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Tissue reaction to orthodontic tooth movement—a new paradigm*

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SUMMARY Direct or indirect resorption are both perceived as a reaction to an applied force. This is in contrast to orthopaedic surgeons who describe apposition as 'the reaction to loading of bone'. The article reviews the literature on intrusion of teeth with periodontal breakdown, and on the basis of clinical and experimental studies. The conclusion is reached that intrusion can lead to an improved attachment level, and that forces have to be to low and continuous.

The tissue reaction to a force system generating translation of premolars and molars in the five *Macaca fascicularis* monkeys is described. Three force levels, 100, 200, and 300 cN were applied for a period of 11 weeks. Undecalcified serial sections were cut parallel to the occlusal plane and a grid consisting of three concentric outlines of the root intersected by six radii was placed on each section so that areas anticipated to be subject to differing stress/strain distributions were isolated. *A posteriori* tests were utilized in order to separate areas that differed with regard to parameters reflecting bone turnover.

Based on these results and a finite element model simulating the loading, a new hypothesis regarding tissue reaction to change in the stress strain distribution generated by orthodontic forces is suggested. The direct resorption could be perceived as a result of lowering of the normal strain from the functioning periodontal ligament (PDL) and as such as a start of remodelling, in the bone biological sense of the word. Indirect remodelling could be perceived as sterile inflammation attempting to remove ischaemic bone under the hyalinized tissue. At a distance from the alveolus, dense woven bone was observed as a sign of a regional acceleratory phenomena (RAP). The results of the intrusion could, according to the new hypothesis, be perceived as bending of the alveolar wall produced by the pull from Sharpey's fibres.

Introduction

The orthodontic literature is characterized by many controversies in relation to tooth movement. This article will suggest possible solutions, supported by the results of studies carried out on intrusion of periodontally damaged teeth. In addition, the biological reaction of alveolar bone to orthodontic tooth movement will be analysed in the light of the strain distribution of the periodontal tissues and, based on this, a new perception of the tissue reaction to orthodontic forces will be suggested.

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A possible explanation for the controversies regarding tooth movement may be that the design of the clinical or experimental studies varies, resulting in conclusions that cannot be compared. It is important to differentiate between what is possible in an adult and in a growing individual. It is likewise important to note that the local environment has a major influence; the healthy and inflammed periodontium reacts differently. The force magnitude is often the only parameter considered by investigators. Different types of tooth movements do, however, generate different force distributions. Since it is most likely that tissue reaction is a result of changes in the stress/strain distribution in the periodontium, information on the moment to force ratio of the force system, on the anatomy of the tooth, and on the constraints determined by the periodontium is required.

Another explanation for the controversies in the orthodontic literature could be the lack of uniformity and definition. An example of the use of similar words for different events is the term ‘intrusion’, which has been used to describe the reaction following both an occlusal onlay, the displacement of a tooth after tipping, and the result of vertical forces developed by different orthodontic appliances. Compression of the marginal periodontium on the side toward which a tooth is tipped as described by Polson *et al.* (1984) may be comparable to the compression of the periodontal ligament (PDL) described by Reitan (1964) after occlusally directed force application.

The evaluation of the amount of intrusion is also controversial. The amount of true intrusion depends on the type of appliance used (Sander *et al.*, 1996; Melsen *et al.*, 1997; Nanda, 1997). Weiland *et al.* (1996) demonstrated that intrusion occurred only when applying the segmented arch approach, whereas this is not the case when a continuous arch is used. The predictive value of treatment time, force level, and amount of intrusion vary between studies, and differences in appliance design renders it impossible to compare the results. The different results can, on the other hand, be explained by the difference in force level and in the load deflection rate used in the two approaches.

A third controversy regarding intrusion is its relationship to root resorption. Reitan (1964) demonstrated that intrusion caused both severe root resorption and reduction in the height of the alveolar process. Dellinger (1967), however, when intruding primate premolars, emphasized the importance of the force level for root resorption. Stenvik and Mjör (1970) analysed human premolars following intrusion and confirmed this. The increased risk of apical root resorption seen in relation to intrusion has been reported in several studies (McFadden *et al.*, 1989; Costpoulos and Nanda, 1996; Baumrind *et al.*, 1996; Faltin *et al.*, 1998; Parker and Harris, 1998).

Intrusion seems to be a treatment with a high risk of adverse effects in patients with a deep overbite caused by an over-eruption of the incisors. If they are to be treated orthodontically with a normal periodontium it can be anticipated that the height of the alveolar process will be reduced as a result of this intrusion. However, this is not desirable in patients with a reduced periodontium who, in addition to a deep overbite, suffer from increased clinical crown length. If intrusion would result in root resorption and a reduced height of the alveolar process as described above, such treatment would seem to be unwise in these patients.

The major concern is therefore to find an answer to the following question: How does intrusion affect the clinical crown length and the marginal bone level in patients with a reduced periodontium?

Subjects and materials

A prospective clinical study of 30 consecutively treated subjects was conducted, where patients with a reduced periodontium and a deep overbite with an identified treatment aim to intrude the upper incisors were selected (Melsen *et al.*, 1989). All patients underwent a prophylaxis programme including motivation and instruction. Once the oral hygiene was satisfactory, a modified Widman flap surgery was performed and the gingiva repositioned apically, so that no pockets above 3 mm were present. Following healing, impressions were made and study casts produced. A lateral head film and four periapical radiographs were taken, the latter by means of a film holder allowing for reproducible exposure of the individual teeth. The orthodontic treatment was then initiated with an appliance comprising three passive segments of full wire size stainless steel: two lateral segments connected transpalatally and an anterior segment consolidating the four upper incisors. The intrusion of the four upper incisors was undertaken using a 0.017 × 0.025-inch TMA base arch adjusted for 50 g of intrusive force corresponding to 12.5 g per tooth. The point of force application and the line of action of the force were monitored according to the need of the patient, so that either an intrusion in combination with a proclination or a retroclination was obtained. The appliance was adjusted monthly until sufficient clinical movement was obtained. The treatment time varied between 8 and 18 months. At the end of treatment a further set of records was obtained.

The amount of intrusion was measured with respect to a co-ordinate system, where the *X*-axis represented the palatal plane and the *Y*-axis a perpendicular through the pterygomaxillary point. The displacement of a best-fit template transferred from the first to the last cephalogram was used in order to minimize the error of the method. Intrusion of the apex, the centroid, and the incisal edge (incision) was recorded. The clinical crown height was measured on the study casts with an electronic calliper to within 0.01 mm. For each of the four upper incisors the distance between the incisal edge, and the highest point of the gingival margin was measured at the beginning and end of treatment, and the difference recorded. Based on the periapical radiographs, drawings were made, and the area of the alveolus for the individual teeth was calculated and corrected for shortening due to root resorption (Melsen *et al.*, 1988).

Results

The results revealed that the intrusion of the individual teeth and the single reference points varied according to the type of movement performed (Table 1 and Figure 1A). The clinical crown height was reduced in 28 subjects and the area of the alveolus was increased in 25 (Tables 2 and 3; Figure 1B,C). Only two patients without reduction of the clinical crown height had pockets above 3 mm at the end of treatment.

Based on these results it was concluded that clinical intrusion with low continuous forces of periodontally healthy teeth is recommended, and that this type of treatment may reduce the clinical crown height and increase the area of the alveolus.

Table 1 True intrusion-range in mm.

	Min	Max
Apex	–2	5
CR	0	4
Iss	–2	6

As a consequence of these results another question arose: How does intrusion of teeth with a reduced periodontium affect the attachment level?

To answer this question an experiment was carried out on six adult *Macaca fascicularis* monkeys. Periodontal breakdown was produced by the placement of orthodontic elastics around the premolars and the upper incisors, which were replaced with new elastics until pockets of 4 mm were obtained. Periapical radiographs verified a breakdown of the marginal bone corresponding to a minimum of 2 mm. At this point, reverse bevel flap surgery was performed and a reference notch corresponding to the most apical part of the epithelial junction was produced with a round burr (Figure 2). Following surgery the right side of the jaw was kept meticulously clean with brushing and chlorhexidine rinsing twice a week, while the other side served as the control. One week following surgery an orthodontic appliance for the intrusion of upper incisors and premolars was inserted in five monkeys whereas one served as the control. The appliance comprised passive anchorage units of cast stainless steel caps for the molars, passive steel wire consolidating the incisors, and active U-shaped intrusion wires (0.018-inch TMA) extending from the molar splint and loading the occlusal surfaces of the premolar with 10 g per tooth. Intrusion of the incisors was undertaken with the same force level by means of a base arch (0.018-inch TMA) extending from the molar splints. The observation time was 3 and 12–16 weeks. At the end of the observation period, the animals were killed under Ketalar anaesthesia with perfusion of buffered formalin. The jaws were excised and the tissue blocks decalcified in EDTA and double embedded in paraffin celloidin. Eight-μm thick serial sections were cut parallel to the mesio-distal axis, and stained alternatively with hematoxylin and eosin, and van Giesen connective tissue stain.

The following parameters were evaluated post-treatment: the relationship between the attachment level at the start of treatment, as indicated by the apical limit of the notch (AM),

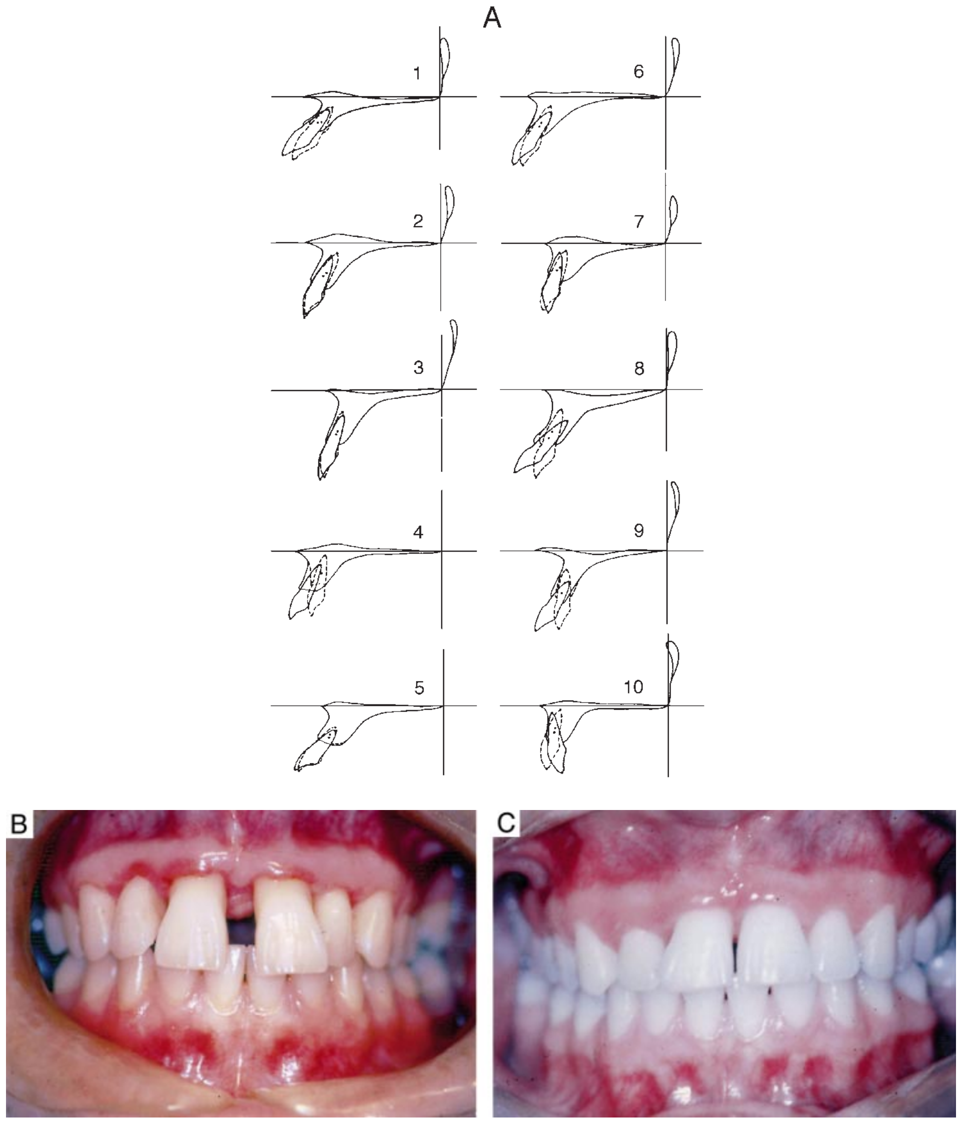

Figure 1 (A) Examples of tooth movements performed in an individual patient. (B) Immediately following periodontal surgery. Note that the clinical crown length is increased, but that there has been previous shortening of the incisors by grinding the incisal edge once the teeth had started to elongate. (C) Following orthodontic intrusion. Note the improved gingival level and aesthetic appearance. Reproduced with kind permission from Melsen *et al*. (1989).

Table 2 Change in bone support area of bony alveolus (expressed as a percentage).

x	Min	Max
676	–15	22

Twenty-five out 30 had an increased area.

Table 3 Reduction in crown length (mm).

x	Min	Max
–1.1	2.1	–4

Twenty-eight out 30 had a reduction.

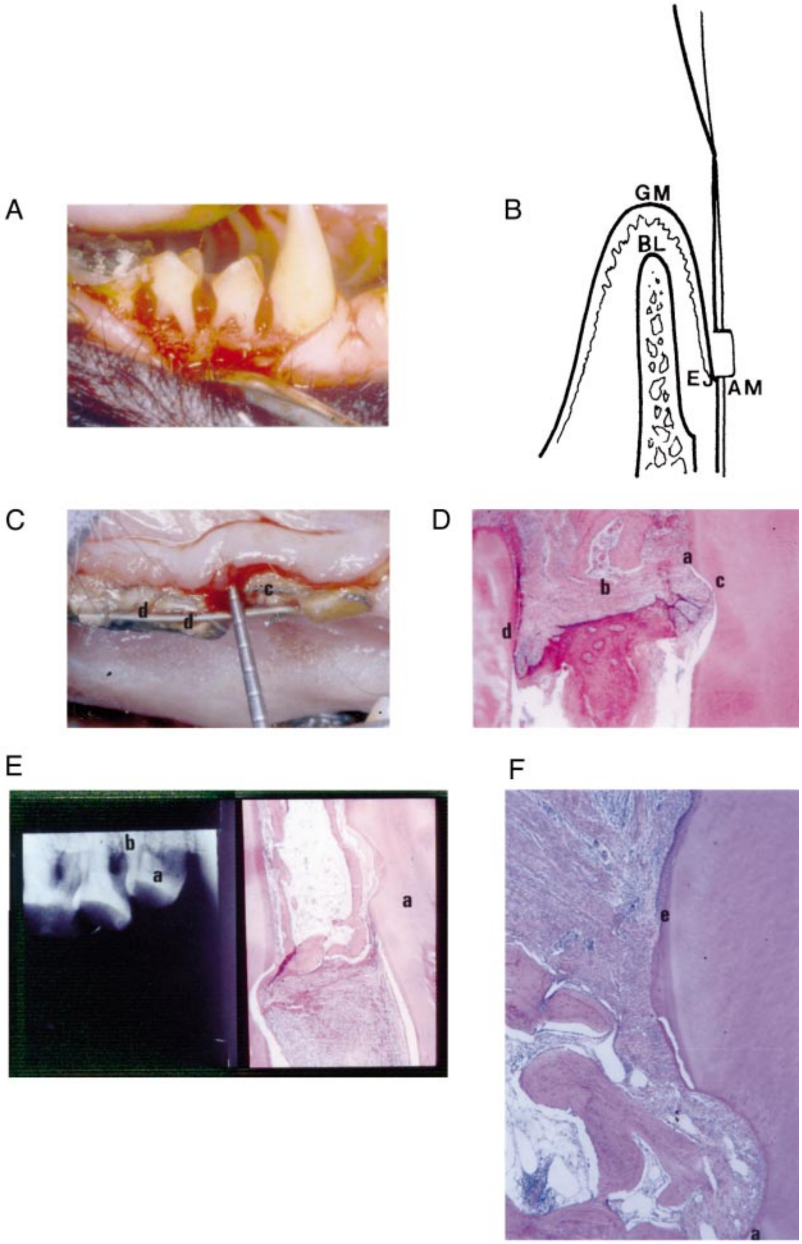

Figure 2 (A) Photograph of the teeth of a monkey during surgery. An important breakdown of the periodontium has taken place. (B) Reference points used for the evaluation of the changes occurring during treatment. (C) Clinical photograph of an intruded tooth (c), where no attention has been given to the periodontal health. The tooth is intruded almost to the level of the neighbouring tooth (d). (D) Microphotograph of the same situation. Note that the attachment level (a) is still at the notch and that there is a clear osteoclast activity reducing the height of the alveolar ridge (b). The intruded tooth (c) has been intruded almost to the level of the apex of the neighbouring tooth (d). (E) Composite of a periapical radiograph and the histological image of the same area. Note that the intruded tooth (a) has kept the same bone level (b) as the non-intruded tooth and the intrusion has thus been 'into' bone. (F) Micrograph illustrating the new attachment generated during intrusion. Note that the notch (n) is significantly below the bone level, and the collagen fibres are inserting into the cellular cementum coronally to the previous attachment level (a, the apical level of the notch). The new epithelial junction (e) has been displaced coronally. Reproduced with kind permission from Melsen *et al.* (1988).

the bone level (BL), the gingival level (GM) and the level of the junctional epithelial (EJ) (Figure 2B). In addition the width of the PDL, the angulation between the collagen fibres of the PDL and the alveolar wall were measured. The cellular density close to the alveolar wall was estimated and finally stereometric measurements were applied for the determination of the nuclear volume of the cells in the vicinity of the alveolar wall (Melsen and Kragskov, 1992).

The results clearly demonstrated that the tissue reaction to intrusion of periodontally-damaged teeth depended on the periodontal status of the teeth. Where inflammation occurred, a breakdown of the alveolar bone was observed (Figure 2C,D). In the case of a good oral hygiene low constant forces passing close to the long axis of the teeth resulted in a coronal displacement of the attachment level in all teeth varying from 0.7 to 2.4 mm, with an average of 1.3 mm (Table 4, Figures 2E,F). The width of the PDL was narrowed, the collagen fibres were stretched in an apical direction and the cell density in the vicinity of the alveolar wall was increased (Table 5). Ischaemic areas were avoided and the cells were stimulated to an increased DNA synthesis, as reflected by the shift of the cell population to a larger component with a large volume of the nucleolus. This study led to the conclusion that, in the case of a healthy periodontium, intrusion improved the periodontal status, since the attachment level was displaced in an apical direction in all intruded teeth.

The discrepancy in the literature regarding intrusion, particularly of periodontally-involved teeth, can be explained by difference in periodontal health (Ericsson and Thilander, 1978; Polson *et al*., 1984). The existence of pockets, even if kept clinically healthy, may still present a risk factor. The tissue reaction generated by

Table 4 Variations in apical limit of the notch (AM), the bone level (BL), the gingival level (GM), and the level of the junctional epithelium (EJ) with and without orthodontic intrusion of the teeth.

	With intrusion				Without intrusion			
	+ Hygiene		– Hygiene		+ Hygiene		– Hygiene	
	x	SD	*x*	SD	*x*	SD	*x*	SD
AM–BL	1.3	0.29	0.3	0.28	0.4	0.21	0.1	0.5
AM–GM	3.7	0.99	2.8	0.94	2.1	–3.7	1.7	0.48
AM–EJ	1.5	0.76	0.9	0.75	0.3	0.32	–0.1	0.67

Table 5 Variation in histological parameters of the periodontal ligament of orthodontically intruded teeth, teeth with mechanical periodontal support and teeth without periodontal disease.

	Intruded teeth		Teeth with reduced support		Teeth with normal support	
	x	SD	*x*	SD	*x*	SD
The width of the periodontal ligament	138.53	9.62	247.44	24.09	188.53	9.75
Angulation of the collagen fibres to the root surface	41.27	3.90	69.55	3.26	57.99	5.57
The relative extension of the root surface covered by cells	59.16	3.32	44.02	4.43	42.41	3.26
Nuclear volume	235.30	44.61	182.03	45.08	177.36	50.02

an orthodontic force system resembles that of inflammation and, if not kept sterile, will result in an uncoupling of tissue resorption and formation, leading to a negative balance, i.e. more breakdowns will occur. Waerhaug (1978) demonstrated that, in the case of a pocket deeper than 4 mm, it is practically impossible to obtain satisfactory cleansing by means of scaling without surgical exposure. Therefore, it can be concluded that intrusion of teeth with a reduced periodontium should only be carried out in patients with a healthy periodontium without pathologically increased pockets.

Differences in the type of force delivery may also contribute to the different results reported in the literature (Polson *et al.*, 1984; Melsen, 1986; Goerigk *et al.*, 1992; Wilson *et al.*, 1994; Costopoulos and Nanda, 1996; Baumrind *et al.*, 1996; Parker and Harris, 1998). Intrusion should be completed with light and constant forces (5–15 g per root) so that the visco-elasticity of the PDL is taken into consideration. High forces will result in a trauma to the PDL followed by repair, which starts a breakdown of the alveolus. Forces above a certain magnitude result in ischaemia of the compressed PDL with initially no true intrusion occurring. This reaction is easily distinguished from the stretching of the PDL fibres seen when the tooth is intruded with light forces along its long axis. With light forces no compression of the marginal part of the alveolus occurs; on the contrary a stretching of the fibres and increased cellular activity is observed (Melsen and Kragskov, 1992). The increased cellular activity could also explain the coronal displacement of the attachment level.

Another controversy in relation to tissue reaction to orthodontic forces is found between the orthodontic and the orthopaedic literature (Rubin, 1998). Orthodontic forces are 'known' to generate a compression and tension zone. Orthodontists have traditionally looked upon the resorption zone as a result of compression and apposition as a result of tension. Related to compression, either direct or indirect resorption can be observed. Direct resorption of the alveolar wall from the PDL occurs in the case of low forces, while indirect resorption starting from the marrow spaces is related to the occurrence of hyalinization of the PDL following high force application. Bone biologists, on the other hand, relate loading to formation (Frost, 1986). The question to be asked was thus: 'Why do orthodontists relate loading to resorption, while bone biologists relate it to formation'?

One of the major theories that relates mechanical load to biological reaction is the 'mechanostat theory' developed by Frost (1987), who described a relationship between various strain values and the balance between modelling and remodelling of bone (Figure 3). In the case of low strain values, a net loss of bone occurs as a consequence of increased remodelling. With increasing strain, modelling is initiated and a positive balance is achieved. Where the strain curve crosses the neutral line resorption and apposition are in balance, and the newly-formed bone consists of lamellar bone. In contrast, woven bone is formed as a result of even larger strains. Still higher strains will result in a negative balance, since repair cannot keep up with the occurrence of micro-fractures (Burr *et al.*, 1985). The borderline between a noxe, i.e. a traumatic stimulus, and mechanical stimulus resulting in an increased bone mass, has not yet been established. It is likely that the present model evokes strain values perceived as trauma, as well as strain values perceived as a mechanical usage provoking a structural adaptation to mechanical

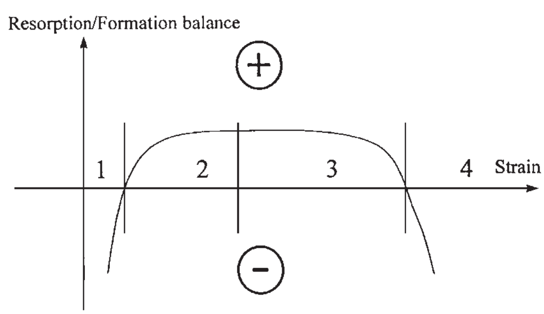

Figure 3 Graphical illustration of bone biological reaction to variation in strain values. In the case of low strain value (1) remodelling is turned on and a negative balance will be the result. With higher strain values (2), modelling is turned on and a formation of lamellar bone is occurring. Further increase in strain (3) results in the formation of woven bone. Severe overloading (4) results in a negative balance as a result of the repair process related to the micro-fractures occurring at this strain level.

usage [SATMU] (Frost, 1986). Frost (1992) listed the threshold strain values for lamellar bone fibrous tissue. A typical minimum effective strain (MES) is reported to be 1500–3000 μm for lamellar bone to start modelling, and if the strain is below 100–300 μ remodelling is activated as a result of inactivity. Based on the loading of bone transferred from implants to trabecular bone, the values recorded for trabecular bone seem to be slightly higher (Melsen *et al.*, 1996). A large body of evidence concerning structural adaptation to changes in strain has been generated experimentally and confirmed Frost's (1992) hypothesis (Goodship *et al.*, 1979; Lanyon *et al.*, 1979; Rubin and Lanyon, 1984). It is logical to ask whether the biological reactions to orthodontic tooth movement could be explained by the mechanostat theory. In this perspective, resorption observed in the direction of the force could be either a result of under- or over-loading. The main question that arose from these speculations was thus: 'How is the stress strain distribution in the periodontium related to the biological reaction of the supporting tissues?'

In order to answer this question an investigation combining strain levels and biological reactions was needed. The tissue reaction was studied in six *Macaca fascicularis* monkeys in which the first and the second molars had been extracted, and an appliance was inserted for approximation of the second premolar and the third molar by translation. (Melsen, 1999). After 11 weeks the monkeys were killed under Ketalar anaesthesia by perfusion with neutral formalin. The alveolar process was subsequently excised, embedded in methylmethacrylate, and prepared for the production of 15–20-μm parallel horizontal sections between the marginal bone level and the apex of the teeth cut with a diamond saw. The sections were then stained with fast green and analysed by histomorphometric measurements. The fractional resorption surface [Sfract (f)) $\mu m^2/\mu m^2$: the extent of resorption lacunae as a fraction of the total trabecular bone surface] and fractional formation surfaces [Sfract (f)) $\mu m^2/\mu m^2$ the extent of osteoid covered surfaces as a fraction of the trabecular surface] were measured. The fractional resting surface was calculated as 100 per cent minus the fraction recorded as resorption or apposition. Bone density was additionally evaluated in the areas mesial and distal to the third molars and second premolars (Gundersen *et al.*, 1988).

The type of tooth movement registered varied from translation to controlled tipping around a centre localized at varying distances above the apices of the teeth. The quantity of tooth movement varied between 0.21 and 0.9 mm per month, measured at the bone margin. No relationship between force magnitude, the type of tooth movement, and the amount of displacement could be verified. All parameters measured in areas surrounding the loaded teeth deviated markedly from the corresponding variables from the unloaded control teeth. There was an increase in the relative extension of resorption from 3–5 per cent observed in the specimens from the control teeth to 7–13 per cent of the total cancellous surfaces surrounding the loaded teeth. There was likewise an increase in the extension of appositional surfaces from 15–20 per cent in the control, to 35–49 per cent around the loaded teeth.

At the time of observation the alveolar wall in the direction of the tooth movement was completely resorbed, while woven bone formation was seen in the alveolar bone ahead of the direction of the tooth movement. Relative to the control teeth, the density in the direction of tooth movement was increased by a factor of ×2–3. The alveolar surface opposite to the tooth movement was clearly appositional (Figure 4).

In order to identify the range of strain levels in the alveolar bone during orthodontic tooth movement, a three-dimensional finite element model was constructed representing a conically-shaped root and the surrounding supporting structures. Young's modulus of the root was 20 GPa, while that of the alveolar bone varied between 0.5 and 2 GPa. The 0.2-mm thick PDL was modelled by non-linear spring elements. In compression, their stiffness corresponded to a Young's modulus of 0.1 MPa, while in tension this stiffness steadily increased from 0.1 MPa at 0 mm deformation to 1000 MPa at maximum deformation. Different loading situations were analysed, where the point of force application shifted along the longitudinal axis of the root

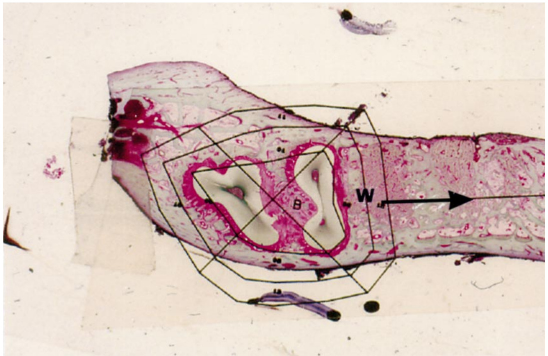

Figure 4 Micrograph of a molar that has been submitted to 11 weeks of orthodontic force in the direction of the arrow. Note that the alveolar wall in the direction of the force is resorbing and that the bone in the direction of the movement consists of dense woven bone (W). Reproduced with kind permission from Melsen (1999).

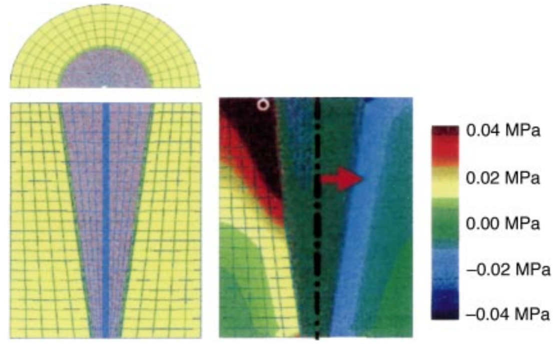

Figure 5 Stress profile of the tissue surrounding an orthodontically loaded tooth moving to the right. Note that the stress of the alveolar wall in the direction of the force is very low, whereas it reaches a high value at the marginal bone level corresponding to the insertion of the stretched periodontal fibres.

from the level of the apical crest, to a little over half the length of the root with a horizontal movement of the root of 25 µm at the level of the point of force application, the maximal tensile stresses in the alveolar bone were found to occur when the point of force application was located at one-quarter of the root's length. The magnitude of these stresses was then 0.2 MPa, while on the 'compression side' the compressive stresses reached a peak value of 0.04 MPa. The magnitude of these stresses appeared to be almost independent of the stiffness of the bone. The corresponding strain levels in the bone were 400 µstrain, on the tension and 80 µstrain on the compression side. When taken into consideration that bone is inhomogeneous and porous, the strain values corresponded to 2.000 µstrain in tension and 400 µstrain in compression (Figure 5).

The strain values found in the direction of the displacement were below the MES. In the light of the mechanostat theory this would release underload remodelling, thus explaining direct resorption in the so-called compression side (Figure 3, region 1). On the other hand, the stretching of the PDL fibres on the opposite side, generated a strain level corresponding to modelling, thus explaining new bone formation on the so-called tension side (Figure 3, region 2).

The woven bone formation seen ahead of the alveolus in the direction of the displacement could be interpreted as an expression of a so-called regional acceleratory phenomena (RAP) (Figure 3, region 3). According to Frost (1986) any regional noxious stimulus of sufficient magnitude can evoke a RAP. The extension of the affected region and the intensity of the response varies directly with the magnitude and the nature of the stimulus. The indirect resorption takes place in the PDL when ischaemia and hyalinization occurs. This is probably due to the disappearance of the lining cells necessary for the communication of the osteocytes. The hyalinized tissue of the PDL is removed by non-clast cells and the underlying bone is simultaneously resorbed by osteoclasts, as a repair response to the damaged tissues (Figure 3, region 4).

In the studies reported, the nature of the stimulus was a controlled orthodontic force. The strain developed, however, varied in magnitude both due to the difference in force, and to biological variations related to root size and structure of the bone surrounding the teeth (Melsen *et al.*, 1996). In that investigation, the most conspicuous result was the increase in both activation level and density of the bone subjected to compression in the direction of tooth movement.

Conclusions

The studies regarding tissue reaction to orthodontic forces were initiated with the purpose of finding an explanation of the controversies in the literature. The intrusion of periodontally damaged teeth was chosen as this movement is particularly controversial. It was found that the biological reaction was dependent on the force level and the stress/strain distribution. Histological examination demonstrated that the PDL fibres were stretched and formation activity was found along the major part of the alveolus. Only apical fibres were not observed to stretch. Interpreting these findings retrospectively in the light of the mechanostat theory, it can be concluded that stretched fibres will most likely lead to the delivery of strain values corresponding to modelling. In the apical region, the loading is minimal as the PDL fibres seem not to be stretched. Apical bone resorption can thus be interpreted as a remodelling. The stretching of the fibres may induce a slight bending of the alveolar wall. This bending in terms of an increase in the curvature of the alveolar wall has previously been suggested by Epker and Frost (1965) as the cause of new bone formation, in an attempt to harmonize the orthodontic and the orthopaedic perception of the tissue reaction to mechanical load. Based on the above-mentioned experiments it is suggested that the mechanostat theory can also be used as a model for understanding orthodontic tissue reaction (Figure 3). Direct resorption will be perceived as a remodelling induced by under-loading of the alveolar wall and apposition as modelling induced by the load exerted by stretched fibres. The woven bone formation observed in the direction of the tooth movement could finally be explained as a RAP phenomenon developing as a reaction to overloading (Frost, 1994). The indirect resorption takes place when ischaemia and hyalinization of the PDL is generated by high stress values. Disappearance of the lining cells (Marotti, 1996) necessary for the communication of the osteocytes probably leads to pathological reaction of the underlying overloaded bone, which is probably affected by microfractures.

Investigations on stress levels in the alveolar bone in the direction of the force and measurement of the occurrence of microcracks in the case of indirect resorption will contribute to the validation of this paradigm.

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