In vitro measurement of orthodontic tooth movement in rats given β-aminopropionitrile or hydrocortisone using a time-lapse videotape recorder

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SUMMARY *In vitro* tooth movement of rat molars in response to an orthodontic force was recorded using a time-lapse videotape recorder and analysed by a computer system. Rats received daily s.c. injections of β-aminopropionitrile (BAPN, 300 mg/kg/day) or hydrocortisone (10 mg/kg/day) for a period of 7 days. After drug administration, the animals were killed and the mandibles dissected. The jaw was then held under a stereomicroscope with a haemostatic clamp and an elastic band was inserted between the first and second molars. The movements of reference points on the occlusal surfaces of the first and second molars were recorded for 20 hours using a time-lapse videotape recorder. Mesiolingual movement of the first molar and distobuccal movement of the second molar were observed. During the experimental period, the greatest amount of total tooth movement in the first and second molars was seen in the group pretreated with BAPN, less movement was observed in the control group, and the group pretreated with hydrocortisone exhibited the least amount of movement. The highest rates of tooth movement were observed during the initial hour in each of the groups, and decreased thereafter. The initial rates of movement were also greatest in the BAPN group, less in the control group, and least in the hydrocortisone group. These results indicate that treatment with BAPN accelerated experimental tooth movements *in vitro* and hydrocortisone treatment inhibited the movements, suggesting that, although a part of the tooth movement measured in this experiment was due to deformation of the alveolar bone, the mechanical properties of the periodontal ligament play an important role in the regulation of orthodontic tooth movement.

Introduction

Previous research has shown that the mechanical response of connective tissues to applied loads is closely related to the soluble or insoluble collagen content of the tissues; the mechanical strength is decreased by lathyrogens, inhibitors of collagen cross-linking, and increased by glucocorticoids, which are known to decrease levels of salt-soluble collagen (Vogel, 1971, 1974, 1975; Dombi *et al.*, 1993).

The effects of lathyrogens, such as β-aminopropionitrile, aminoacetonitrile, and hydrocortisone on the mechanical properties of the periodontal ligament in rat incisors (Ohshima, 1982; Yamaguchi, 1992), rat molars (Ohkawa, 1982; Yumoto, 1986; Koizumi, 1986; Ohshima *et al.*, 1989; Kondo, 1991), and rabbit

incisors (Moxham and Berkovitz, 1984) have been thoroughly examined. Changes in the soluble and insoluble collagen content of the periodontal ligament (in rat molars and incisors), following the administration of lathyrogens, have also been examined (Taverne *et al.*, 1986).

Although orthodontic tooth movement is affected by a number of factors, such as the magnitude of the force applied (Reitan, 1960, 1964), duration of force application (Reitan, 1960, 1975), and the number and shape of roots (Macapanpan *et al.*, 1954), the mechanical characteristics of the periodontal ligament are thought to have the most profound effect. Despite numerous studies of orthodontic tooth movement, a detailed analysis of the effects of periodontal ligaments with different mechanical properties, produced experimentally by expo-

sure to lathyrogens or glucocorticoids, on orthodontic tooth movement has yet to be performed. Therefore, in the present study, *in vitro* tooth movement, in the dissected jaws of rats which had received daily injections of β-aminopropionitrile or hydrocortisone, were recorded during the application of an orthodontic force.

Materials and methods

Experimental animals

Male Wistar rats ($n = 33$), 7–8 weeks old, with an average body weight of 219 ± 9 g (mean $\pm$ 1SD) were divided into three groups of 9–12 animals each. The rats were given a powdered diet (CE-2; Clea Japan, Tokyo, Japan) and water *ad libitum* during the experimental period. One group of rats received daily s.c. injections of 300 mg of β-aminopropionitrile fumarate (BAPN) (Tokyo Kasei, Tokyo, Japan) per kg of body weight, for a period of 7 days. A different group received daily s.c. injections of 10 mg of hydrocortisone acetate (HC) (Nippon Merck-Banyu, Tokyo, Japan) per kg of body weight, also for a 7-day period. The remaining group of rats received daily subcutaneous injections of the same volume (0.2 ml/100 g body weight) of saline for a period of 7 days (control group). At the end of the experimental period, the animals were anaesthetized with ether and decapitated. Immediately after death, the right mandibles were dissected and the adhering soft tissues removed.

Mandible immobilization and labelling of reference points

The angular process of the dissected mandible was held in place with a haemostatic clamp; the tip of the clamp and the bone surface were cemented together with self-curing resin. The body of the clamp was fixed to the metal bar of a magnetic stand (Fig. 1). The approximal cusps of the first and second molars were flattened, using a dental diamond disc, and regions on the surface were painted with oily marking ink (Fig. 2) to provide clear reference points. The mandible was placed in a small dish and exposed to a continuous flow of phosphate-buffered saline containing antibiotics (50 units of penicillin G and 50 μg of streptomycin/ml; GIBCO, New York, USA), at a flow rate of 2 ml/h with a peristaltic pump. The experiment was performed at room temperature, which ranged from 23–27°C.

Recording of tooth movement with a time-lapse videotape recorder

Two clear reference points were chosen, one on the distal surface of the first molar and the other on the mesial surface of the second molar,
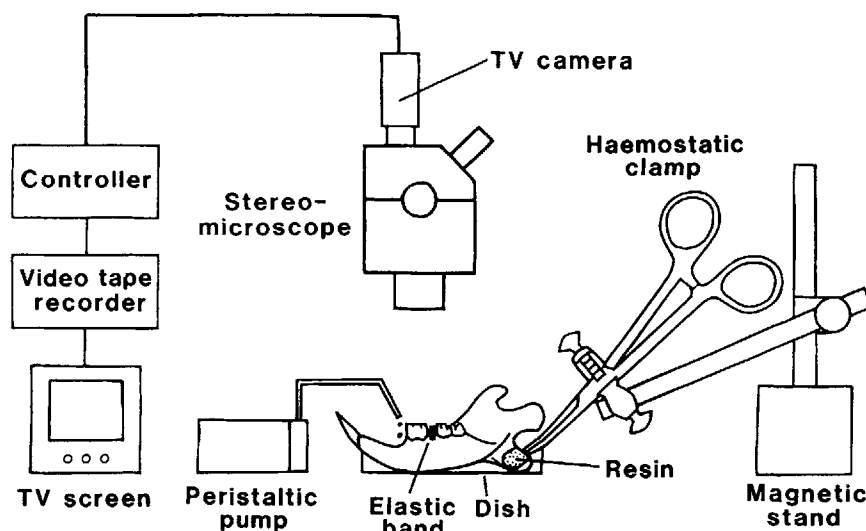

Figure 1 Diagrammatic representation of the procedure used to record tooth movement *in vitro*. The angular process of the mandible was attached to the haemostatic clamp. Pictures of the reference points were taken at hourly intervals with a television camera set on a stereomicroscope and recorded using a time-lapse videotape recorder.
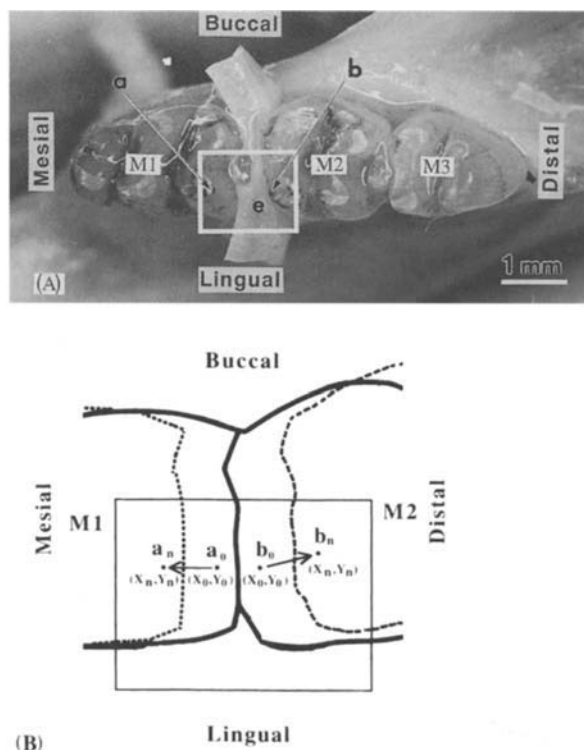
Figure 2 (A) The occlusal surfaces of the right mandibular molars following the insertion of an elastic band (e). The rectangle outlines the microscopic field. The lower margin of the microscopic field was set parallel to the midline of the dental arch. Arrows show reference points (a) and (b) on the first and second molars, respectively. M1, M2 and M3 represent the first, second and third molars, respectively. (B) Diagrammatic representation showing the movement of the reference points on the distal surface of the first molar and the mesial surface of the second molar. The rectangle outlines the microscopic field. a_0 and b_0 show the position of the reference point just before insertion of an elastic band and a_n and b_n show the position of the reference point, n hours after insertion of an elastic band. Solid line shows the position of the first and second molars just before insertion of an elastic band and dotted line shows the position of the first and second molars n hours after insertion of an elastic band. M1 and M2 represent the first and second molars, respectively.

using a stereomicroscope (Fig. 2). The microscopic image was recorded at 1 hourly intervals for 20 hours, through a television camera (C2400-77; Hamamatsu Photonics, Hamamatsu, Japan) positioned on the stereomicroscope, and linked to a time-lapse videotape recorder (SIV-JS; Sankei, Tokyo, Japan). Filming began after insertion of a latex elastic band (No. 404-126; Unitek, Monrovia, CA, USA), with an average thickness of 594 µm, in the interproximal space between the right mandibular first and second molars. The lower margin of the microscopic field was set parallel to the midline of the dental arch; the rectangle in Figure 2 depicts the microscopic field. The period of time between the death of the animals and the insertion of the elastic band was 88 ± 12 minutes (mean $\pm$ 1SD) in the control group,

86 ± 10 minutes (mean $\pm$ 1SD) in the HC group, and 90 ± 25 minutes (mean $\pm$ 1SD) in the BAPN group.

Data analysis using an image analyser

The videotaped data were analysed using an image analyser (Luzex 3U; Nikon, Tokyo, Japan) linked to a personal computer (PC9801N; NEC, Tokyo, Japan). The reference-point co-ordinates were first successively measured at 1 hourly intervals. Then, reference-point movements were depicted as traced lines and values of tracings were cumulated with the personal computer. Both the total amount of movement (µm) and the rates of movement (µm/h) were calculated for each reference point as follows: The position (the co-ordinates) of the reference point before band insertion was

determined as position 0 (x_0, y_0) on the monitor screen of the image analyser and the positions after band insertion were determined as position 1 (x_1, y_1), position 2 (x_2, y_2), position n (x_n, y_n) etc. (Fig. 2B). The co-ordinates were stored in the computer memory. The distance between the two successive points was calculated by using the co-ordinates. The cumulated distances were regarded as the total amount of tooth movement. The distance between the two successive points/hour was regarded as the rate of tooth movement. The resolution was estimated to be 2.5 μm.

Statistical analysis

The differences of the mean values between the control and BAPN groups, the control and HC groups, and the BAPN and HC groups were compared by Student's *t*-test.

Results

Table 1 shows the weights of animals, mandibles, and adrenal glands after daily injections of saline, HC, or BAPN for a 7-day period. Significant decreases were observed in the weights of animals and adrenal glands in the HC group $(P < 0.001)$ at the end of the experimental period, but weights in the BAPN group remained stable. Mandible weights did not undergo significant changes in any of the groups.

Movement of the reference points on tooth surfaces

Figure 3 shows tracings of the movement of reference points on the surfaces of the first and second molars of rats which had received daily injections of saline, BAPN, or HC, during a
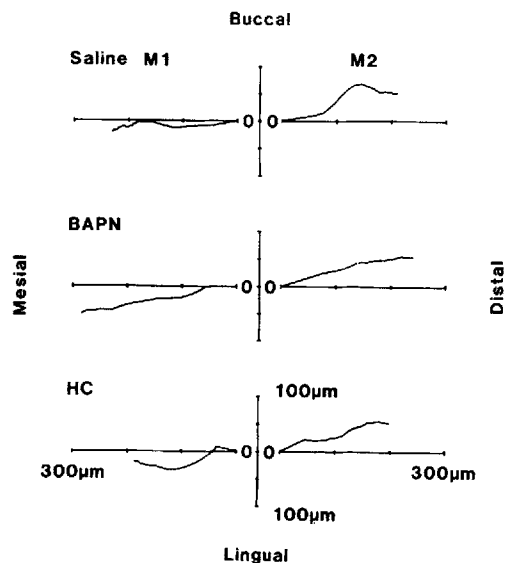
Table 1 The weights of animals, mandibles, and adrenal glands after daily injections of hydrocortisone or β-aminopropionitrile (BAPN). Data shown is the mean ± 1 SD for each group.

	Control (n=9)	Hydrocortisone (n=12)	BAPN (n=12)
Animal (g)	252 ± 13	211 ± 8*	248 ± 10
Mandible (mg)	359 ± 16	357 ± 14	358 ± 20
Adrenal gland (mg)	25 ± 3	15 ± 2*	27 ± 3

*$P < 0.001$ (significant difference between the control and experimental groups)

Figure 3 Movement of reference points on the tooth surfaces of the first and second molars of rats which had received daily injections of saline, β-aminopropionitrile (BAPN), or hydrocortisone (HC). The movements are depicted as traced lines and were taken during a 20 hour period following the insertion of an elastic band between the teeth. The horizontal axis is parallel to the midline of the dental arch. The position of the reference point before band insertion is labelled as 0, and each point represents the mean of data collected from 9–12 animals.

20 hour period following the insertion of an elastic band between the teeth. Mesial movement of the first molars and distal movement of the second molars was recorded in all of the groups. However, the movements were not parallel to the midline of the dental arch. Lingual movement of the first molars and buccal movement of the second molars (lateral movement) were also observed in each group. Tracing lines depicting movement of the first and second molars were not always straight, particularly in the control and HC groups.

Amount of tooth movement

Figures 4 and 5 show the total amount of tooth movement in the first (Fig. 4) and second (Fig. 5) molars, following the insertion of an elastic band between the teeth. In both the first and second molars in each of the groups, tooth movement was the most pronounced during the initial hour of exposure to orthodontic force, but all of the teeth continued to move throughout the experimental period. The average
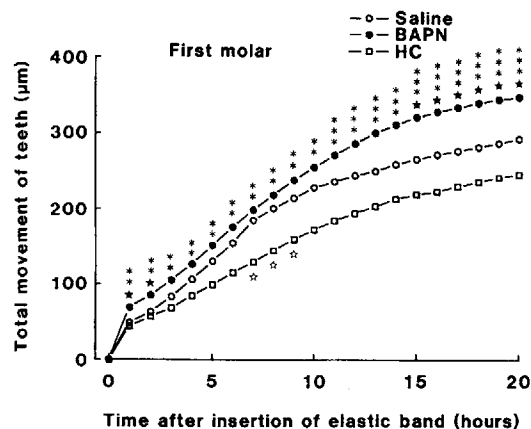
Figure 4 Total movement (μm) of the reference points in the first molar, following the insertion of an elastic band between the teeth, in rats which had received daily injections of saline, β-aminopropionitrile (BAPN) or hydrocortisone (HC). The position of the reference point before band insertion is labelled as 0. Each point represents the mean of data collected from 9–12 animals. Significant differences between the control and BAPN groups: ★$P<0.05$; between the control and HC groups, ☆$P<0.05$; and between the BAPN and HC groups, **$P<0.01$, ***$P<0.001$.
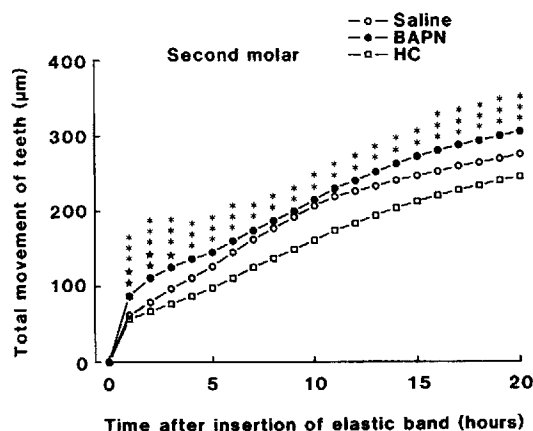

Figure 5 Total movement (μm) of the reference points in the second molar following the insertion of an elastic band between the teeth, in rats which had received daily injections of saline, β-aminopropionitrile (BAPN) or hydrocortisone (HC). The position of the reference point before band insertion is labelled as 0. Each point represents the mean of data collected from 9–12 animals. Significant differences between the control and BAPN groups, ★$P<0.05$, ★★$P<0.01$; and between the BAPN and HC groups, **$P<0.01$, ***$P<0.001$.

amount of tooth movement, in both the first (Fig. 4) and second (Fig. 5) molars, was largest in the BAPN group, less in the control group, and least in the HC group at any time-point.

Differences between the control and the BAPN groups, or between the control and the HC groups were only significant at a few time-points, as indicated in Figures 4 and 5. In contrast, differences between the BAPN group and the HC group, in both the first and second molars, were all significant. The differences between the first and second molars were also examined; the average values at the end of the experimental period were virtually identical in the HC group (246 ± 38 μm in the first and 246 ± 44 μm in the second molar), slightly greater (not significant) in the first (293 ± 70 μm) than in the second (276 ± 58 μm) molars in the control group, and significantly greater ($P<0.05$) in the first (348 ± 34 μm) than in the second (306 ± 30 μm) molars in the BAPN group.

Rates of tooth movement

Figures 6 and 7 show changes in the rates of movement in the first (Fig. 6) and second (Fig. 7) molars following the insertion of an elastic band between the teeth. The highest rates of tooth movement were observed during the initial hour following band insertion, in both the first and second molars, in each of the groups. The rates of movement in both the first
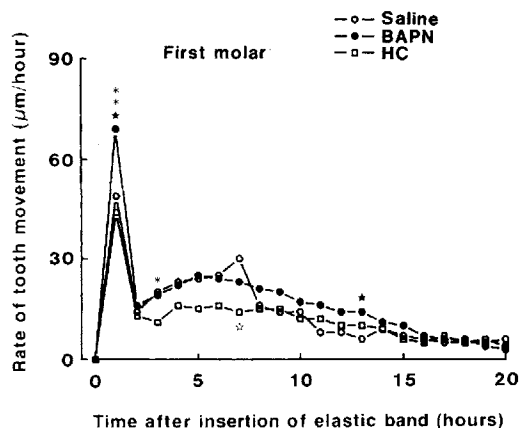

Figure 6 Rates of movement (μm/h) of the reference points in the first molar, following the insertion of an elastic band, in rats which had received daily injections of saline, β-aminopropionitrile (BAPN) or hydrocortisone (HC). The position of the reference point before band insertion is labelled as 0. Each point represents the mean of data collected from 9–12 animals. Significant differences between the control and BAPN groups, ★$P<0.05$; between the control and HC groups, ☆$P<0.05$; and between the BAPN and HC groups, *$P<0.05$, **$P<0.01$.
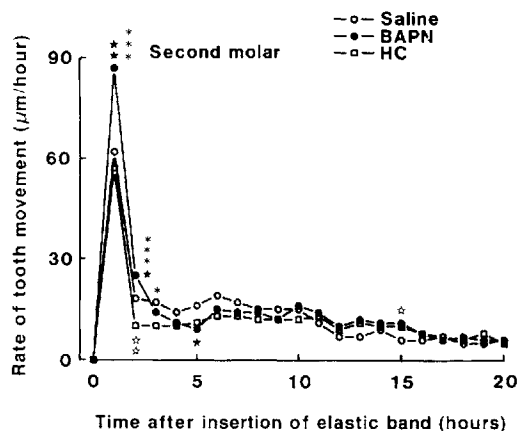
Figure 7 Rates of movement (μm/h) of the reference points in the second molar, following the insertion of an elastic band, in rats which had received daily injections of saline, β-aminopropionitrile (BAPN) or hydrocortisone (HC). Position of the reference point before insertion of the band is labelled as 0. Each point represents the mean of data collected from 9 12 animals. Significant differences between the control and BAPN groups, ★$P < 0.05$, ★★$P < 0.01$; between the control and HC groups, ☆$P < 0.05$, ☆☆$P < 0.01$; and between the BAPN and HC groups, *$P < 0.05$, ***$P < 0.001$.

and second molars, during the initial hour, were highest in the BAPN group, lower in the control group, and lowest in the HC group. However, in all cases during the initial hour the rates were higher in the second molars than in the first molars. After the initial period, the rates decreased gradually, without any marked differences among the groups or between the first and second molars.

Discussion

Previous reports have described instances of weight loss in lathyritic animals, due to a reduction in food intake (Fry et al., 1962; Sarnat and Sciaky, 1965; Berkovitz et al., 1972). Lathyrogens have also been reported to cause an increase in the weight of mandibles, by inducing abnormal bone formation (exostosis) (Marwah et al., 1963; Sarnat and Sciaky, 1965; Koizumi, 1986; Kondo, 1991; Yamaguchi, 1992). However, in the present experiment, there were no significant differences in the weights of animals and mandibles between the control group and the BAPN group (Table 1). Previous studies have shown that the soft tissues can be removed from mandibles completely and

reliable statistical evaluation of the mandible weight can be obtained (Yamane, 1990; Yamane et al., 1990).Therefore, it appears that systemic reactions to the drug were minimal in the present experiment. Other research has shown that glucocorticoids can lead to a reduction in body weight and in the weight of the adrenal glands, due to atrophy (Winter et al., 1950; Parmer et al., 1951; Ball, 1977). Significant decreases in the weights of animals and adrenal glands were observed in the present study (Table 1), and in previous experiments (Ohkawa, 1982; Yumoto, 1986), suggesting that hydrocortisone had a noticeable systemic effect on the experimental animals.

The time-lapse videotape method used to monitor in vitro tooth movement has several advantages: fixation of the jaw and determination of reference points are technically simple, complex tooth movement can be recorded as traces of the reference points, two-dimensional tooth movement can be easily visualized, and the images can all be stored on videotapes. However, there are also several limitations and problems inherent in this technique. The most important problem is that in vitro results are not directly applicable to in vivo conditions. In the interpretation of in vitro results, various biological factors affecting orthodontic tooth movement, such as vasculature (Zaki and Van Huysen, 1963; Kuitert et al., 1988, 1989), bone resorption and apposition (Macapanpan et al., 1954; Engström et al., 1988; Tanaka et al., 1990), and remodelling of periodontal fibres (Azuma, 1970; Diaz, 1978), should be taken into account. In addition, three-dimensional tooth movement, tipping, and vertical movement (Macapanpan et al., 1954; Waldo and Rothblatt, 1954; Zaki and Van Huysen, 1963; Baumrind, 1969) cannot be recorded using this technique. It is also assumed that the tooth movement recorded might be caused not only by deformation of the periodontal ligament but also by that of the alveolar bone and tooth, particularly when the magnitude of an orthodontic force was relatively great. Despite these limitations, useful information could be obtained regarding the complex orthodontic tooth movements associated mainly with the biomechanical properties of the periodontal ligament.

Macapanpan et al. (1954) previously showed that the rat maxillary first molar moved in a

mesiobuccal direction and the second and third molars moved in a straight distal direction, after a piece of rubber dam was inserted between the first and second molars. In the present experiment, the rat mandibular first molar also moved in a mesiolingual direction, but the second molar moved in a distobuccal direction (Fig. 3). It is likely that the direction of orthodontic tooth movement primarily reflects the direction of the force applied to the teeth; thus the discrepancies observed may result from structural differences between the maxillary and mandibular molars.

The amount and rate of tooth movement was highest during the initial hour after band insertion in both the first and second molars in all of the groups (Figs. 4–7). Ohkawa (1982) suggested that the magnitude of force exerted on the teeth by an elastic band decreases gradually as the interdental space widens and the rubber deteriorates; a force initially estimated to be a few kilograms was eventually reduced to a few hundred grams. The greatest tooth movement in this study was observed during the time in which the band was being inserted between the teeth ($\sim$1–7 minutes). The tooth movement during that period ranged from 61–96 per cent of the total movement observed in the initial hour. Therefore, it appears that the level of force exerted on the teeth was greatest during band insertion, rapidly and markedly decreased soon after the procedure, and continued to decrease gradually throughout the remaining experimental period.

The total tooth movement throughout the experimental period was greater in the first molar than in the second molar in the BAPN and control groups, but not in the HC group (Figs. 4 and 5). Several previous studies have shown that a tipping movement occurs in rat molars following the insertion of an elastic band between the teeth (Waldo and Rothblatt, 1954; Zaki and Van Huysen, 1963; Baumrind, 1969). The tipping movement probably contributes to the total amount of tooth movement and was greater in the first molar than in the second molar, particularly at the end of the experimental period in the control and BAPN groups.

The mean rate of tooth movement during the initial hour was greater in the second than in the first molars in all of the groups (Figs. 6 and 7). Macapanpan *et al.* (1954) have suggested that the number, spatial arrangement, relative

strength, and divergence of the roots determine movement in multi-rooted teeth. The rat mandibular first molar is larger than the second molar and has four rather thick roots; the second molar has four rather thin roots. Therefore, the first molar may become more firmly anchored to the alveolar bone than the second molar when an orthodontic force is applied.

Previous research has shown that the level of soluble collagen in various connective tissues increased (e.g. Smith and Shuster, 1962; Vogel, 1975; Taverne *et al.*, 1986) and the mechanical strength of the periodontal ligament of the rat molar decreased, following the administration of lathyrogens (Koizumi, 1986; Ohshima *et al.*, 1989; Kondo, 1991). In contrast, glucocorticoids have been shown to cause a decrease in salt-soluble collagen in the skin (Houck and Patel, 1965; Vogel, 1974) and an increase in the mechanical strength of the periodontal ligament in the rat molar (Ohkawa, 1982; Yumoto, 1986). In the present experiment, BAPN accelerated experimental tooth movement *in vitro*, whereas tooth movement was inhibited by hydrocortisone (Figs. 3–7). From these results, it appears that changes in the visco-elastic nature of the periodontal ligament occurred as a result of changes in soluble and insoluble collagen content within the ligament, in rats which had received daily injections of BAPN or hydrocortisone. Therefore, although a part of the tooth movement recorded in this study might be caused by the deformation of the alveolar bone, the mechanical properties of the periodontal ligament seem to play an important role in the regulation of orthodontic tooth movement.

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References

Azuma M 1970 Study on histologic changes of periodontal membrane incident to experimental tooth movement. Bulletin of Tokyo Medical and Dental University 17: 149–178

Ball P C 1977 The effect of adrenal glucocorticoid administration on eruption rates and tissue dimensions in rat mandibular incisors. Journal of Anatomy 124: 157–164

Baumrind S 1969 A reconsideration of the propriety of the 'pressure-tension' hypothesis. American Journal of Orthodontics 55: 12–22

Berkovitz B K B, Migdalski A, Solomon M 1972 The effect of the lathyritic agent aminoacetonitrile on the unimpeded eruption rate in normal and root-resected rat lower incisors. Archives of Oral Biology 17: 1755–1763

Diaz E A 1978 Periodontal ligament collagen response to tooth movement: histochemical and autoradiographic reactions. American Journal of Orthodontics 73: 443–458

Dombi G W, Haut R C, Sullivan W G 1993 Correlation of high-speed tensile strength with collagen content in control and lathyritic rat skin. Journal of Surgical Research 54: 21–28

Engström C, Granström G, Thilander B 1988 Effect of orthodontic force on periodontal tissue metabolism. A histologic and biochemical study in normal and hypocalcemic young rats. American Journal of Orthodontics and Dentofacial Orthopedics 93: 486–495

Fry P, Harkness M L R, Harkness R D, Nightingale M 1962 Mechanical properties of tissues of lathyritic animals. Journal of Physiology 164: 77–89

Houck J C, Patel Y M 1965 Proposed mode of action of corticosteroids on the connective tissue. Nature 206: 158–160

Koizumi T 1986 The effect of oral administration of β-aminopropionitrile (BAPN) on the mechanical strength of the periodontal ligament in the rat mandibular and maxillary molars. Japanese Journal of Oral Biology 28: 590–604

Kondo I 1991 Analysis of stress-strain curves in the rat molar periodontal ligament following administration of β-aminopropionitrile (BAPN). Folia Pharmacologica Japonica 97: 297–306

Kuitert R B, Van de Velde J P, Hoeksma J B, Prahl-Andersen B 1988/89 Tissue changes in the rabbit periodontal ligament during orthodontic tooth movement. Acta Morphologica Neerlando-Scandinavica 26: 191–206

Macapanpan L C, Weinmann J P, Brodie A G 1954 Early tissue changes following tooth movement in rats. Angle Orthodontist 24: 79–95

Marwah A S, Dasler W, Meyer J 1963 Reversibility of lathyritic damage to the periodontal structures. Journal of Periodontology 34: 142–144

Moxham B J, Berkovitz B K B 1984 The mobility of the lathyric rabbit mandibular incisor in response to axially-directed extrusive loads. Archives of Oral Biology 29: 773–778

Ohkawa S 1982 Effects of orthodontic forces and anti-inflammatory drugs on the mechanical strength of the periodontium in the rat mandibular first molar. American Journal of Orthodontics 81: 498–502

Ohshima S 1982 Effects of lathyrogens on the mechanical properties of the periodontium in the rat mandibular incisor. Tsurumi University Dental Journal 8: 345–356

Ohshima S, Nakamura G, Chiba M 1989 Effects of lathyrogens on the mechanical strength of the periodontal ligament in the rat mandibular first molar. Journal of Periodontal Research 24: 343–350

Parmer L G, Katonah F, Angrist A A 1951 Comparative effects of ACTH, cortisone, corticosterone, desoxycort-icosterone, pregnenolone on growth and development of infant rats. Proceedings of Social, Experimental and Biological Medicine 77: 215–218

Reitan K 1960 Tissue behavior during orthodontic tooth movement. American Journal of Orthodontics 46: 881–900

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

Reitan K 1975 Biomechanical principles and reactions. In: Graber T M, Swain B F (eds.) Current orthodontic concepts and techniques, W B Saunders Co., Philadelphia, pp 111–229

Sarnat H, Sciaky I 1965 Experimental lathyrism in rats: Effects of removing incisal stress. Periodontics 3: 128–134

Smith D J, Shuster R C 1962 Biochemistry of lathyrism. I. Collagen biosynthesis in normal and lathyritic chick embryos. Archives of Biochemistry and Biophysics 98: 498–501

Tanaka T, Morioka T, Ayasaka N, Iijima T, Kondo T 1990 Endocytosis in odontoclasts and osteoclasts using micro-peroxidase as a tracer. Journal of Dental Research 69: 883–889

Taverne A A R, Lemmens I G, Tonino G J M 1986 Lathyrogens and the role of collagen in the eruption of rat incisors. Archives of Oral Biology 31: 127–131

Vogel H G 1971 Antagonistic effect of aminoacetonitrile and prednisolone on mechanical properties of rat skin. Biochimica et Biophysica Acta 252: 580–585

Vogel H G 1974 Correlation between tensile strength and collagen content in rat skin. Effect of age and cortisol treatment. Connective Tissue Research 2: 177–182

Vogel H G 1975 Collagen and mechanical strength in various organs of rats treated with D-penicillamine or amino-acetonitrile. Connective Tissue Research 3: 237–244

Waldo C M, Rothblatt J M 1954 Histologic response to tooth movement in the laboratory rat: procedure and preliminary observations. Journal of Dental Research 33: 481–486

Winter C A, Silber R H, Stoerk H C 1950 Production of reversible hyperadrenocortinism in rats by prolonged administration of cortisone. Endocrinology 47: 60–72

Yamaguchi S 1992 Analysis of stress-strain curves at fast and slow velocities of loading in vitro in the transverse section of the rat incisor periodontal ligament following the administration of β-aminopropionitrile. Archives of Oral Biology 37: 439–444

Yamane A 1990 The effect of age on the mechanical properties of the periodontal ligament in the incisor teeth of growing young rats. Gerodontology 9: 9–16

Yamane A, Ohshima S, Komatsu K, Chiba M 1990 Mechanical properties of the periodontal ligament in the incisor teeth of rats from 6 to 24 months of age. Gerodontology 9: 17–23

Yumoto C 1986 Effects of hypofunction and hydrocortisone on the mechanical strength of the periodontal ligament in the mesial root of the rat mandibular first molar. Tsurumi University Dental Journal 12: 19–33

Zaki A E, Van Huysen G 1963 Histology of the periodontium following tooth movement. Journal of Dental Research 42: 1373–1379