orthopedics 127: 186–195

Chan E K M, Darendeliler M A, Jones A S 2004a A new method of volumetric measurement of orthodontically induced root resorption craters. European Journal of Oral Science 112: 134–139

Chan E K M, Darendeliler M A, Jones A S, Kaplin I J 2004b A calibration method used for volumetric measurement of orthodontically induced root resorption craters. Annals of Biomedical Engineering 64: 880–888

Dellinger E L 1967 A histologic and cephalometric investigation of premolar intrusion in the *Macaca speciosa* monkey. American Journal of Orthodontics 53: 325–355

Harry M R, Sims M R 1982 Root resorption in bicuspid intrusion: a scanning electromicroscopic study. Angle Orthodontist 52: 235–258

Henry J L, Weinmann J P 1951 The pattern of resorption and repair of human cementum. Journal of the American Dental Association 42: 270–290

Jones S J, Boyde A 1972 A study of human root cementum surfaces as prepared for and examined in the scanning electron microscope. Zeitschrift fur Zellforschung und Mikroskopische Anatomie 130: 318–337

Ketcham A H 1929 A preliminary report of an investigation of apical root resorption of permanent teeth. International Journal of Orthodontics 15: 310–328

King G J, Fischlschweiger W 1982 The effect of force magnitude on extractable bone resorptive activity and cemental cratering in orthodontic tooth movement. Journal of Dental Research 61: 775–779

Kvam E 1972a SEM of human premolars following experimental tooth movement. Transactions of the European Orthodontic Society, pp. 1–11

Kvam E 1972b SEM of tissue changes on the pressure surface of human premolars following tooth movement. Scandinavian Journal of Dental Research 80: 357–368

Malek S, Darendeliler M A, Swain M V 2001 Physical properties of root cementum: Part I. A new method for 3-dimensional evaluation. American Journal of Orthodontics and Dentofacial Orthopedics 120: 198–208

Owman-Moll P 1995 Orthodontic tooth movement and root resorption with special reference to force magnitude and duration. A clinical and histological investigation in adolescents. Swedish Dental Journal Supplement 105: 1–45

Owman-Moll P, Kurol J, Lundgren D 1995 Continuous versus interrupted continuous orthodontic force related to early tooth movement and root resorption. Angle Orthodontist 65: 395–401; discussion 401–402

Owman-Moll P, Kurol J, Lundgren D 1996a Effects of a doubled orthodontic force magnitude on tooth movement and root resorptions. An inter-individual study in adolescents. European Journal of Orthodontics 18: 141–150

Owman-Moll P, Kurol J, Lundgren D 1996b The effects of a four-fold increased orthodontic force magnitude on tooth movement and root resorptions. An intra-individual study in adolescents. European Journal of Orthodontics 18: 287–294

Reitan K 1964 Effects of force magnitude and duration of tooth movement on different alveolar bone types. Angle Orthodontist 34: 244–255

Reitan K 1974 Initial tissue behavior during apical root resorption. Angle Orthodontist 44: 68–82

Reitan K 1985 Biomechanical principles and reactions. In: Graber T M, Swain B F (eds) Orthodontics: current principles and techniques. C V Mosby, St. Louis, pp. 101–192

Srivicharnkul P, Kharbanda O P, Swain M V, Petocz P, Darendeliler M A 2005 Physical properties of human cementum. Part 3: Hardness and elastic modulus after application of light and heavy forces. American Journal of Orthodontics and Dentofacial Orthopedics 127: 168–176

Stenvik A, Mjör I A 1970 Pulp and dentine reactions to experimental tooth intrusion – a histologic study of the initial changes. American Journal of Orthodontics 57: 370–385