Orthodontic forces are capable of reorganizing and remodeling the periodontal ligament, to facilitate tooth movement. Optimal forces will produce favorable tissue responses, but whenever this balance is lost (as in the case of high force magnitudes, or in the presence of reduced periodontal support), the periodontal ligament may respond differently. This review highlights the responses of the periodontal ligament reactions when orthodontic forces—both normal and extreme—are applied. We also attempt to discuss how orthodontic movement differs in patients with good periodontal health and in those with periodontal disease. (Semin Orthod 2007;13:234-245.) © 2007 Elsevier Inc. All rights reserved.
Orthodontic movement creates clinical, cellular, and molecular level changes in the alveolar bone. In periodontal pressure sites, bone resorption occurs by osteoclasts, while in the periodontal tension sites, bone apposition occurs by osteoblasts. Orthodontically generated dental movement thus is strictly related to physiological processes of cellular activity, both in the soft connective tissue and in the alveolar bone compartments.\textsuperscript{17}

This article will review experimental and clinical reports that may be helpful in trying to understand the effect of orthodontic movement on periodontal tissue levels, and to determine when abnormal force application can create a risk for further periodontal breakdown.

**Periodontal Responses to Orthodontic Force Application**

Classically, when an orthodontic force is applied, tooth movement will occur in the direction of the force, by narrowing the periodontal ligament (PDL) at the site of compression, with subsequent bending and resorption of the alveolar bone. In this way teeth can be moved a small distance, until the resisting bone stops the movement. This resistance is eventually overcome by the ensuing resorption of the bone opposite the compressed PDL. At sites of force-induced tension in the PDL, a concomitant apposition of bone will occur, until the PDL has regained its normal width. Thus, tooth movement occurs as a direct outcome of force-induced tissue remodeling around the dental root. Such a remodeling requires the presence of cells capable of resorbing and forming the extracellular matrix (ECM) of the PDL and alveolar bone. When this mechanism is kept under control, initial anatomic limitations such as sinuses, sutures, or cortical barriers can be exceeded, and tooth movement can be performed even through the maxillary sinus.\textsuperscript{18}

Figure 1. (A-D) Adult patient affected by a chronic periodontitis showing flaring of the anterior teeth due to loss of bone support. After surgical periodontal treatment, orthodontic therapy was started to realign migrated teeth. Note the esthetic improvement obtained at the end of treatment together with a healthy periodontal support. (Color version of figure is available online.)
When orthodontic treatment is commenced, a force system should be planned to reach the proposed objectives. Increasing or decreasing force levels, are always associated with a tissue reaction. Under normal conditions, chewing and phonetic forces act on teeth surfaces, but no dental movement results, since teeth are placed in a so-called neutral zone. Moreover, this equilibrium is also maintained by means of an active stabilization, mediated by the metabolic activity of the PDL. To overcome this equilibrium and move a tooth, a minimal force of 5 to 10 g/cm² is required. Dental movements can be classified as movement “with the bone” or “through the bone.” To achieve “with the bone” movement, frontal (direct) resorption of the bone in the direction of the movement should occur, with a balance between resorption and apposition. With excessive force application, indirect resorption occurs in areas surrounding the compressed, necrotic (hyalinized) PDL, and tooth movement will be of “through the bone” type, with only small amounts of bone apposition. However, once the bony barrier is dissolved, the tooth moves rapidly in the direction of the force, while the PDL in the tension sites is stretched, and bone apposition proceeds vigorously.

When an orthodontic force is applied, a cascade of events initiated by mechanical deformation of cells and ECM takes place. The mechanical deformation of cells, their change in shape (ovoid or round), and the release of arachidonic acid from the cell surface and its metabolism through either the lipooxygenase or cyclooxygenase pathway leads to release of first messengers (prostaglandins and leukotrienes), which in turn activate or stimulate the release of second messengers (cyclic AMP, inositol phosphate, diacyl glycerol, and mitogen-activated tyrosine kinases). These second messengers evoke cellular reactions, such as bone and PDL remodeling. In addition, pressure generated in the PDL alters the vascular support, contributing to the cellular reactions and remodeling changes.

In the presence of heavy and intermittent forces, as are produced during mastication, a dental response is completed within a few seconds. These heavy intermittent forces cause an instantaneous microdeformation of the alveolar bone since the fluid component of the PDL cannot be compressed. After 1 to 2 seconds, fluid leaks out of the periodontal ligament and the teeth are deflected in the PDL space. After an additional 3 to 5 seconds, this fluid leaks out of the ligament, which generates compression and pain, leading to a cessation of any damaging force. However, the pattern of the tissue response to orthodontic forces differs and can be related to the intensity of the applied force. It differs in accordance with the magnitude of the applied orthodontic force, whether light or heavy. When light forces are used, a deformation of the alveolar bone develops within 1 second, since the PDL fluids cannot be compressed. After 1 to 2 seconds, the fluids leak out of the ligament, allowing the tooth to move in the ligament space. After 3 to 5 seconds the PDL blood vessels will be compressed in pressure sites and stretched in tension sites. Within a few minutes, a decrease of the \( P_{O_2} \) (partial pressure of oxygen) will develop, along with an increase in the concentrations of prostaglandins and cyto-

Figure 2. Cat maxillary canine after 7 days of orthodontic treatment showing compressed PDL and undermining resorption. Tissue section stained with hematoxylin and eosin. (Color version of figure is available online.)
kines. After a few hours, metabolic alterations will increase the incidence and rate of cellular differentiation, and after 2 days, noticeable initiation of tooth movement can be found. This process occurs predominantly due to the load-induced bone remodeling performed by a combined activity of both osteoclasts and osteoblasts. This kind of tissue reaction will generate a direct bone resorption (Fig 2), with a synchronization of tissue resorption and apposition in PDL pressure and tension sites (Fig 3), respectively.

In contrast, when heavy forces are applied to teeth, alveolar bone deformation will develop within 1 second, since the PDL fluids cannot be compressed. After 2 seconds, the fluids leak out of the ligament, allowing the teeth to move in the ligament space. After 3 to 5 seconds, the PDL blood vessels will be occluded, and within few minutes, the blood supply to compressed areas of the ligament will stop altogether. Within a few hours, signs of cellular death will appear in these zones, with the development of necrosis, which resembles the appearance of hyaline cartilage when viewed with a microscope (the so-called hyalinized zone). After 3 to 5 days, new cellular differentiation starts, along with the beginning of indirect bone resorption in all areas surrounding the hyalinized zone (Fig 4). One to 2 weeks later, the lamina dura will be removed, facilitating tooth movement.

Based on these findings, it can be concluded that light forces are more efficient in developing continuous tooth movement, preserving both bone and PDL from necrosis. With light forces, tooth movement begins after about 2 days of treatment, and this early movement can sometimes exceed 0.5 mm. The movement then continues, and if an appropriate system of force application is continued, a 2-mm space change may be detected after about 3 weeks. In contrast, tooth movement with heavy forces will not be continuous, but will occur with alternating periods of movement and a break, because of the need for resorption of the necrotic areas. However, it is difficult to quantify the amount of force delivered to each tooth, and to determine whether it should be categorized as “light,” since such quantification may depend on various pa-
rameters, such as root surface area, tooth anatomy, and the extent of periodontal support height. In the case of periodontal disease with loss of attachment, a “normal” force may be “excessive” in relation to the existing support of the teeth, which often leads to tissue hyalinization, excessive bone resorption, and further periodontal breakdown. It is obvious that in the case of severe periodontal disease, this scenario could even lead to tooth loss. To provide a numeric quantification useful for the clinician, it is suggested that a force not greater than 10 to 15 g should be applied to a maxillary incisor with loss of periodontal support, to minimize further tissue breakdown.19

Tooth movement in regions outside the alveolar process is undesirable and may occur due to an altered and poorly designed force system. Force distribution in tissues surrounding dental roots is controlled by the force magnitude, and by the moment/force ratio at the center of resistance of the root. The force magnitude, especially at the onset of treatment and in adult patients, should be very low, to avoid areas of hyalinization and to promote proliferation of periodontal cells,22 while the moment/force ratio should be high,23 to achieve a good distribution of the forces along the PDL. Adult age per se is not a contraindication for therapy, even though tissue response to orthodontic forces, including cell mobilization, activation, and responses, is slow when compared with those of children. This difference can be attributed to reduced cellular activity with tissues rich in collagen in adult subjects. In adults, hyalinized zones can form readily in pressure sites, temporarily preventing the tooth from moving in the intended direction.23 Eventually, these necrotic zones are eliminated through resorption by osteoclasts and macrophages derived from the adjacent marrow spaces, followed by regeneration of the PDL.24

In summary, when strong/heavy forces are applied, the compressed PDL is crushed, resulting in local ischemia and hyalinization, which delay tooth movement. When even moderate forces are applied, the PDL may become strangulated, resulting in a delay in bone resorption. However, light forces will produce only a partial PDL ischemia, along with direct bone resorption, resulting in a continuous tooth movement.

Orthodontic Movement of Teeth with Loss of Periodontal Support

Periodontitis is a multifactorial disease, which develops as a result of bacterial infection, superimposed on a genetic predisposition. Orthodontic forces per se are unlikely to convert gingivitis into a destructive periodontitis, but poorly executed orthodontic therapy in patients with periodontitis can easily lead to further periodontal breakdown (Fig 5). The combination of inflammation with occlusal trauma or dental movement will produce a rapid destruction of the support apparatus. The loss of alveolar bone in periodontitis patients results in an apical displacement of the center of resistance of the involved teeth, making bodily movement (translation) very difficult. The subsequent effect is that the teeth become prone to tipping. In addition to these mechanical difficulties, the formation of a hyalinized zone adjacent to a peri-

Figure 4. Cat maxillary canine after 7 days of orthodontic treatment showing compressed PDL and direct alveolar bone resorption. Tissue section stained with hematoxylin and eosin. (Color version of figure is available online.)
odontally compromised tooth can be deleterious, since regeneration of the PDL does not occur in the presence of a bacterial infection, resulting in extensive loss of alveolar bone (Fig 6). Thus, in case of a deep periodontal infection, teeth should be moved only after proper periodontal therapy has been performed, and deep infection has been eliminated.25,26

From a clinical point of view, in many patients with a periodontally involved dentition the migration of the anterior teeth leads to spacing and eruption, resulting in serious functional and esthetic problems. In these cases, orthodontics can be a reliable therapeutic treatment, because it does not result in a decrease of the marginal bone level, provided gingival inflammation is controlled (Fig 7). Proper and timely combination of orthodontic and periodontal treatment has been shown to improve reduced periodontal conditions, suggesting the possibility for a long-term success.25 Best results are obtained when orthodontic movements are performed with light forces, and the line of action of the force passing close to the center of resistance.26 The central point for the effectiveness of such treatments is in the ability of the procedure used to remove subgingival plaque and calculus from the root surface. Following these guidelines orthodontic treatment is no longer contraindicated when major marginal bone loss has occurred due to periodontal disease. The treatment of patients with severe periodontal disease is now being performed with interdisciplinary teamwork between the orthodontist and the periodontist, to improve the possibilities of saving and restoring a deteriorated dentition.

**The Influence of Orthodontic Forces on the Inflamed Periodontal Ligament**

The development of destructive periodontal disease may result in the formation of infrabony
pockets, that is, angular bony defects with the inflamed connective tissue and the dentogingival epithelium located apical to the crest of the alveolar bone. Furthermore, infrabony pockets may be created by orthodontic tipping or intruding movements of teeth harboring bacterial plaque, or both. Experimental studies have demonstrated an aggravating effect on the progression of periodontal disease when trauma, caused by “jiggling” forces, was superimposed on periodontal lesions associated with angular bony defects. This effect may indicate an increased

Figure 6. (A-D) Adult patient with malocclusion who underwent orthodontic therapy without a proper periodontal and mucogingival evaluation. After the alignment of the two lower central incisors, a deep recession developed, which can be attributed to uncontrolled labial movement. The intrasurgical view show the hard tissue level, with the bone dehiscence. The situation was partly improved by the combination of guided tissue regeneration and connective tissue graft. (Color version of figure is available online.)

Figure 7. (A-C) Interdisciplinary treatment of an adult patient with chronic periodontitis. After proper nonsurgical periodontal treatment, osseointegrated implants were inserted in the posterior areas to replace the missing teeth and orthodontic treatment was performed to align the migrated dentition. At the end of therapy, anterior teeth were splinted by means of resin-bonded Maryland-type bridges. (Color version of figure is available online.)
risk for progression of plaque-associated periodontal disease, when orthodontic mechanics is applied to a tooth, which already has angular defects. However, a similar study performed in monkeys failed to demonstrate additional loss of connective tissue attachment when jiggling trauma was superimposed on periodontally diseased sites.

The effect of bodily movement of teeth into infrabony periodontal defects has been evaluated in an experimental study in monkeys. The study reported that no deleterious effect was observed on the level of the connective tissue attachment. The angular defect was eliminated by the orthodontic treatment but no gain in attachment level was obtained. There remained only a thin epithelial lining covering the root surface. However, in this study periodontal treatment was performed before the orthodontic tooth movement was instituted, and the animals were subjected to plaque control measures during the entire course of the experiment. In another study performed in 4 beagle dogs, angular bony defects were prepared at the mesial aspect of the third premolars and an experimental periodontitis was induced. Orthodontic tooth movement was performed, to move one premolar into and through the angular bony defect. Clinical, radiographic, and histological evaluations revealed that it was possible to establish and maintain an infrabony pocket with a subcrestal, plaque-induced inflammatory lesion during the entire course of the study. While the control teeth had maintained their attachment levels, the orthodontically moved teeth did show additional loss of attachment. It was concluded that orthodontic therapy involving bodily tooth movement may enhance the rate of destruction of the connective tissue attachment in teeth with inflamed, infrabony pockets. The risk for additional attachment loss is particularly evident when the tooth is moved into the infrabony pocket.

Clinical studies that have examined the effect of orthodontic movement in periodontal patients with infrabony defects also abound in the literature. A combined therapy, made of open flap surgery and orthodontic intrusion, resulted in the realignment of the treated teeth with radiological bone fill, gain in clinical attachment level and probing pocket depth reduction, confirming the possibility of achieving a final healthy periodontium. These clinical studies demonstrated that it is possible to perform tooth movement into infrabony defects in patients with advanced periodontal disease, but emphasizing the importance of preorthodontic periodontal therapy.

A common problem in adult patients who have periodontal disease is the migration, overereruption, and spacing of incisors. These positional changes can be the result of the lack of equilibrium between the periodontal support and the forces acting on the teeth. Anterior teeth are specifically prone to overeruption, since they are not protected by occlusal forces and have no anteroposterior contacts inhibiting migration. Moreover, masticatory forces are predominantly directed anterolaterally and there exists little resistance, particularly in cases of increased overjet. With progressive bone loss, the center of resistance moves more apically, and the forces acting on the crowns generate a progressive displacement. From a functional and esthetic point of view, the intrusion of these teeth seems to be the logical solution even if orthodontic treatment, involving intrusive movements, does include a risk for an aggravation of the periodontal condition. These types of movements might have some beneficial effect on clinical crown lengths and marginal bone levels (Fig 8). Furthermore, histological investigations suggest that orthodontic intrusion may lead to new attachment formation: an experimental study on monkeys demonstrated new connective tissue attachment formed during the intrusion of periodontally involved teeth. It is possible that once the gingival infection is eliminated and the root surfaces are thoroughly scaled, it is possible for a new cementum layer to form on the former infected root surface. In another study, performed with the help of metric and histological analyses in monkeys, it was found that only about 60% of the distance moved is covered by the gingiva when the teeth are intruded with a continuous force of 80 to 100 g.

In contrast to the latter, an experiment performed on dogs demonstrated that intrusive orthodontic forces are prone to shift supragin-
gival plaque into a subgingival position, and thereby result in formation of an infrabony pocket. However, contraindication of intrusive movement should not be a major concern if a meticulous oral hygiene and a healthy gingival status are maintained. Once the periodontal treatment leads to a healthy gingival condition and susceptibility is controlled, and if the applied orthodontic forces are well calibrated, it is possible to intrude teeth with periodontal bone loss. This intrusion may lead to a certain gain in connective tissue attachment.

The orthodontically induced extrusion of teeth can be indicated to increase the clinical crown length of teeth, or to reduce differences in alveolar bone levels. The so called forced eruption has been described for the treatment of infrabony pockets, in which the extrusive movement leads to a coronal positioning of intact connective tissue attachment, to shallow out the bony defect. One contraindication to this technique is that, following the extrusion, the teeth will be in supraocclusion and the crown will need to be shortened, often requiring endodontic therapy and prosthetic restoration (Fig 9 A-F).

Depending on the different clinical situations, on occasion it may be desirable to have the periodontium follow the tooth in the extrusive movement, while in other situations it may be desirable to move a tooth out of the periodontal support. An experimental study on monkeys revealed that free gingiva moved about 90% and attached gingiva about 80% of the extruded distance. The width of the attached gingiva and the clinical crown length increased significantly, while the position of the mucogingival junction was unchanged. Therefore, the extrusion of a single tooth that would be extracted at a later time can be a reliable method to improve the marginal bone levels, when implant placement is a treatment option. The supporting soft tissues will move vertically with the corresponding tooth during the forced eruption, so as to create the ideal conditions for implant placement. On the other hand, in teeth with crown-root fracture at a subgingival level, the target of the treatment may be to force the tooth to erupt out of the periodontium to perform a prosthetic rehabilitation. In the latter situation, the extrusive movement should be combined with gingival fiberotomy. This excision of the coronal portion of the fiber attachment around the tooth should be performed once every 14 days, so that the tooth can be moved out of the bone without affecting the bony and gingival levels of the neighboring teeth.

Orthodontic Movement and Anatomic Limitations

Orthodontic treatment may on occasion be performed in adult patients who have partially edentulous dentitions (as the result of agenesis or previous extractions), and in these circumstances there may be anatomic limitations that can complicate tooth movement. Atrophic bone ridges, with a reduction of the horizontal volume, are not a limit to orthodontic tooth movement if direct bone resorption is obtained. Clinical and
histological observations have confirmed that if light forces are applied and teeth are moved more bodily into an area of reduced bone height, a thin bone plate is recreated ahead of the moving teeth.44 The same conclusions can be reached regarding the possibility of moving a tooth through anatomic limitations such as sinus, suture, or cortical barriers. Limitation of tooth movement in regions outside the alveolar process, as the maxillary sinus, is the result of an “abnormal force system,” but if a proper distribution of the forces along the periodontal ligament can be obtained, the limitations of the cortical bone of the alveolar process or the maxillary sinus can be overcome.

A clinical study in humans has demonstrated the movement of a premolar into the maxillary sinus. After 6 months of active orthodontics, the radiographic evaluation of the displacement revealed that bodily movement was achieved, with the translation of the root in the distal direction, without any vertical displacement. Direct resorption allowed the movement even if the sinus floor seemed to set a limit to it. After the distal movement, the direct remodeling caused a displacement of the lamina dura, leading to a complete remodeling of the sinus contours. The tooth maintained normal vital response to pulp testing during this period. It seems that the tooth did not fall into the sinus but moved with its supporting bone, without experiencing loss of connective tissue attachment. Moreover, this controlled movement left the bone necessary for implant insertion into the alveolus of the displaced tooth.45 Hence, based on the findings in the studies referred to, it seems reasonable to assume that a tooth moved through the maxillary sinus will maintain the original height of the

Figure 9. (A-F) Patient presenting crown-root fracture at a subgingival level. A gold-alloy post was cemented into the root canal and orthodontic extrusion initiated performing circumferential fiberotomy every 2 weeks. At the end of treatment a permanent ceramic crown was inserted. (Color version of figure is available online.)
supporting apparatus, the connective tissue attachment, and the alveolar bone height.

Conclusions

The orthodontic treatment of patients with deteriorated dentitions requires an interdisciplinary team approach that involves different dental specialties to obtain satisfactory functional and esthetic outcome. Orthodontic therapy is based on the principle of displacing teeth by applying mechanical forces and remodeling the PDL and alveolar bone. Clinical and histological evidence support the need for using light continuous forces during orthodontic treatment. Light forces evoke direct bone resorption, a so-called with-the-bone resorption, in the direction of the movement, with a balance between resorption and apposition. In contrast, heavy forces create blood vessel strangulation with subsequent necrosis (hyalinization) in PDL compression zones. This kind of tissue reaction will delay tooth displacement and increase the risk for bone loss. In the presence of a periodontally involved dentition, a risk for further periodontal breakdown is unacceptable since it may lead to tooth loss. On the other hand, orthodontic therapy performed with well-calibrated forces and applying appropriate force systems can be useful in realigning migrated teeth in adult patients with periodontal disease following elimination of the periodontal infection.

An understanding of the basic clinical and biological principles of orthodontic tooth displacement is an essential requirement for the implementation of a successful therapeutic regimen in patients of all age groups with normal as well as compromised periodontal tissues.

Acknowledgment

The authors thank Drs. Stefania Re, Giuseppe Corrente, and William Manuzzi for their contribution in the clinical treatment. The authors also express their sincere gratitude to Dr. Ze’ev Davidovitch for providing histologic figures as well as with a critical review and revision of the manuscript.

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