Long-term orthodontic tooth movement response to short-term force in the rat

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Minimal exposures to forces at physiological levels have been shown to stimulate significant bone remodeling. Four consecutive loading cycles per day of 8 seconds each will totally prevent disuse osteoporosis in immobilized avian wings.[1] Strain cycles of 1 hour per day stimulate significant increases in bone density in sheep forelimbs.[2] One 5-minute exposure to compression will result in periosteal bone formation within the next 5 days in skeletally mature avian ulnae.[3] These studies clearly demonstrate that bone architecture is responsive to short-term alterations in its strain environment.

Similarly, interrupted orthodontic forces have been reported to produce tooth movement equivalent to continuous forces with less damage to the structures of the periodontal ligament.[4-6] Light intrusive forces applied 50% or 25% of the time have also been shown to intrude or prevent the eruption of rabbit incisors.[7] Although the precise relationship between force duration/frequency and tooth movement remains unclear, it does seem evident that light cyclic force applications can alter tooth positions comparable to continuous forces. The purpose of this study was to compare orthodontic tooth movement as a function of time in a well characterized rodent model in response to appliances activated for 1 hour, 1 day and 14 days.

Materials and methods

Animals:

Adult male Sprague-Dawley strain rats (80 to 90 days old) (Charles River Breeding Labs Cambridge, Mass.) were acclimatized for 2 weeks under experimental conditions, including being housed in wire cages, fed a diet of ground laboratory chow and

Abstract

Both the amount of force applied and the duration of the application affect tooth movement. To study the effect of duration, adult male Sprague-Dawley rats were fitted with orthodontic appliances delivering a 40-gm initial mesial tipping force to the maxillary molars. The animals were divided into two longitudinal groups (I: 1 hour and II: 24 hours; N=15). Sham-treated control (III) and 14 day (IV) continuous cross-sectional force tooth movement data were also included for comparison (72 rats per group). Extraoral cephalometric radiographs were obtained at appliance placement and at 1, 3, 5, 7, 10, &14 days. Tooth movement was determined with respect to palatal implants. ANOVA indicated significant differences existed over time in each group (p=0.0001). Continuous force applied for 14 days generated a classic three-part tooth movement curve. Short-term forces were characterized by initial mesial movement, a distal relapse period (d3-d5), and a late mesial movement period (d7-d14). The results suggest short-term forces of 1 and 24 hours initiate remodeling events, which result in tooth movement 7 to 14 days later and that the minimum effective duration of a 40-gm activation is less than 1 hour in this animal model.

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Key Words

Tooth movement • Force duration • Bone remodeling

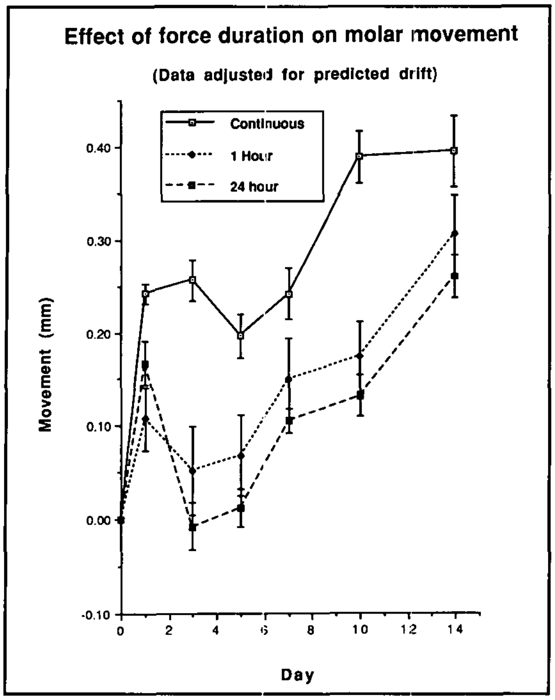

Figure 1
Cumulative tooth movement in the three force groups minus sham controls. Each point represents the mean of 12 to 15 observations and the vertical bars are standard errors of the mean.

distilled water *ad libitum*, and maintained on a 12-hour light-dark cycle. Fifteen rats were radiographed six times each, at 1, 3, 5, 7, 10 and 14 days, in two longitudinal groups (I and II). In two cross-sectional groups (III and IV), 12 rats were radiographed and sacrificed at each timepoint.

Appliances:

Bilateral appliances were placed in all rats using a method which has previously been described.[8] Briefly, each rat was anesthetized and placed head up in a specially-designed device with its mouth propped by suction devices. Modified orthodontic cleats were attached to the occlusal surfaces of maxillary first molars using orthodontic adhesive. Short lengths of endodontic barb broach were inserted subperiosteally palatal to the molars as superimpositional landmarks. Rats were allowed to fully recover (3 weeks) prior to commencing the experiment. A 7mm length of closed coil (0.006 inch Hi T; arbor diameter: 0.022 inch, Unitek, Monrovia, Calif.) was attached to a steel ligature wire loop. This was then slipped over the molar cleat. The anterior end of the coil was attached with suture material to a 40 gm weight which was suspended over a pulley, delivering a precise, anteriorly directed force. The anterior end of the coil was then attached to the labial surface of the maxillary incisors using orthodontic adhesive and the weight removed. All animals except the shams received 40 gm activations which were designed to tip the maxillary molars mesially. Opposing molars had previously been extracted in all groups to prevent occlusal interferences. In group I, the springs remained in place for 1 hour. Group II, had them removed after 1 day and group III at sacrifice. Group IV had all procedures except spring placement.

Tooth movement:

Tooth movement was assessed cephalometrically using a previously described method.[8] Four independent radiographic exposures were made on each rat immediately prior to appliance activation (i.e. spring placement) and four more at each timepoint. Molar, maxillary implant and incisor positions were digitized (Hipad, Houston Instruments) from acetate tracings of enlarged radiographs. Adjusting for magnification, distances were measured using a computer (IBM-PC/AT) along the molar-to-incisor vector by projecting the maxillary implant landmark perpendicular to that line and then superimposing on the projected landmark. Differences between molar positions at appliance placement and each timepoint were recorded as tooth movement. Molar positions were determined in quadruplicate, calculating the mean. Movement of the right and left molars was averaged and recorded as the molar movement for each animal. The 95% confidence limits for the mean of four independent determinations of molar position using this method has been shown to be 23 microns,[8] representing 5% to 10% of the initial tooth movement stimulated in these experiments.

Statistical methods:

The means and standard errors of molar movement were calculated for each time-point in each group. Movement in shams was subtracted from the appropriate time-points in each group. ANOVA was performed to examine differences among groups at each time-point and across times within each group. Pairwise (Scheffe) comparisons were then performed between individual groups/days if ANOVA indicated significant differences existed ($p<0.05$).

Results

Cumulative tooth movement kinetics for the 14 day, 1 hour, and 24 hour force groups are shown in Figure 1. ANOVA indicated that significant differences in movement occurred over time in all three force duration groups ($p<0.05$). In the 24 hour group, 1, 7, 10 and 14 day were significantly different from zero. Movement at day 1 differed from days 3 and 5; day 3 from days 7, 10, and 14; day 5 from days 10 and 14; and days 7 and 10 from day 14 ($p<0.05$).

No differences were detected at any time point between the 1 hour and 24 hour groups ($p>0.05$). Groups I and II were characterized by less movement at day 1 than was group III ($p<0.01$).

In the 14 day group, movement at all days differed from zero; movement at 1, 3, 5 and 7 days differed from that at 10 and 14 days, but not from each other ($p<0.05$). In the 1 hour group, movement at days 1, 7, 10 and 14 differed from zero, while movements at 1, 3, 5, 7, and 10 days were not different but did differ from movement at day 14 ($p<0.05$).

Discussion

The 1 and 24 hour groups demonstrated tooth movement kinetics similar to the 14 day force group (Figure 1). All three generated three-part tooth movement curves consisting of an initial deflection, a delay or relapse period, and continued movement in the direction of force. The relapse period in both short-term groups was consistent with the demonstration that molars drift distally in rats without appliances[8] and that dental relapse from applied forces is rapid and significant.[9] The most important finding of this study and the point which requires discussion is the observation that both short-term duration groups displayed significant mesial molar movement after the delay/distal relapse period in the absence of continued mesial force.

Frequency and duration are known to be significant characteristics of the mechanical signal stimulating bone remodeling changes. It seems clear that very short exposures to mechanical signals can stimulate remodeling. One study demonstrated that the resorptive remodeling associated with the removal of load bearing forces from avian bone can be prevented by functional loads consisting of four cycles per day of 8 seconds each, with higher frequencies or longer durations being no more effective.[1] In another study sheep radii and ulnae which were subjected to strain cycles of 1 hour each day responded with significant bone remodeling.[2] Again, longer exposures were not found to be more effective. Skeletally mature avian ulnae, subjected to one 5-minute exposure to compressive loading within physiologic limits has been reported to stimulate periosteal bone formation within 5 days.[3] This reported new bone formation occurred without prior resorption, suggesting that a single loading signal is sufficient to initiate the events leading to bone formation.

Data relating orthodontic tooth movement to force frequency/duration were reported by Reitan.[4] Dog incisors were placed under a load which was interrupted for 20 seconds every 10 minutes or for 2 minutes every 2 hours over a 36 hour period. Tooth movement was the same for continuously and intermittently applied forces in this study. In another investigation, approximately 6 grams of force was delivered to a dog premolar over a 12 day period in a pulsating fashion.[5] The force was interrupted for 3 seconds, 3 times per minute. Tooth movement was also equivalent to a continuous force control in this investigation. A maxillary molar in one human patient was treated with a force frequency of 42 cycles per minute at an average force level of 20 ounces.[6] Distal movement of the experimental tooth was reported to be greater than that of the continuous control. However, this cyclic force was superimposed over a continuous headgear force of unknown magnitude, making interpretation difficult. In another study, 1 or 3 gram intrusive loads were applied to erupting rabbit incisors for 1 second on, 9 seconds off (1:9); 1 second on, 3 seconds off (1:3); or 1 second on and 1 second off (1:1) over a 5 hour period. The 1:9 frequency produced little effect on incisor eruption, whereas a 1:1 frequency produced the same intrusive effect as a continuous force. The effect of a 1:3 frequency fell between these two.[10] Although the precise relationship relating frequency/duration and tooth movement remains unclear, it seems evident that cyclic or pulsating forces can produce bone remodeling and tooth movement responses similar to those recorded with continuous forces.

Traditional fixed orthodontic appliances can be considered to be decaying or static force systems. There is evidence that dynamic loading may be a more effective means for evoking cellular response in bone.[25] However, dynamic versus static loading remains to be adequately evaluated in the orthodontic context. Clearly, intermittent, short-term dynamic deformations, as in mastication, may be a source of superimposed signal and may alter the signal characteristics of orthodontic appliance systems. In the current study, the 1 hour group was sedated during the entire activation period. There were probably no significant intermittent forces applied to the springs prior to removal. The 24 hour and continuous groups may have had superimposed intermittent dynamic forces through mastication though these were probably minor as the opposing dentition was extracted 1 week prior to spring placement.

Interpretation of experimental data on bone remodeling responses to mechanical stimuli in relation to orthodontic tooth movement should be approached with a degree of caution. First, most orthopedic studies evaluate the response of long bones to mechanical signal. Differences in origin, location, or function alone or collectively of craniofacial and long bones may dictate that different steps are involved in their respective bone growth and remodeling processes. Second, most of the orthopedic studies have evaluated changes of bone density, rather than bone shape, in response to mechanical stimulation. Last, force magnitudes much greater than those considered to be within physiologic limits have been used in most of the orthopedic investigations. These force magnitudes are generally much greater than those used in orthodontic studies. Although numerous studies have evaluated orthodontic tooth movement in relation to continuous force systems,[11,12,13] there has been limited investigation of short duration signals and orthodontic tooth movement. There are several clinical examples which indicate that less than continuous orthodontic forces are an effective means of producing tooth relocations. Restorations with deflective interferences have been shown to cause tooth movement and mobility.[14] Functional appliances have been widely reported to generate orthodontic tooth movement with less than full-time wear.[15-17] Headgear also clearly produces orthodontic tooth movement with non-continuous usage.[18] Empirically, 12 to 16 hours per day of wear has been considered acceptable. One study assessed the long-term effects of limited duration forces in an animal model. In this autoradiographic study, Kvam[19] reported two significant waves of labelled cells in the rat periodontal ligament after an appliance activation of 2 days. It is apparent from clinical experience and these data that force durations which fall short of the continuous activations are capable of producing orthodontic tooth movement and biological responses.

Histomorphometric data are available on orthodontic tooth movement in response to a 40 gram tipping force indicating that paradental alveolar bone experiences a wave of resorption which begins after an induction period of 2 days and ends between 5 and 7 days. Resorption is followed by reversal and a period of enhanced alveolar bone formation which persists for at least 14 days.[20] Very similar results have been obtained during molar supereruption following extraction of its antagonist.[21] In the current study, tooth movement was only assessed in the anteroposterior direction along the incisor-molar vector. Tooth movements in the other two planes of space were not measured. However, it may be reasonable to expect vertical changes because of the extraction of the opposing molars.

The processes of resorption and formation are known to be coupled resulting in these two remodeling activities being generally balanced in healthy adults.[22] The mechanisms controlling this coupling process are poorly understood today, but it seems clear that a finite amount of time is required for the complete response to occur. It also seems reasonable to postulate that once the process is initiated at a particular site, local mechanisms may carry remodeling events to completion without additional signal. In the present study, significant mesial molar movement was recorded radiographically by day 10 in the 24 hour group and by day 14 in the 1 hour group. These delays were similar to the times required to stimulate sequential waves of alveolar bone resorption and formation.[20] Such delays are also characteristic of tooth movement under conditions of continuous force and may not be an unexpected finding in the experimental groups. The suggestion has also been made that bone has a "strain memory" which is created by mechanical distortion of its extracellular matrix, possibly proteoglycans.[23,24] Such a mechanism may also explain why cells could continue to be stimulated to facilitate mesial tooth movement after the initial mechanical signal has been removed.

Though inferences between species should be made with caution, there may be some clinical advantage in applying forces of short duration in human orthodontic tooth movement. If one accepts that short duration forces are capable of producing tooth movement, then it may be possible to sum or overlap short-term activations. Such an approach might cause less hyalinization, tissue damage, and cementum resorption. It has been reported that interrupted continuous forces produce less reduction in cellular activity than continuous forces.[4] After 1 hour of force application, early cell changes involving the nucleus, erythrocyte packing in blood vessels, and limited endothelial cell damage may be expected.[23,24] To avoid cellular death in pressure zones, it seems critical that forces be in place for less than 1 hour in this model. After 24 hours, more extensive cellular damage including cell free zones, areas of hyalinization, endothelial and red blood cell breakdown, and extravascular red blood cells can be anticipated. Ultimately, with increasing durations the disappearance of cell structures and the destruction of blood vessels will occur in the pressure zones. Forces of short duration may be expected to cause a transient ischemia with less tissue damage, rather than the more severe sequelae reported with continuous forces. Whether decreased cementum resorption or increased magnitudes of tooth movement can be produced by this approach remains unknown. Well controlled studies directed toward the most effective mechanical signal characteristics for orthodontic tooth movement are required to provide the information necessary to deliver more effective orthodontic treatment. In the absence of histomorphometric data comparing an approach similar to that described here with the more conventional application of force throughout tooth movement, the relative risks and benefits remain to be demonstrated.

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