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CRANIOFACIAL SKELETON (G ROBERTS, SECTION EDITOR)

Low-Magnitude Forces for Bone Modeling and Remodeling in Dentofacial Orthopedics

Achint Utreja [1]

Abstract

Purpose of Review To examine the evidence in support of light continuous forces for enhancing bone adaptation (modeling and remodeling) in orthodontics and dentofacial orthopedics.

Recent Findings Clinical evidence suggests that light continuous orthodontic force can achieve physiologic expansion of the maxillary arch, but the long-term stability and the biological effects of the procedure are unclear. Compared to conventional orthodontic appliances that deliver heavy interrupted forces for tooth movement, the application of low-magnitude forces in animal models leads to anabolic modeling and remodeling of the alveolar bone in the path of orthodontic tooth movement. This results in dental translation and expansion of the alveolar process.

Summary Light continuous forces are preferable to heavy forces for more physiologic dentofacial orthopedics. The interaction of low-magnitude loads with soft tissue posture achieves therapeutic adaptation of the craniofacial skeleton. The increasing emphasis on genomic medicine and personalized treatment planning should focus on low-magnitude loads in orthodontics and dentofacial orthopedics.

Keywords Orthodontic tooth movement · Maxillary expansion · Light continuous force

Introduction

The dental specialty of Orthodontics and Dentofacial Orthopedics is a unique amalgamation of bone biology and biomechanics. Orthodontic tooth movement (OTM) occurs because of biologic responses to applied loads [1]. During OTM, the reactions of the periodontal tissues surrounding a tooth are rather similar to the changes seen during physiologic tooth movement [2, 3]. However, certain characteristics of an externally applied mechanical force on a tooth, such as the pattern of application, magnitude, duration, and direction of the force, are important determinants of the cellular changes that are likely to occur [4]. As a result, orthodontic forces applied to the teeth affect the periodontal ligament (PDL) with molecular [5] and immunologic mechanisms [6]. They also produce histopathologic changes like osteocyte death [7] in the supporting alveolar process. On the other hand, heavier, orthopedic forces are aimed at changing the dimensions of the jaws and surrounding craniofacial structures [8]. This distinction in the magnitude of applied forces is crucial for the delineation and better understanding of the underlying biologic response during dentofacial orthopedic therapy.

Biological Effects of Orthodontic Forces

Various characteristics of OTM have been studied and reported in the literature over the years. According to the traditional viewpoint, OTM can be broadly divided into three distinct divisions: PDL displacement, lag phase, and progressive tooth movement [2]. Initial displacement of the tooth in its alveolar socket is brought about by compression and tension of the PDL as a viscoelastic combination of collagen fibers and ground substance [9, 10]. In the areas of tensile strain, angiogenesis is induced via type IV collagen degradation by matrix metalloproteinase-12 [11]. Although areas of tension are primarily characterized by anabolic activity, high initial expression of IL-1β has been reported on the tension side following application of orthodontic force [12]. Incidentally, IL-1β

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regulates inflammatory mediators in a tensile strain-dependent manner [13], with low-magnitude strains inhibiting the release of pro-inflammatory cytokines [14] and high-magnitude strains promoting their release [15]. On the compression (opposite) side in the PDL, elevation of stress > 10 kPa results in necrosis [16], which inhibits tooth movement and increases root resorption [17]. This lag phase in tooth movement due to a necrotic PDL negatively affects cell proliferation and differentiation [18]. Following a 2 to 10-week period of undermining resorption to clear the area of PDL necrosis, tooth movement resumes [2–4].

The response of the alveolar bone to an orthodontic force can be perplexing when analyzed from the point of view of the conventional paradigm proposed in the bone biology literature. Based on Harold Frost's "Mechanostat Theory" [19], mechanical loading of bone triggers anabolic stimuli, whereas unloading is catabolic in nature. With OTM, however, areas under compression (loaded) are sites of bone resorption, whereas areas under tension (unloaded) are sites of bone deposition [2–4, 20]. Over the years, researchers have attempted to compare and contrast the underlying biological response of long bones and the alveolar bone to mechanical loading. One such explanation, the "alveolar bone bending hypothesis" [1] states that, in addition to the previously highlighted changes in the PDL fibers and ground substance, orthodontic force leads to flexure or bending of the walls of the alveolar socket surrounding a tooth. As a result, both modeling and remodeling of the alveolar bone play crucial roles in orthodontics and dentofacial orthopedics [2]. Anabolic and catabolic modeling is characterized by independent actions of osteoblasts and osteoclasts resulting in activation-formation (A➔F) or activation-resorption (A➔R) sequences [19, 3]. Bone remodeling is a turnover process affecting trabecular bone surfaces and compacta that follows the activation-resorption-formation (A➔R➔F) sequence. The magnitude and direction of an applied mechanical load elicits a specific biologic response that determines the overall outcome. As osteoclast recruitment is an essential component in both situations, the RANKL/RANK/OPG system regulates remodeling of the alveolar bone during OTM [21].

Tissue Response to Orthodontic Forces

The mechanical forces applied in orthodontics are categorized as continuous, interrupted, or intermittent based on the duration of action and frequency of re-activation [8]. Contemporary fixed orthodontic appliances are designed to deliver light continuous forces, but applied loads are actually interrupted in nature because the appliances are "adjusted" every few weeks during treatment [22]. From a biological standpoint, a light continuous force is advantageous for inducing optimal bone modeling and remodeling changes during OTM [23, 24]. Unwanted side effects, such as the occurrence of hyalinized regions devoid of cellular activity (PDL necrosis), can be minimized if relatively low force levels are maintained [25]. In most circumstances, particularly when the surrounding periodontium is healthy, OTM can be accomplished with little to no unwanted side effects in the sagittal and axial directions [26, 27]. However, the effect of tooth movement in the transverse direction following the application of light continuous orthodontic force is unclear.

Orthopedic forces are utilized to address significant discrepancies in the size and relationship of the maxilla and mandible. Craniofacial growth decreases in the transverse direction in late childhood [28]. The deceleration of craniofacial growth in the transverse dimension occurs considerably earlier than in the anteroposterior and vertical directions. Particularly affected are individuals with maxillary arch constriction and Class II malocclusion, caused by either deficient mandibular growth or excessive maxillary growth [29].

Maxillary Expansion in Orthodontics

Clinically, patients with a transverse arch deficiency often present with a posterior crossbite [30]. In this situation, the mandibular molars and premolars bite outside (lateral) to the upper arch. Significant dental crowding or overlap of teeth in the maxillary arch is also routinely seen [31]. Typically, the orthodontic treatment plan includes maxillary palatal expansion with a jackscrew mechanism to expand the maxilla and correct the crossbite. Depending on the frequency for reactivating the jackscrew, expansion protocols range from rapid palatal expansion (RPE) [32] to semi-rapid [33] or slow [20] expansion. However, the unifying theme underlying all maxillary palatal expansion protocols is the transmission of heavy, intermittent forces to the teeth as well as to the surrounding periodontium. Forces from RPE appliances are reported to be as high as 15–50 N [34]. Deleterious side effects of maxillary expansion with such heavy forces can be seen in the mid-palatal suture and temporomandibular joint (TMJ) [35]. Shortening of the roots of the teeth or root resorption is also seen following maxillary expansion with heavy forces [36]. Additionally, there are concerns about moving the roots of teeth through the buccal plate of the alveolar bone, which produces further periodontal deterioration and compromises the long-term prognosis of the teeth involved.

Light Continuous Expansion Force

Given the biological advantages of light continuous forces during orthodontic treatment, a practical alternative to RPE is the application of low mechanical loads for inducing bone modeling and remodeling to expand the arch more physiologically. Although this concept is appealing in theory, a thorough understanding of the clinical and biological responses to light forces is paramount. Clinical outcomes after delivering light

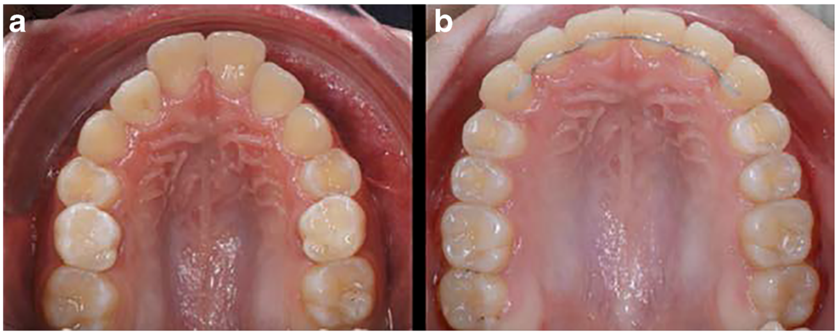

Fig. 1 An orthodontic appliance system that utilizes arch-wire activation to deliver light expansion (buccal) force during treatment leads to expansion of the maxillary arch without a rapid palatal expansion (RPE) appliance. Comparison of pre-treatment (**a**) and post-treatment (**b**) clinical photographs shows a significant increase in inter-molar width

continuous forces [37] suggest that "physiologic arch expansion" is possible (Fig. 1). This approach may avoid the need for dental extractions to provide space for aligning the teeth during orthodontic treatment. However, the underlying biological mechanism and consistency of the approach are unclear.

Buccal tipping of the maxillary posterior teeth (molars) is the usual outcome with RPE appliances [38]. Tipping of a tooth (or teeth) is due to the point of force application relative to the center of resistance of the tooth or segment. With a very light continuous expansion force, a counter-force due to the surrounding musculature of the cheeks results in translation of the tooth or teeth. This very small counter-force on a moving tooth is due to the perioral structures that strive to maintain equilibrium of tooth position at rest [39–41].

Equilibrium Theory of Tooth Position

Weinstein [41] suggested that physiologic forces of low-magnitude produced by the oral musculature play a crucial role in determining tooth position. Under normal, resting conditions, an equilibrium is maintained by opposing muscular forces acting on the labial (lips/cheeks) and lingual (tongue) surfaces of the teeth [39]. In order to maintain a physiologic position, the net resultant of these alternating labial and lingual forces is zero. Application of a light continuous expansion force alters this balance in favor of the labially directed force, leading to OTM.

Fig. 2 Micro-computed tomography (CT) analysis showed an increase in inter-molar width (transverse distance between the maxillary molars) following maxillary expansion with a light continuous force in an animal model

Besides the role of intrinsic forces on the teeth (exerted by the tongue, lips, and cheeks), Proffit [40] also highlighted the importance of extrinsic factors such as oral habits and orthodontic appliances in dental equilibrium. Additionally, forces from dental occlusion as they affect the PDL were added to the list of primary equilibrium factors. The tongue pressure was greater than lip pressure at both rest and during swallowing. Light continuous extrinsic forces such as those from orthodontic appliances could produce OTM due to their long duration of action, whereas transient forces during speaking and swallowing were of insufficient duration for OTM [40].

An individual's age as well as the maxillo-mandibular occlusal relationship affects the muscular forces that are required to maintain dental equilibrium. In young growing children with a primary dentition, the resting pressure from the tongue was significantly lower than the pressure exerted by the lips and cheeks [42]. Class III malocclusion (prominent mandible) in children, caused by either deficient maxillary or excessive mandibular growth, has a significant difference in the labial and lingual muscular pressures [43]. Collectively, these data demonstrate the importance of forces, due to opposing and balanced muscular posture, in maintaining the equilibrium that dictates the alignment of the dentition.

Biologic Effect of Light Continuous Expansion Force

There is continued interest in understanding the biologic response of the alveolar bone to a light orthodontic force. Two recent animal studies have focused on this topic. Kraus et al. [44•] utilized an OTM model in dogs to analyze the dento-alveolar changes following the application of a continuous, light-to-moderate orthodontic force. One of their objectives was to analyze whether low-magnitude forces lead to bodily movement of the teeth instead of the tipping movement that is

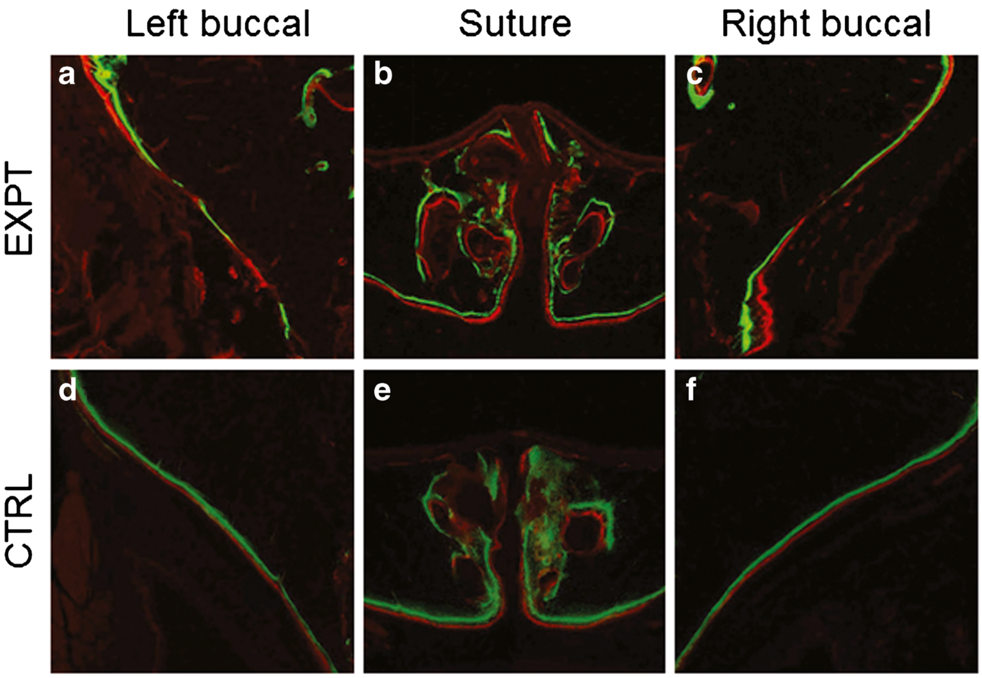

Fig. 3 Fluorochrome bone labeling was used to analyze bone modeling and remodeling in the mid-palatal suture (**b**, **e**) and buccal bone (left—**a**, **d**; right—**c**, **f**). Increased inter-label separation was seen in the experimental group compared to the controls. **Figure reproduced with permission from The Angle Orthodontist*

usually seen with conventional RPE appliances. Micro-CT and histology were used to compare the outcomes in this split-mouth study. The results indicated that although expansion was achieved, the teeth still tipped. Histological analysis showed subperiosteal bone deposition along the buccal surface of the alveolar bone, leading the authors to conclude that bone apposition favorable to arch expansion occurs with light-force OTM.

A recently published animal study analyzed the biologic response of the periodontal tissues to maxillary expansion with light continuous force [45••]. In the experimental group, a light-force orthodontic wire made of 0.014″ copper-nickel-titanium alloy (CuNiTi) was attached to the left and right maxillary first molars bilaterally. Equal and opposite distribution of the 5cN force with a 5-mm range of activation resulted in a 2.5cN load with a 2.5-mm range of activation delivered to each half of the maxilla. Fluorochrome labels, calcein, and alizarin were injected 3 days apart, and the inter-label separation was compared between the experimental and control groups. Following 3 weeks of maxillary expansion with the light wire, frontal sections of the maxilla were analyzed with micro-computed tomography (CT) and histologic analyses focused on the fluorescent bone labels. Micro-CT scans demonstrated an increase in the inter-molar width in the experimental animals compared to the controls at the region of both the first and second maxillary molars (Fig. 2). The area of the mid-palatal suture was increased and bone labels documented bone apposition (sutural expansion). Comparison of the separation between the fluorescent labels in the mid-palatal suture as well as the right and left buccal bone showed increased inter-label width in the experimental group compared to the controls (Fig. 3). Histologic analyses showed increased bone deposition as well as bone resorption in the region of the buccal bone lateral to the maxillary molar. Overall, these results indicated that the application of light continuous expansion force led to a more physiologic expansion of the maxilla via sutural anabolic modeling, molar movement in a buccal (lateral) direction, and subperiosteal apposition on the alveolar bone surface. The bone modeling and remodeling patterns in this animal model were consistent with a physiologic maxillary expansion and translation (bodily movement) of the maxillary first molars [45••].

Conclusions

The increasing emphasis on genomic-based personalized medicine is consistent with a more physiologic approach to dentofacial orthopedic therapy. Long-term stability has eluded many of the traditional clinical procedures. It is proposed that therapeutic outcomes be based on the interaction of applied biomechanics of low-magnitude forces with the natural loads of oropharyngeal function and soft tissue posture. Clinical and animal studies have achieved a more physiologic expansion of the maxillary arch. Very low loads interact with the natural forces of cheek posture to produce a net translation of maxillary molars in a buccal direction. Although these promising outcomes are similar to natural growth and adaptation, long-term stability studies are indicated to determine if low-force maxillary expansion is a stable therapeutic procedure. Physiologic therapy associated with long-term stability requires a better understanding of physiologically acceptable, low-magnitude forces on bone modeling and remodeling of craniofacial structures.

Compliance with Ethical Standards

Conflict of Interest Achint Utreja declares that he has no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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