

Orthodontic forces and periodontal compression

A new method and its application

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A new method for measuring the width of the periodontal ligament (PDL) in orthodontically treated rats has been presented. For the present experiment the first upper molar in twelve young adult Sprague-Dawley rats were moved buccally with forces up to 700 mN. The appliance used was modified according to Kvam (13) and Rygh (32). After 24 h the rats were sacrificed and the skulls were embedded in carboxymethylcellulose and frozen. In a predetermined area the surfaces of the specimens were stained with silver-nitrate and photographed. Some sections were also collected on tape and stained with hematoxylin and eosin.

The width of the PDL decreased with increasing forces following a logarithmic function. When the PDL was compressed more than 30% on the buccal side and 40% on the palatal side, red areas indicating extravasated blood were found in the pressure zones. Bending of the buccal alveolar plate was associated with strong orthodontic forces. The contralaterals to the orthodontically treated teeth were also affected.

The method described seems to be the first attempt to systematically correlate the compression of the PDL to the strength of the orthodontic force and to allow a simultaneous evaluation of histochemical and histological changes.

Key-words: Force measurement: periodontal width: cryo-sectioning

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When a mechanical force is applied on a tooth, the periodontal ligament (PDL) and the supporting alveolar bone are gradually remodelled. This fact has been taken advantage of in orthodontic tooth movement. The cellular and structural reactions, which take place in the PDL during this process, have been studied in a number of investigations (1, 9, 13, 14, 15, 16, 17, 18, 26,

27, 28, 31, 32, 33, 34, 35, 36, 38). In a few studies the reactions in the alveolar bone and the cementum have also been examined (8, 10, 17, 18, 21, 29, 41). However, very little is known about the mechanisms behind the tissue reactions and the influence and importance of general factors such as age, nutritional state, hormones, vitamins, trace elements or local factors such as perio-

dontitis, pulpitis or trauma. In order to be able to experimentally study these latter problems, it is necessary to have a method which allows the application of well defined, predetermined orthodontic forces as well as the analysis of tooth movement and tissue reactions with minimal post-experimental changes. The purpose of the present investigation was to develop such a method for experimental studies in rats.

The first method for orthodontic tooth movement of rat molars was described by Waldo & Macapanpan (18, 42). A rubberdam was inserted between the molar teeth and the induced changes in the PDL were studied in the light microscope. The orthodontic force was neither defined nor measured. Kvam (13) developed an orthodontic appliance which was cemented to the rat incisors and acted to move the first upper molar in a buccal direction. Light (4g), moderate (10g) and heavy (30g) forces were distinguished and related to the tissue reactions in the PDL at the light microscopic level. This orthodontic appliance was modified and utilized by Rygh (31, 32, 34, 35, 36) who studied the ultra-structural changes in the PDL and neighbouring cementum and bone.

The orthodontic appliance by Kvam (13) has been further modified by the authors of the present paper in order to get a well defined point for the application of the force on the tooth and the measurement of the applied force. This has been combined with a highly sensitive method for the force measurements. For the analysis of the induced tooth movement and tissue reactions the freeze-sectioning technique by Ullberg (39, 40) and the modification of this technique by Rauschnig (25) have been combined with conventional tissue staining procedures.

MATERIAL AND METHODS

Technical procedure

The orthodontic appliance is a modification of the one used by Kvam (13) and Rygh (32) for experimental tooth movement of maxillary molars in rats. The appliances (Fig. 1) were constructed on individual models in dental gypsum (Vel-mix stone, Kerr, USA). The maxillary incisors were banded and to this band a sectional arch (0.028") was welded. An active spring (0.010") ending in a loop was coiled and welded to the sectional arch. The loop of the spring provided a well defined spot for the application of the force to the lingual side of the first upper molar and made it possible to make force measurements in exactly the same point. Measurements of the orthodontic forces were made on the models as well as on the animals as described below. In the 12 experiments described in the *application* the reproducibility of a force measured on the model and in place *in vivo* was ± 10 mN (1.0 gram force).

The force measuring equipment (Fig. 2) consisted of a force transducer (Swema, Sweden, SG 3-0.25) a power supply (Grass, USA, S 8), a differential amplifier (Techtronix 5 A 22) and a storage oscilloscope (Techtronix D15). The force transducer, which allowed measurements with a precision of ± 2.5 mN contained four resistance wires

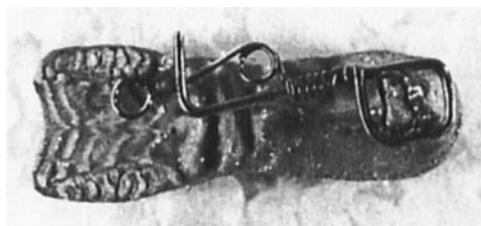


Fig. 1. The orthodontic appliance was constructed on a model of the upper jaw. The maxillary incisors were banded and to this band a sectional arch was welded. An active spring ending in a loop was coiled and welded to the sectional arch.

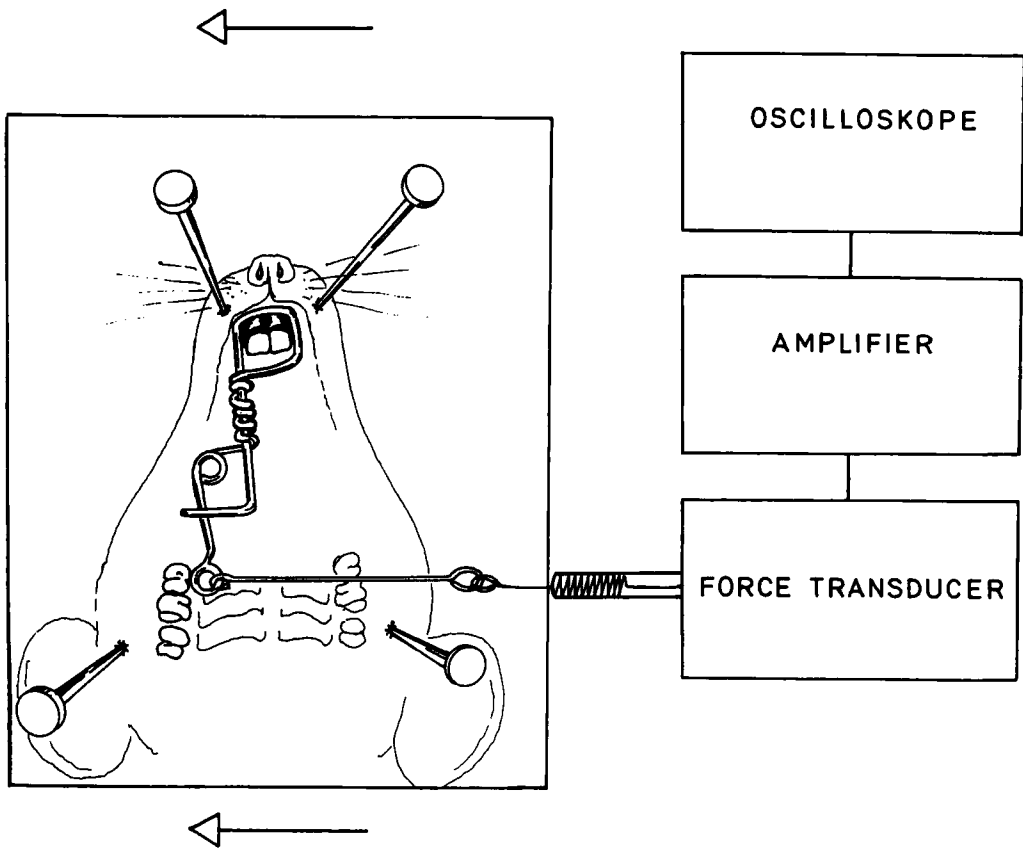


Fig. 2. The orthodontic force was measured with a force transducer. The skull of the rat with the appliance *in situ* was fixed to a cork disk and moved away from the transducer during the force measurements (arrows).

in a Wheatstone bridge. It was supplied with the necessary voltage from the power supply unit. The signal from the transducer was amplified by the differential amplifier and displayed on the storage oscilloscope. The transducer was mounted on a metal frame. This frame also contained a cork disk which was movable in relation to the transducer. To this disk the skull of the rat was fixed so that the orthodontic force could be measured in the same direction as it acted on the tooth. During the measurements the cork disk was moved away from the transducer until the spring lost contact with the tooth. A dissection microscope was used to determine this.

Tooth displacement measurements. At the end of the experiments the upper jaws, with the orthodontic appliances in place, were carefully dissected free from the skulls and embedded on microtome stages in a 4% aqueous solution of carboxymethylcellulose.

The carboxymethylcellulose did not cover the most incisal part of the specimens. In order to obtain sections in the same plane from all specimens the jaws had to be reproducibly fixed during the embedding. This was done by means of two rods which were inserted into the frame and used at the embedding (Fig. 3). The jaws were placed with the occlusal plane of the molars facing the two parallel rods thus orienting the plane of

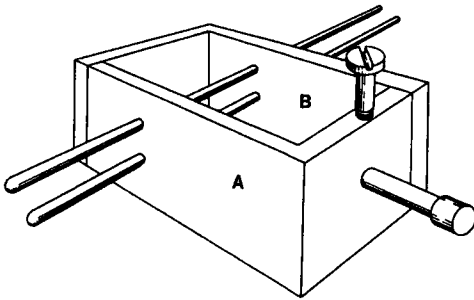


Fig. 3. The form for embedding consisted of two parts (A, B) which could be separated. The jaw was placed with the occlusal plane facing the two parallel rods and fixed with the third rod. The sectioning plane or frontal plane thus became perpendicular to the plane of occlusion.

occlusion perpendicular to the sectioning or frontal plane. The whole preparation was then frozen in hexane cooled with solid CO₂. The anterior part of each maxilla was separated from the skull by means of a diamond disk after freezing. The orthodontic appliances were then gently heated and pulled out of the frozen carboxymethylcellulose.

The first maxillary molar which was used in the present study, had four or five roots. At least three of them are small and needle-shaped. The mesial root is the largest one and was used in the present study. It deviates mesially in the sagittal plane but in the frontal plane it is almost perpendicular to the occlusal plane. It was thus possible to measure the thickness of the palatal and buccal parts of the PDL in frontal sections.

Tooth displacement measurements were carried out on microphotographs of the surface of the frozen tissue blocks at different predetermined levels taken according to the modification by Rauschnig (25) of the Ullberg method (39, 40). The contrast between the mineralized and the soft tissues was improved by applying a minimal amount of 10% silver-nitrate on the frozen surface. The silver-nitrate

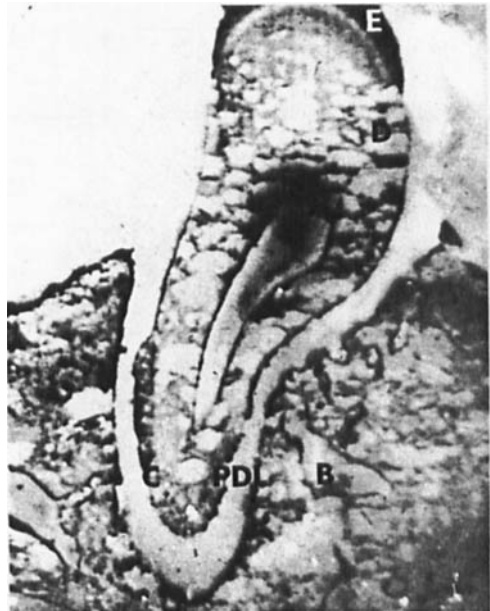


Fig. 4. The surface of the frozen block was photographed with an original magnification of x4, after applying a minimal amount of silver-nitrate. This dye stains all mineralized tissues such as bone (B), cementum (C), dentin (D) and enamel (E) black, making the periodontal ligament (PDL) clearly visible. This tooth has not been subjected to any force.

was applied with a brush. The mineralized tissues were then stained black making the non-stained PDL clearly visible.

Both the orthodontically moved teeth and their contralaterals were photographed with an original magnification of x4. The camera used was an Olympus OM2 with an Auto Bellow (Olympus) and a Zuiko Macro 20 mm F3.5 objective. The photographs were taken on Ektachrome 50 tungsten (Kodak). The light source was a Schott KL 150 with fiber optics. At the beginning and the end of each film a 2 mm microscale (Zeiss) with 0.1 mm division was photographed and used as reference. The measurements of the width of the PDL were done on a projection of the photographs on a screen. The first photograph selected for the

measurements showed the whole root from the apex to the enamel-cementum border (Fig. 4). The area for the measurements extended 10 levels 50 μm apart (total distance 500 μm) in a distal direction. The smallest width of the PDL was measured in the buccal cervical third and in the palatal apical third. These areas were easily found in all the examined teeth and both pressure zones could be seen. The width of the PDL was also measured at the alveolar crest. All measurements were made perpendicular to the root surface and repeated by two persons independently. From these measurements a mean value was calculated. The maximal deviation from this value and the discrepancy between the two independent measurements were also recorded.

Histological examination was carried out on 10 μm thick freeze-sections from the same area as the PDL measurements were performed. Sections were taken on tape (No. 810 Minnesota Mining & Manufacturing Co.) according to the method described by Ullberg (39,40). The sections were stained with hematoxylin and eosin either immediately after sectioning (freeze-thawing) or after freeze-drying. After staining, the sections were mounted in glycerin-gelatin.

The same tissue block can be used for tooth displacement measurements and sectioning for histological and histochemical examination, but usually the displacement measurements and the histological staining were made on separate tissue specimens. The silver-nitrate used to increase the contrast in the tooth displacement measurements gradually diffused in the frozen tissue blocks and stained all mineralized tissues black. This could interfere with the histological examination of the sections.

Application

Animals. Twelve young adult female Sprague-Dawley rats weighing 280 ± 40 g were treated orthodontically for tooth displacement measurements. Two additional female rats of the same weight were used as controls.

Experimental procedure. Each rat was anesthetized with 0.1 ml Hypnorm® vet. (Leo Pharmaceutical Co., Sweden) per 100 g bodyweight, and an impression of the upper jaw was taken in alginate (Zelgan, DeTrey, USA). Individual models in dental gypsum (Vel-mix stone, Kerr, USA) were made, on which the orthodontic appliances were constructed as previously described. The activation force was measured and adjusted on the models.

In each rat the orthodontic appliance was cemented to the maxillary incisors and allowed to act on the first maxillary molar for 24 h. The rats were then killed by ether inhalation. The lower jaw was removed, the head of each rat with the orthodontic appliance *in situ* fixed to the cork disk and the orthodontic force measured as previously described. An average of three measurements was calculated. The heads of the rats with the appliances *in situ* were then embedded as described above. After gentle heating the appliances were removed. The frozen tissue blocks were then placed in a deep freezer (-13°C) and allowed to equilibrate with its temperature. At 50 μm intervals the frozen surface was stained with 10% silver-nitrate and photographed. Sections (10 μm thick) were taken through the root of the first maxillary molar. Some of the sections were collected on tape and immediately stained with hematoxylin and eosin. The microphotographs of the surfaces were projected on a screen and used for measurements of the width of the PDL. The stained sections were examined in the light microscope.

RESULTS

The frozen surface of an untreated first maxillary molar stained with silver-nitrate is shown in Fig. 4. The non-stained PDL can be followed around the mesial root. The width of the PDL at different levels varied between 123 μm and 85 μm in the non-treated rats (Fig. 5). It was widest at the alveolar crest and in the most apical part and narrowest in the middle of the root. It thus had the shape of a bell glass. The maximal discrepancy between the thickness of the PDL in any of the ten levels selected for the measurements and the mean thickness was 9 μm . (Figs. 8, 9). The two independent calculations of the mean PDL thickness differed not more than 5 μm .

The stained sections showed cells and collagen fibers in the PDL (Figs. 6 A, B). The adjacent cementum and alveolar bone were clearly demarcated. The cementum and bone were lined by a 3–4 μm thick layer of cementoid or osteoid, respectively (Fig. 6 B). These non-mineralized layers were rather uniform in thickness in all parts of the PDL and they were not stained by the silver-nitrate.

When an orthodontic force was applied on the palatal side of a molar it was moved in a buccal direction. Orthodontic forces which were less than 40 mN compressed the whole PDL on the buccal side, and consequently the PDL on the palatal side was wider than normal (Fig. 7). The mesial root was thus translated buccally. When the orthodontic force was 50 mN the PDL in the pressure zones on the buccal side was compressed from 107 μm to 84 μm . This was about one fifth of the total width. When the orthodontic force exceeded 50 mN there was almost no further compression of the PDL on this side. Not even orthodontic forces as high as 700 mN compressed the buccal part of

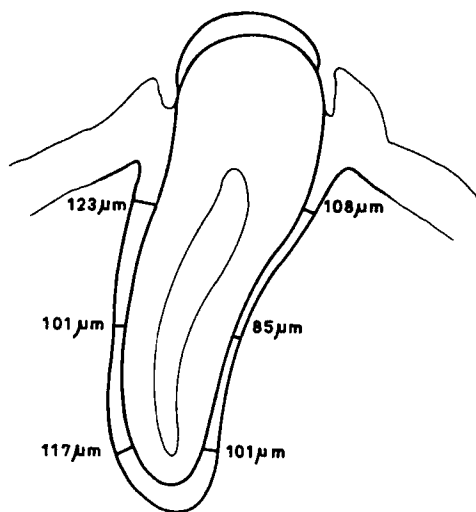


Fig. 5. The normal width of the periodontal ligament. The narrowest part was found in the middle of the root.

the PDL significantly more than 50 mN did. This is in contrast to the PDL in the palatal apical region which was gradually more compressed at forces exceeding 50 mN. Thus at 50 mN the translation of the tooth changed into a tipping movement. The maximal compression in the palatal pressure zone was from 117 μm to 41 μm . The relationship between the orthodontic forces and the widths of the PDL in the buccal and palatal pressure zones were found to be logarithmic (Figs. 8 & 9). Regression analysis showed that the correlation was very good on both sides ($r_{\text{buc}} = -0.83$ and $r_{\text{pal}} = -0.97$).

The width of PDL at the alveolar crest initially followed the same pattern as the width of the PDL in the pressure zones (Fig. 10). At forces above 50 mN, however, the width on the palatal side increased with increasing forces while the PDL on the buccal side could not be compressed to less than about 100 μm .

When the orthodontic force exceeded approximately 100 mN red spots, probably indicating extravasated blood, appeared in the buccal cervical pressure zone (Figs. 7, 11). The com-

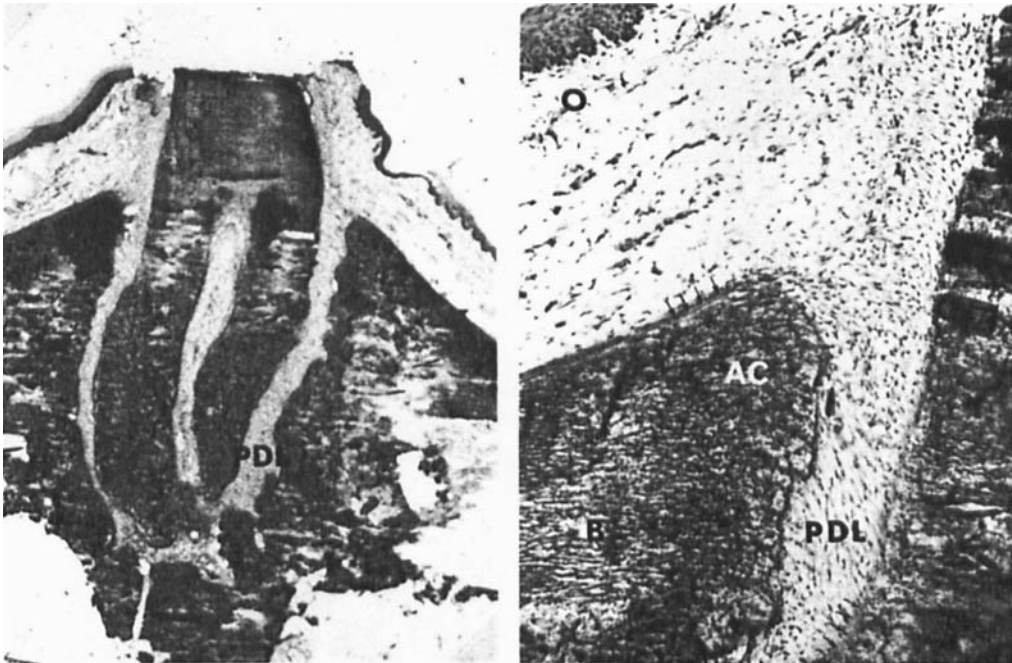


Fig. 6. A. Hematoxylin and eosin stained freeze-section (x4) from the level selected for the measurements of the width of the periodontal ligament (PDL). The enamel has been removed prior to embedding. B. Detail showing the palatal alveolar crest (AC). The periodontal ligament (PDL) contains cells and fiberrich connective tissue. The oral mucosa (0) can be seen covering the palatal surface of the bone (B). A thin layer of osteoid and cementoid can be seen covering the bone and cementum respectively (arrows).

pression was then about 30 % buccally and 40 % palatally. Similar spots were noticed in the palatal apical pressure zone with orthodontic forces higher than 200 mN (Figs. 7, 11).

The width of the PDL of the untreated first upper molars was also markedly affected by the orthodontic treatment of the contralaterals (Fig. 12). With increasing forces the smallest width of the PDL in the areas, corresponding to the pressure zones in the orthodontically treated teeth, increased on the buccal side while it decreased slightly on the palatal side. The width of the PDL in the buccal cervical part increased from about 100 μm in the non-treated rat to 140 μm in the rat treated with an orthodontic force of 680 mN. No signs of bleeding were seen in the PDL of the non-treated teeth.

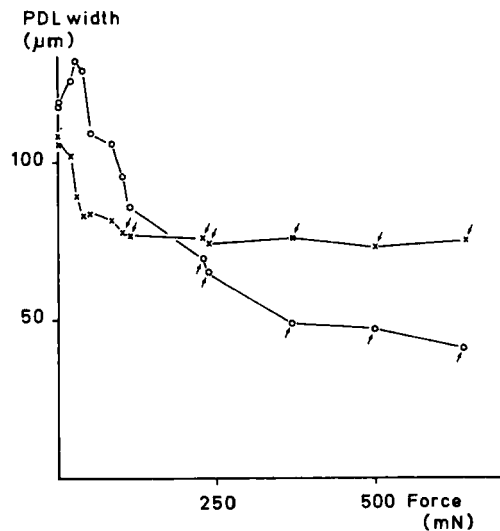


Fig. 7. The smallest width of the periodontal ligament in the palatal (O) and buccal (x) pressure zones as a function of the orthodontic force. The arrows indicate when red spots, probably areas of bleeding, could be seen within the pressure zones.

DISCUSSION

Previous experimental studies on orthodontic tooth movement have concentrated on the histological changes in the PDL (1, 13, 14, 15, 16, 17, 18, 26, 27, 28, 31, 32, 34, 35, 36, 38). Very few attempts have been made to measure the width of the PDL. However, in a study of the cellular reactions following hyalinization of the PDL Kvam (14) measured the smallest width of the PDL on the pressure side. Rygh (32), who studied the ultrastructural features of orthodontically induced hyalin zones in rats, also measured the width of the PDL in his epon embedded specimens. After 24 h Rygh found that the PDL was less than 50 μm . Over a 5 day period it was even further reduced. This is in contrast to our findings where the PDL could not be compressed to less than about 70 μm . Kvam also noted in his experiments that the PDL was not compressed to more than 70 μm after 2 days.

The present study seems to be the first attempt to systematically correlate the compression of the PDL to the strength of the orthodontic force. To be able to do this the orthodontic force must be well defined and the measurements of the PDL must have a high precision. The introduction of a loop on the orthodontic appliance made the force well defined both with respect to point of application and direction of the force. This also made it possible to measure the force in the point of application. In previous studies with a similar appliance with the exception of the 100p - Kvam (13) found the precision of the force measurements to vary. With low and moderate forces it was ± 15 mN and with high forces ± 25 mN. Rygh (31) suggested that forces less than 40 mN were not possible to produce with this type of appliance. This may be compared with the precision of

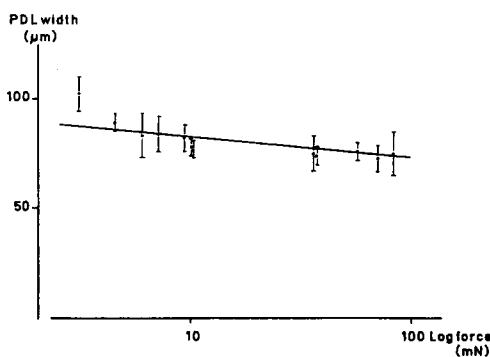


Fig. 8. The mean width of the periodontal ligament in the buccal pressure zone vs. log orthodontic force. The brackets show the maximal deviation from the mean values. The correlation coefficient for the regression line was found to be $r = -0.83$.

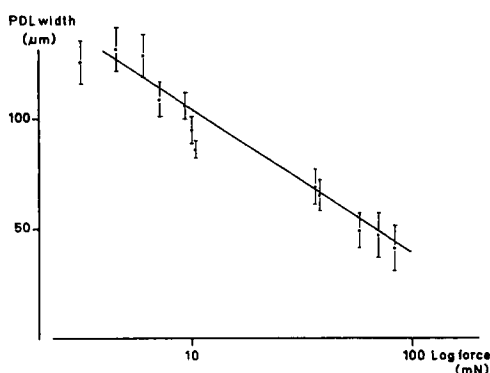


Fig. 9. The width of the periodontal ligament in the palatal pressure zone vs. log orthodontic force. The brackets show the maximal deviation from the mean values. The correlation coefficient for the regression line was found to be $r = -0.98$.

± 2.5 mN obtained with the appliance and equipment used in the present study. The high precision also made it possible to use very low forces and to measure them with a reasonable degree of accuracy.

The results obtained of the width of the PDL should represent the true values since the measurements of the width were done on frozen specimens where special care was taken to avoid movement of the tooth within its alveolus after removal of the orthodontic appliance. However, the silver-nitrate

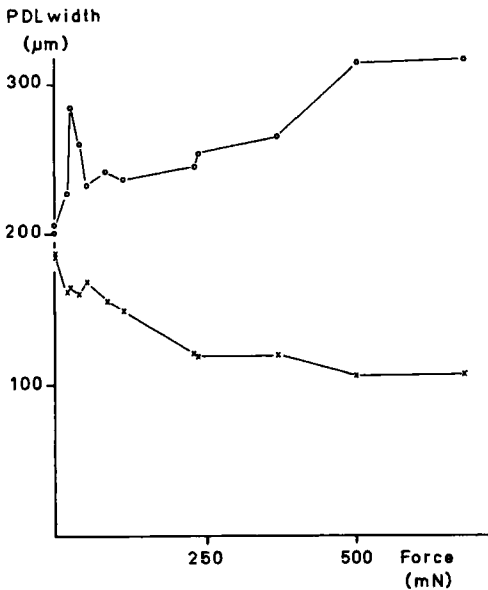


Fig. 10. The width of the periodontal ligament at the palatal (0) and buccal (x) alveolar crests as functions of the orthodontic forces.

did not stain the cementoid or the osteoid, consequently the results obtained may thus be somewhat too high. In sections stained with hematoxylin and eosin the total width of these two non-mineralized layers were found to be in order of a few microns which is also in agreement with other studies (2, 30, 37). The points of measurements may sometimes be difficult to define. However, repeated measurements by two of the authors independently resulted in very little variation of the obtained values. The variation from the mean value in the various zones of the PDL was 9 µm, which is in the order of 10 % of the normal PDL width.

When a tooth is tipped buccally with a very light force the movement performed by the tooth is known to be a combination of a translational and rotational movement (20). In the present study the widening of the whole PDL on the palatal side and the compression on the buccal side are signs of this translation. The translational move-

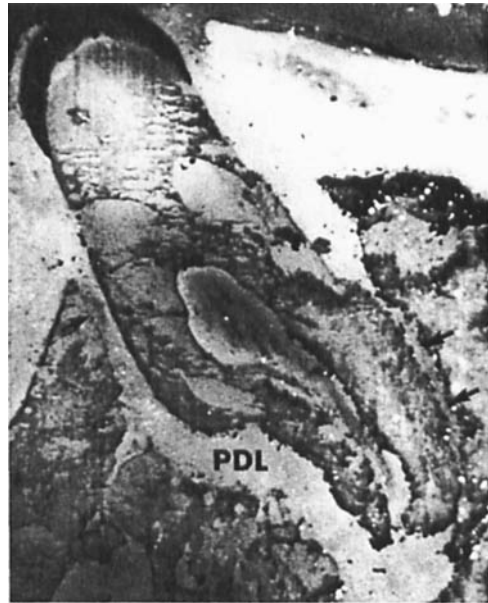


Fig. 11. The surface of the frozen block stained with silver-nitrate. The tooth has been moved buccally with a force of 680 mN. In the buccal and palatal pressure zones within the periodontal ligament (PDL) dark areas (arrows) indicating extravasated blood can be seen.

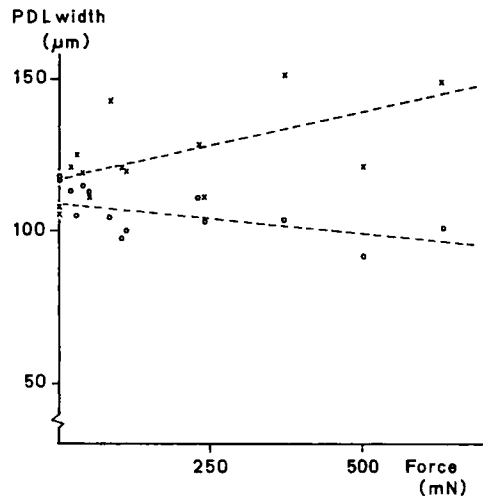


Fig. 12. The smallest width of the periodontal ligament on the palatal (0) and buccal (x) sides of the contralateral to the orthodontically moved teeth. The measurements were made in the areas corresponding to the pressure zones in the experimental teeth. The correlation coefficients for the regression lines were $r = 0.6$ for the buccal side and $r = -0.5$ for the lingual side.

ment was found with forces not exceeding 50 mN (Figs. 7, 10).

The orthodontic appliance used in the present study produces a tipping movement along an axis called «the center of rotation» (7, 24). The position of the center of rotation is determined by the point where the force is applied and the anatomy of the root (7). In this study the loop of the spring made it possible to apply the force in exactly the same point on all the teeth. This produced identical rotational movements of all the teeth regardless of the force. Thus, the compressed areas of the PDL appeared in the same place in all the rats.

There seemed to be a limit in the compressibility of the PDL. In the buccal pressure zone it was not compressed more than one third even at the strongest forces used (Fig. 7). Since the width of the PDL at the palatal alveolar crest increased with increasing forces the tipping of the tooth was associated with bending of buccal alveolar plate (Fig. 10). At the buccal alveolar crest the width of the PDL followed the same pattern as the pressure zones on this side. Picton (23) and others (3, 10, 43) have reported that bending of the crestal bone can be achieved by applying a light orthodontic force on a tooth. The pressure zone in the palatal apical region is surrounded by a more rigid bone and in this zone the PDL could be compressed by two thirds of its original width by the maximal force used in this study (Fig. 7). The force-displacement graphs for both pressure zones showed a good correlation to logarithmic functions. The correlation coefficient for the palatal pressure zone was -0.97 and -0.83 for the buccal pressure zone (Figs. 8 & 9). The feature of bone bending might account for the lower value on the buccal side.

The compression of the PDL incident to orthodontic forces is a slow

process. The resistance to compression is mainly due to a hydrodynamic damping (5, 22). After 24 h the PDL is considered to have reached its final thickness (18). In the present study this evidence was supported by the finding that the PDL was not further compressed with forces exceeding 100 mN on the buccal side and 400 mN on the palatal side (Fig. 7). If the PDL had not reached its final thickness after 24 h the force-displacement graph in this study would have been linear rather than logarithmic. By this time no or negligible osteoclastic resorption had begun (17). This made it possible to study the thickness of the PDL at maximal compression before resorption of the alveolar bone had started.

It has been suggested that the blood pressure in the PDL plays an important role for the damping of the tooth in its alveolus, under normal conditions (5, 6, 11, 38). Loads of short duration do not produce any damage even though they might exceed the capillary blood pressure (19). However, if a tooth is exposed to a continuous load as in orthodontic tooth movement, disruption of blood vessels can occur (19, 35). In the present investigation red areas, probably indicating bleeding, were found in the pressure zones. The degree of compression seemed to determine the extravasation of blood (Fig. 7). Previous investigations have shown that bleeding incident to orthodontic forces may play a role in the formation of a hyaline zone and in the initiation of bone resorption (1, 12, 31, 32). Both disrupted blood vessels and breakdown products have been found in the pressure zones. Miura (19) has shown that the blood flow in the PDL of cats was permanently altered if the PDL was compressed by more than one third.

The PDL of the contralateral tooth to the one which was orthodontically moved was also affected (Fig. 12). The

tooth was tipped in a palatal direction, a finding which is in agreement with previous studies by Kvam (13). An altered metabolic activity in the PDL under similar conditions has been reported by Baumrind & Buch (4). The altered activity was probably due to a change in masticatory function. This makes the contralateral tooth unsuitable as control in histological studies on tissue changes associated with orthodontic tooth movement.

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