European Journal of Orthodontics 25 (2003) 335–342

Constant versus dissipating forces in orthodontics: the effect on initial tooth movement and root resorption

F. Weiland
Department of Orthodontics, University Dental School, Graz, Austria

SUMMARY The aim of this clinical and confocal laser scanning microscopic study was to compare the effects of two frequently used archwires on tooth movement and root resorption. A total of 84 premolars in 27 individuals (10 boys, 17 girls, with a mean age of 12.5 years) was moved buccally with an experimental fixed orthodontic appliance. In a split mouth experimental design the premolar on one side was activated with a stainless steel wire with a buccal offset of 1 mm, which was reactivated every four weeks and the contralateral premolar was moved with a superelastic wire with a force plateau of 0.8–1 N. This wire had an initial activation of 4.5 mm and was not reactivated during the 12-week experimental period. At the end of the experimental period the teeth were extracted. Six premolars were used as control teeth and were extracted before the experiment started. Tooth displacement was studied three-dimensionally on dental casts with a co-ordinate measuring machine. The depth, perimeter, area, and volume of the resorption lacunae was measured using three-dimensional digital images made with a confocal laser scanning microscope (CLSM). On these images the resorbed portions of the root surface were 'reconstructed' mathematically.

The results show that the teeth activated with the superelastic wire moved significantly more than the teeth with the steel wire during the experimental period. The depth of the resorption lacunae did not differ significantly between the groups; however, perimeter, area, and volume of the resorption lacunae on the teeth of the 'superelastic group' were 140 per cent greater than on the teeth of the 'steel group'.

It may be concluded that a greater amount of tooth movement occurred with superelastic wires, offering a force level of 0.8–1 N compared with stainless steel wires, with initially higher but rapidly declining forces in an experimental set up for a period of 12 weeks. The amount of root resorption was significantly larger in the superelastic group.

Introduction

There are several causes for the occurrence of external root resorption, such as trauma, ectopic eruption of neighbouring teeth, inflammation, excessive occlusal loading, and tooth mobility due to periodontal breakdown (Stuteville, 1938; Baden, 1970; Herd, 1971; Hylander, 1977; Goultschin *et al*., 1982; Feiglin, 1986; Wehrbein *et al*., 1990). The most common cause, however, in westernized societies is the directed tooth movement of orthodontic treatment (Rudolph, 1940; Linge and Linge, 1983; Harris *et al*., 1993).

In most patients root resorption during orthodontic treatment is minimal (Hollender *et al*., 1980; Linge and Linge, 1983) and is not judged to negatively influence the health of the stomatognathic system (Sjølien and Zachrisson, 1973; Linge and Linge, 1983; Remington *et al*., 1989). A small number of patients, however, develop extensive root resorptions during orthodontic treatment. Linge and Linge (1991) found loss of root length exceeding 4 mm in 2.3 per cent of teeth. Levander and Malmgren (1988) found resorptions exceeding half the original root length in 1 per cent of teeth tested.

Among the factors influencing the development of root resorption that can be controlled by the orthodontist are the type and level of force. Reitan (1957, 1970, 1985) advocated the use of intermittent forces to prevent the development of root resorption and to enable reparative processes to occur during periods with little or no force. Maltha and Dijkman (1996) reported more resorptions in dogs when using continuous than intermittent forces. Most authors have found a positive relationship between force level and resorptive activity (Dellinger, 1967; Kvam, 1967; Stenvik and Mjör, 1970; Reitan, 1974; Rygh, 1977; Bondevik, 1980; Harry and Sims, 1982; King and Fischlschweiger, 1982).

Stainless steel and nickel titanium archwires with superelastic properties are among the most frequently used wires in fixed appliance therapy (Gottlieb *et al*., 1991). Whereas stainless steel wires generate a rapidly declining force during deactivation, superelastic wires deliver a constant force over an extended portion of the deactivation range (Miura *et al*., 1986). Type and level of force, however, have a bearing on the occurrence of root resorption during orthodontic treatment. The aim of this investigation was, therefore, to study root resorption in adolescents resulting from these two differing force regimens.

Material and methods

Study sample

Ninety premolars from 27 patients (10 boys and 17 girls) aged 10.2–14.5 years (mean age 12.5 years) were used in this study. The children had been referred for orthodontic specialist treatment and showed malocclusions requiring the extraction of premolars. The scheduled extractions were postponed to use the teeth as test and control teeth for the experiment. In 14 patients all four first premolars were used as experimental teeth, in one patient all four second premolars, and in six patients only the maxillary first premolars. Due to agenesis of single premolars, a further six patients needed extraction of three premolars. In these patients the two contralateral teeth in the same arch were used as experimental teeth, whereas the single premolar from the opposing arch was used as a control. The control teeth were extracted before the start of the experiment. As a result, 84 teeth were actively moved and six teeth were used as the controls. The position of each tooth (maxilla, mandible) was registered. Impressions using alginate were taken immediately before insertion of the experimental appliance. The impressions were poured with hard stone.

Orthodontic appliance

A fixed orthodontic appliance was cemented at the start of the experiment. It consisted of an acrylic splint covering all but the experimental teeth in one arch. Brackets (0.018 inch slot) were bonded to the experimental teeth. The brackets were incorporated in the splints in such a way that a normal interbracket distance existed between the brackets on the splint and the bracket on the experimental tooth, and the base of the slot of the 'splint brackets' was 4.5 mm more buccally positioned than that of the bracket on the experimental tooth in the middle. This was controlled using a special jig when making the splint in the laboratory. On one splint the distance was set at 5.5 mm. The experimental tooth on one side was moved buccally with a superelastic archwire (Sentalloy™-blue, 0.016 inch, GAC International inc., Central Islip, NY, USA), ligated through the three brackets using steel ligatures. On the contralateral side a stainless steel archwire (0.016 inch, Ormco Corporation, Glendora, CA, USA) was used. This was adjusted to a 1 mm buccal offset in relation to the slot of the bracket on the experimental tooth and was tightly ligated. After 4 weeks, the stainless steel wire was readjusted to a 1 mm offset. Four weeks later this was repeated and 4 weeks thereafter (12 weeks after starting the experiment) the appliances were removed. The superelastic wire was not adjusted during the experiment. The teeth were cleaned and impressions were taken. The experimental teeth were then extracted with forceps under local anaesthesia. A typical patient is shown in Figure 1.

The force characteristics of the two wire materials used in the experimental set-up are shown in Figure 2. During deactivation, the stainless steel wire shows an initially high, rapidly declining force, whereas the Sentalloy™-blue wire has true superelastic properties: a lower force of approximately 1 N that is constant from 4 to 0.25 mm deflection.

Dental cast analysis

With a sharp pencil, a point was marked on the buccal and lingual cusps of the test teeth. The tips of the mesiobuccal and palatal cusps of the first molars and an easily identified point on the incisal edge of one of the central incisors were also marked.

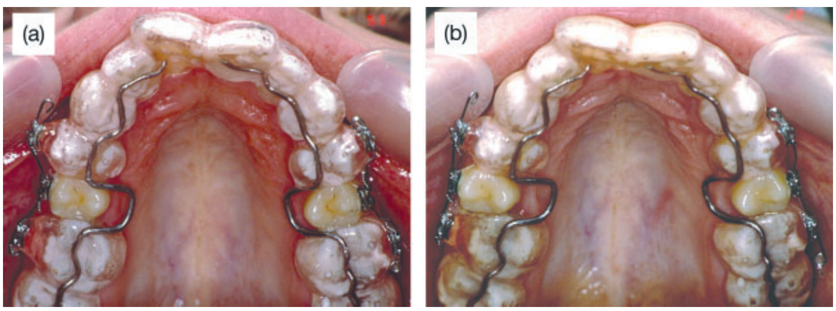

Figure 1 (a) Occlusal view of the maxillary arch of a girl, 13 years 10 months of age, immediately after the start of experiment. Tooth 15 was moved with a 0.016 inch superelastic archwire, whereas tooth 25 was moved with a 0.016 inch stainless steel wire with a 1 mm buccal offset. (b) 8 weeks after the start of experiment. Reproduced with kind permission from Quintessenz Verlags-GmbH.

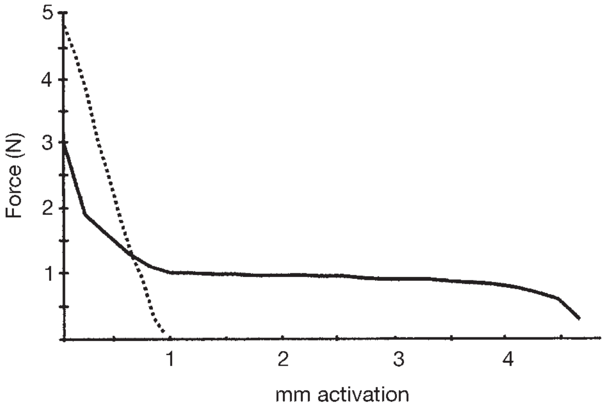

Figure 2 Force–deflection diagrams of the two archwires used in this experiment. Dashed line, 0.016 inch stainless steel wire; solid line, 0.016 inch Sentalloy™-blue; interbracket distance 5 mm. The curves show the means of 10 measurements made in a computer-controlled measuring unit.

A co-ordinate measuring machine (Ögussa GmbH, Vienna, Austria) and an appropriate software package (Gamma, Klosterneuburg, Austria) were used to measure the tooth movements three-dimensionally. The amount of movement (mm) and the rotations (degrees) in the three planes of space were calculated.

Analysis of root resorptions

The teeth were rendered inorganic in 10 per cent sodium hypochlorite. After washing they were kept in 70 per cent alcohol until analysed.

Images of the resorption lacunae were made in a confocal laser scanning microscope (CLSM; Lasertec 1LM21W, Lasertec Corporation, Japan), producing three-dimensional (3D) digital images. CLSM is a non-destructive, 3D technique of microscopic tomography. The confocal principle is based on the elimination of stray light from out-of-focus planes by a confocal aperture. Images are obtained by scanning the sample with a spot-size laser source (diameter ≈ 1 μm) and recording the light reflected from the in-focus plane. Tomography is undertaken by recording a series of consecutive images in the vertical plane. These consecutive images are then stacked up in a computer to obtain one image. These images were stored in a computer. The lacunae were measured using an image analysis program (analySIS; SIS Soft Imaging Software GmbH, Münster, Germany). A computer program was written to estimate the unknown part of a surface using a knowledge of the surrounding 'non-damaged' surface (Howell and Boyde, 1998). The program utilizes a series of image co-ordinates and the corresponding height values extracted from the intact border areas adjacent to any resorption area. A new perfect surface is generated. Subtracting the original image from the newly generated one gives an image corrected for its curvature and where the surface appears flat. A suitable grey level offset is added to ensure a pixel's value does not become negative or greater than 256. Measurements of volume made from this corrected image refer each pixel's position to the original surface (Howell and Boyde, 1998). Greatest depth (μm), perimeter (μm), area (μm^2), and volume (μm^3) of each resorption lacuna were measured. Perimeter, area, and volume were summed for each tooth.

Statistical analysis

Median and range were calculated for each parameter and the differences were tested with Wilcoxon's matched pairs, signed ranks test. The influence of the covariate position of the tooth was tested with an analysis of variance. Correlations were determined with the Spearman test.

The errors of the method were evaluated by calculating the systematic and accidental errors. Duplicate measurements were made on 10 casts and 15 randomly selected teeth. The mean difference between the two determinations (systematic error) was not significant for any variable. The accidental error (Si) was calculated with the formula $Si = \sqrt{(\Sigma d^2/2n)}$, where d is the difference between the two determinations and n is the number of duplicate measurements. Table 1 summarizes the errors of the method.

The design of the study was approved by the Ethics Committee of the Faculty of Medicine, Karl-Franzens-University, Graz, Austria.

Results

The amount of linear movement and the rotations are shown in Table 2. The teeth with the superelastic wire moved significantly more (3.50 versus 2.30 mm; $P < 0.001$) and tipped buccally to a larger degree (rotation xz, 9.26° versus 7.81°; $P < 0.01$) during the 12-week experimental period than those moved with the stainless steel wire. The rotational movement

Table 1 Medians of the differences between duplicate measurements and error of the method (Si).

Variable	Median of the difference between the duplicate measurements	Si
Movement[a] (mm)	0.04	0.07
Depth[b] (μm)	2.91	4.45
Perimeter[b] (μm)	293	817
Area[b] (μm^2)	2.0×10^5	2.8×10^4
Volume[b] (μm^3)	2.0×10^6	1.75×10^8

[a]Number of duplicate measurements = 10.
[b]Number of duplicate measurements = 15.

Table 2 Median and range of the experimental tooth movement in both force groups and significant intergroup differences.

Variable	Steel		Superelastic		Significance
	Median	Range	Median	Range	
Movement (mm)	2.31	0.96 – 3.47	3.50	1.53 – 5.50	***
Rotation *xy* (°)	3.41	–10.94 – 12.73	2.73	–14.82 – 15.92	
Rotation *xz* (°)	7.81	0.45 – 12.11	9.26	1.22 – 29.13	*
Rotation *yz* (°)	0.96	–14.17 – 9.45	0.82	–12.54 – 9.26	

Rotation *xy*, rotation around the long axis of the tooth; rotation *xz*, buccolingual tipping; rotation *yz*, mesiodistal tipping; +, mesial; –, distal; *0.01 < P < 0.05; ***P < 0.001.

around the long axis of the tooth (*xy*) and the amount of mesiodistal tipping (*yz*) did not differ to a significant extent. The range displayed large individual variations.

Resorptions

An exact analysis of the roots of the control teeth revealed only one very small resorptive area. Macroscopically, the roots of the experimental teeth displayed an array of resorptions (large, small, superficial, deep).

Figure 3 shows the CLSM images of two macroscopically visible resorption lacunae. The coronal resorption shows the typical aspect of an active resorption site characterized by smooth multilocular surfaces (Barber and Sims, 1981).

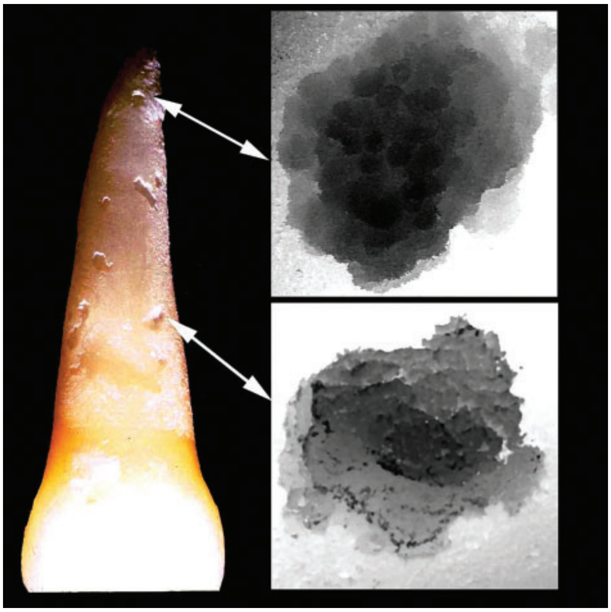

Figure 3 Experimentally moved tooth with macroscopically visible resorptions; two resorption lacunae depicted with confocal laser scanning microscopy (tooth 24, force steel, original CLSM magnification ×20). Reproduced with kind permission from Quintessenz Verlags-GmbH.

The distribution of the resorptive areas is shown in Table 3. The number of resorptions on the roots of the teeth moved with a superelastic wire was significantly greater than those moved with a stainless steel wire (median 22 versus 16, P < 0.001). The number of resorptions increased from the the cervical to the apical area in both groups. The cervical resorptions were mainly located on the buccal side, whereas the resorptions in the apical area were seen on the palatal/lingual side.

The amount of resorptive damage, defined as the largest depth, perimeter, area, and volume, found in both groups after a period of experimental tooth movement that lasted 12 weeks, is shown in Table 4. As analysis of the covariate position of the tooth in the maxillary or mandibular arch did not reveal any significant influence on the amount of root resorption, the maxillary and mandibular teeth were analysed as one group.

The largest depth of the resorption lacunae found on a single tooth did not differ significantly beween the groups (268 μm in the steel group, 279 μm in the superelastic group, P > 0.05). The teeth moved with the superelastic wire showed significantly more resorptive damage regarding perimeter (4.43×10^4 μm versus 1.81×10^4 μm, P < 0.001), area (2.59×10^6 μm^2 versus 1.07×10^6 μm^2, P < 0.001), and volume (4.51×10^9 μm^3 versus 1.91×10^9 μm^3, P < 0.001) of the lacunae. The range shows the large individual variation.

There was a correlation between the amount of linear tooth movement and the area and volume of the resorptions of the steel-activated teeth and the volume of the resorptions of the superelastic-activated teeth, respectively. The correlation coefficient was 0.35 (P < 0.05) for all three variables.

Discussion

This clinical study in humans analysed and compared the effect of two commonly used orthodontic archwires on the rate of tooth movement and the effects on the roots, i.e. occurrence and severity of root resorption.

Table 3 Medians and range of the distribution of the resorptive areas and significant intergroup differences.

Variable	Steel		Superelastic		Significance
	Median	Range	Median	Range	
Number of resorptions total	16	4–45	22	3–46	***
Number of resorptions cervical 1/3	4	1–14	5	0–14	
Number of resorptions middle 1/3	4.5	0–17	9.5	0–19	***
Number of resorptions apical 1/3	7	0–31	10.5	0–23	

(***$P < 0.001$).

Table 4 Medians and range of the amount of resorption and significant intergroup differences.

Variable	Steel		Superelastic		Significance
	Median	Range	Median	Range	
Depth (µm)	268	106–472	279	140 – 648	
Perimeter (µm)	1.81×10^4	2.10×10^3–6.71×10^4	4.43×10^4	2.12×10^3–1.36×10^5	***
Area (µm^2)	1.07×10^6	1.21×10^5–6.52×10^6	2.59×10^6	1.26×10^5–8.08×10^6	***
Volume (µm^3)	1.91×10^9	1.87×10^6–7.93×10^9	4.51×10^9	4.64×10^6–1.06×10^{10}	***

(***$P < 0.001$).

Experimental tooth movement in humans, followed by extraction of the teeth, excludes movement in a mesiodistal direction. It was decided to use a predominantly tipping movement in a buccal direction, as one of the aims of this investigation was to study the volume of resorptions. It was expected that intrusive movements would lead to a shortening of the root and, consequently, would not allow any volumetric analysis. For ethical and practical reasons the duration of the experiment was limited to 12 weeks, which seems appropriate compared with earlier reports (Stenvik and Mjör, 1970; Kvam, 1972; Harry and Sims, 1982; Küçükkeles *et al*., 1995; Owman-Moll, 1995; Faltin *et al*., 2001).

The results show that there was a significant difference in the amount of buccal premolar displacement after 12 weeks with a superelastic archwire when compared with a stainless steel wire. The teeth moved faster with a continuous force than with dissipating or interrupted forces. This confirms the results from earlier investigations (Storey and Smith, 1952; Gibson *et al*., 1992; Owman-Moll *et al*., 1995; Daskalogiannakis and McLachlan, 1996; Darendeliler *et al*., 1997).

The distribution of the resorption lacunae can be related to the tooth movement that occurred: mainly a buccal tipping of the crown and lingual tipping of the apex.

The measurement of the depth and volume of resorption lacunae depends on the reconstruction of the original root surface. The principle of mathematical reconstruction of parts of objects based on the form of the surface surrounding the defect has not been undertaken previously in orthodontic research. Acknowledging that one cannot be certain that the reconstructed surface corresponds exactly to the resorbed surface, this method enables a more exact approximation of the amount of damage due to resorption than methods described in the literature. The mathematical model itself is very exact: on a mathematically generated surface the method produces an exact replica of itself. The quality of the CLSM image and the number of points selected have a bearing on the fit of the surface reconstruction (Howell and Boyde, 1998). As 3D analysis has not been performed previously, comparisons with results from other studies are difficult.

The depth of the resorptions seen in this investigation are comparable with the values mentioned by Odenrick *et al*. (1991). After intruding premolars for 70 days, Harry and Sims (1982) found lacunae measuring up to 2200 × 2900 µm. This compares well to the largest areas found on the teeth that were moved with steel wires in this study. Küçükkeles *et al*. (1995) found lacunae of 200–300 µm diameter after intruding premolars. Volume measurements were not found, however, in the literature.

Perimeter, area, and volume of resorption lacunae were significantly larger (140%) when the teeth were moved with superelastic compared with steel wires. A continuous force of 0.8–1 N used for a tipping tooth movement is more detrimental than an initially higher, but rapidly dissipating force. This is in agreement with reports from Oppenheim (1929, 1933ab, 1936) and Reitan (1957, 1970, 1985). Rygh and Brudvik (1993) showed, in animal experiments, that the duration of the root resorptive process seems to be associated with the duration of force and presence of necrotic tissue in the periodontal ligament. Compared with the orthodontic force magnitude recommended for premolar tipping (0.5 N) (Gianelly and Goldman, 1971; Jarabak and Fizzell, 1972; Ricketts *et al*., 1979; Rygh, 1985; Proffit, 1986), the force level of the superelastic wires used in this investigation (0.8–1 N) may have been too high. Additionally, the duration of the force should not be such that the repair process is prevented. This presumption, however, is almost contradictory to superelastic properties. Faltin *et al.* (2001) confirmed that a reduction of continuous force magnitude should be considered to preserve the integrity of the tissues. Clinically it could be seen that the steel wire was passive when removed after 4 weeks. Although it is not known how long this passivity existed, it may be speculated that the progress of the resorptive activity was slowed due to an interruption in active force application.

Individual variations have been reported to be an important factor for both tooth movement (Hixon *et al*., 1970; Maltha *et al*., 1993; Lundgren *et al*., 1996) and root resorption (Henry and Weinman, 1951; Massler and Malone, 1954; Kvam, 1972; Reitan, 1974; Zachrisson, 1976; Linge and Linge, 1983). This clinical study confirms these findings.

It could not be confirmed that maxillary teeth are at higher resorptive risk than mandibular teeth, as has been stated in the literature (Ketcham, 1927, 1929; Massler and Malone, 1954; Massler and Perreault, 1954; Phillips, 1955; McFadden *et al*., 1989). The differing sensitivity is mostly explained by the differing mechanical load of the upper and lower teeth during treatment or differing amounts of tooth movement during orthodontic therapy. In this investigation the force system used in the maxilla and mandible was the same.

The amount of tooth movement and the amount of resorptive activity were correlated. This confirms data from the literature (Stuteville, 1937, 1938; Morse, 1971; Von der Ahe, 1973; Hollender *et al*., 1980; Sharpe *et al*., 1987; Kelley *et al*., 1993; Beck and Harris, 1994; Baumrind *et al*., 1996; Costopoulos and Nanda, 1996). However, this correlation was weak, the correlation coefficient (r) being 0.35. Consequently, the coefficient of determination r^2 is 0.12, which means that 12 per cent of the variation in resorption could be explained by the variation in linear movement of the tooth. In comparison, Baumrind *et al*. (1996) found a coefficient of determination of 0.20 for loss of root length and amount of tooth movement in a radiographic analysis of adult orthodontic patients during normal fixed appliance therapy.

It may be concluded that tooth movement will go faster with superelastic wires offering a force level of 0.8–1 N compared with stainless steel wires with initially higher but rapidly declining forces. A negative side effect seems to be an increase in severity of root resorption. The difficulty of the decision between ease and peril is possibly best stated by Rygh and Brudvik (1993):

'New wire qualities pose challenges for the orthodontist who must try to avoid continuous forces that are heavy enough to lead to necrosis of the periodontal ligament and last long enough to prevent the root from recovering from damage inflicted on its surface'.

Address for correspondence

Dr Frank Weiland
Untere Schmiedgasse 16
A-8530 Deutschlandsberg
Austria

Acknowledgements

The root resorptions were imaged and measured at the Hard Tissue Resarch Unit, Department of Anatomy and Developmental Biology, University College London. The generous help of Professor A. Boyde and Dr P. Howell is gratefully acknowledged. Statistical advice was given by Professor K. P. Pfeiffer, University of Innsbruck, Austria. This research was supported financially by a European Orthodontic Society Research Grant.

References

Baden E 1970 Environmental pathology of the teeth. In: Gorlin R J, Goodman H M (eds.) Thoma's oral pathology. 6th edn. C V Mosby Co, St. Louis, pp. 184–238

Barber A F, Sims M R 1981 Rapid maxillary expansion and external root resorption in man: a scanning electron microscope study. American Journal of Orthodontics 79: 630–652

Baumrind S, Korn E L, Boyd R L 1996 Apical root resorption in orthodontically treated adults. American Journal of Orthodontics and Dentofacial Orthopedics 110: 311–320

Beck B W, Harris E F 1994 Apical root resorption in orthodontically treated subjects: analysis of edgewise and light wire mechanics. American Journal of Orthodontics and Dentofacial Orthopedics 105: 350–361

Bondevik O 1980 Tissue changes in the rat molar periodontium following application of intrusive forces. European Journal of Orthodontics 2: 41–49

Costopoulos G, Nanda R 1996 An evaluation of root resorption incident to orthodontic intrusion. American Journal of Orthodontics and Dentofacial Orthopedics 109: 543–548

Darendeliler M A, Darendeliler H, Üner O 1997 The drum spring (DS) retractor: a constant and continuous force for canine retraction. European Journal of Orthodontics 19: 115–130

Daskalogiannakis J, McLachlan K R 1996 Canine retraction with rare earth magnets: An investigation into the validity of the constant force hypothesis. American Journal of Orthodontics and Dentofacial Orthopedics 109: 489–495

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

Faltin R M, Faltin K, Sander F G, Arana-Chavez V E 2001 Ultrastructure of cementum and periodontal ligament after continuous intrusion in humans: a transmission electron microscopic study. European Journal of Orthodontics 23: 35–49

Feiglin B 1986 Root resorption. Australian Dental Journal 31: 12–22

Gianelly A A, Goldman H M 1971 Biologic basis of orthodontics. Lea & Febiger, Philadelphia, p. 164

Gibson J M, King G J, Keeling S D 1992 Long-term orthodontic tooth movement response to short-term force in the rat. The Angle Orthodontist 62: 211–215

Gottlieb E L, Nelson A H, Vogels DS 1991 1990 JCO study of orthodontic diagnosis and treatment procedures. Part 1. Results and trends. Journal of Clinical Orthodontics 25: 145–156

Goultschin J, Nitzan D, Azaz B 1982 Root resorption. Oral Surgery, Oral Medicine, Oral Pathology 54: 586–590

Harris E F, Robinson Q C, Woods M A 1993 An exploratory analysis of causes of apical root resorption in patients not treated orthodontically. Quintessence International 24: 417–428

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

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

Herd J R 1971 Apical tooth root resorption. Australian Dental Journal 16: 269–274

Hixon E H, Aasen T O, Clark R A, Klosterman R, Miller S S, Odom W M 1970 On force and tooth movement. American Journal of Orthodontics 57: 476–489

Hollender L, Rönnerman A, Thilander B 1980 Root resorption, marginal bone support and clinical crown length in orthodontically treated patients. European Journal of Orthodontics 2: 197–205

Howell P G T, Boyde A 1998 SURFACE—a surface reconstructing software written in Pascal. Scanning 20: 151

Hylander W L 1977 The adaptive significance of Eskimo craniofacial morphology. In: Dahlberg A A, Graber T M (eds.) Orofacial growth and development. Mouton Publishers, The Hague: pp. 129–169

Jarabak J R, Fizzell J A 1972 Technique and treatment with lightwire-edgewise appliances. 2nd edn. C V Mosby Co, St. Louis

Kelley D L, Beck B W, Harris E F 1993 Predicting root resorption from the directions of orthodontic tooth movement. Journal of Dental Research 72: 421 (Abstract)

Ketcham A H 1927 A preliminary report of an investigation of apical resorption of permanent teeth. International Journal of Orthodontia 13: 97–127

Ketcham A H 1929 A progress report of an investigation of apical root resorption of permanent teeth. International Journal of Orthodontia, Oral Surgery and Radiography 15: 310–328

King G J, Fischlschweiger W 1982 The effect of force magnitude on the extractable bone resorptive activity and cemental cratering in orthodontic tooth movement. Journal of Dental Research 6: 775–779

Küçükkeles N, Acar A, Okar I 1995 Root resorption during premolar intrusion with varying force magnitudes. European Journal of Orthodontics 17: 342 (Abstract)

Kvam E 1967 Tissue changes incident to movement of rat molars. Universitetforlaget, Oslo

Kvam E 1972 Scanning electron microscopy of tissue changes on the pressure surface of human premolars following tooth movement. Scandinavian Journal of Dental Research 80: 368–375

Levander E, Malmgren O 1988 Evaluation of the risk of root resorption during orthodontic treatment: a study of the upper incisors. European Journal of Orthodontics 10: 30–38

Linge B O, Linge L 1983 Apical root resorption in upper anterior teeth. European Journal of Orthodontics 5: 173–183

Linge L, Linge B O 1991 Patient characteristics and treatment variables associated with apical root resorption during orthodontic treatment. American Journal of Orthodontics and Dentofacial Orthopedics 99: 35–43

Lundgren D, Owman-Moll P, Kurol J 1996 Early tooth movement pattern after application of a controlled continuous orthodontic force. A human experimental model. American Journal of Orthodontics and Dentofacial Orthopedics 110: 287–294

Maltha J C, Dijkman G E H M 1996 Discontinuous forces cause less extensive root resorption than continuous forces. European Journal of Orthodontics 18: 420 (Abstract)

Maltha J C, Kuijpers-Jagtman A M, Pilon J J G M 1993 Relation between force magnitude and orthodontic tooth movement. European Journal of Orthodontics 15: 452 (Abstract)

Massler M M, Malone A J 1954 Root resorption in human permanent teeth. American Journal of Orthodontics 40: 619–633

Massler M M, Perreault J G 1954 Root resorption in the permanent teeth of young adults. Journal of Dentistry for Children 21: 158–164

McFadden W M, Engström C, Engström H, Anholm J M 1989 A study of the relationship between incisor intrusion and root shortening. American Journal of Orthodontics and Dentofacial Orthopedics 96: 390–396

Miura F, Mogi M, Ohura Y, Hamanaka H 1986 The superelastic property of the Japanese NiTi alloy for use in orthodontics. American Journal of Orthodontics and Dentofacial Orthopedics 90: 1–10

Morse P H 1971 Resorption of upper incisors following orthodontic treatment. Dental Practitioner and Dental Record 22: 21–35

Odenrick L, Karlander E L, Pierce A, Kretschmar U 1991 Surface resorption following two forms of rapid maxillary expansion. European Journal of Orthodontics 13: 264–270

Oppenheim A 1929 Über Wurzelresorptionen bei orthodontischen Maßnahmen. Zeitschrift für Stomatologie 27: 605–653

Oppenheim A 1933a Die Krise in der Orthodontie. Verlag Urban und Schwarzenberg, Wien

Oppenheim A 1933b Verbürgt die Verwendung kontinuierlich wirkender Kraft den optimalsten biologischen und klinischen Erfolg? Zeitschrift für Stomatologie 31: 723–735

Oppenheim A 1936 Biologic orthodontic therapy and reality. Part III. The Angle Orthodontist 6: 69–116

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

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

Phillips J R 1955 Apical root resorption under orthodontic therapy. The Angle Orthodontist 25: 1–22

Proffit W R 1986 Contemporary orthodontics. C V Mosby Company, St. Louis

Reitan K 1957 Some factors determining the evaluation of forces in orthodontics. American Journal of Orthodontics 43: 32–45

Reitan K 1970 Evaluation of orthodontic forces as related to histologic and mechanical factors. Schweizerische Monatschrift für Zahnheilkunde 80: 579–596

Reitan K 1974 Initial tissue behavior during apical root resorption. The 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 Co, St. Louis, pp. 101–192

Remington D N, Joondeph D R, Årtun J, Riedel R A, Chapko M K 1989 Long-term evaluation of root resorption occurring during orthodontic treatment. American Journal of Orthodontics and Dentofacial Orthopedics 96: 43–46

Ricketts R M, Bench R W, Gugino C F, Hilgers J J, Schulhof R J 1979 Bioprogressive therapy. Rocky Mountain Orthodontics

Rudolph C E 1940 An evaluation of root resorption occurring during orthodontic treatment. Journal of Dental Research 19: 367–371

Rygh P 1977 Orthodontic root resorption studied by electron microscopy. The Angle Orthodontist 47: 1–16

Rygh P 1985 Orthodontic forces and tissue reactions. In: Thilander B, Rönning O (eds.) Introduction to orthodontics. Tandläkarförlaget, Stockholm, pp. 205–224

Rygh P, Brudvik P 1993 Root resorption and new wire qualities. European Journal of Orthodontics 15: 343 (Abstract)

Sharpe W, Reed B, Subtelny J D, Polson A 1987 Orthodontic relapse, apical root resorption, and crestal alveolar bone levels. American Journal of Orthodontics and Dentofacial Orthopedics 91: 252–258

Sjølien T, Zachrisson B U 1973 Periodontal bone support and tooth length in orthodontically treated and untreated persons. American Journal of Orthodontics 64: 28–37

Stenvik A, Mjör I A 1970 Pulp and dentin reactions to experimental tooth intrusion. American Journal of Orthodontics 57: 370–385

Storey E, Smith R 1952 Force in orthodontics and its relation to tooth movement. Australian Journal of Dentistry 56: 11–18

Stuteville O H 1937 Injuries of the teeth and supporting structures caused by various orthodontic appliances, and methods of preventing these injuries. Journal of the American Dental Association 14: 1494–1507

Stuteville O H 1938 Injuries caused by orthodontic forces and the ultimate result of these injuries. American Journal of Orthodontics 24: 103

Von der Ahe G 1973 Postretention status of maxillary incisors with root-end resorption. The Angle Orthodontist 43: 247–255

Wehrbein H, Harhoff R, Diedrich P 1990 Wurzelresorptionsrate bei orthodontisch bewegten, parodontal geschädigten und gesunden Zähnen. Deutsche Zahnärztliche Zeitschrift 45: 176–178

Zachrisson B U 1976 Cause and prevention of injuries to teeth and supporting structures during orthodontic treatment. American Journal of Orthodontics 69: 285–300