Rate of mesial translation of mandibular molars using implant-anchored mechanics

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Histological analyses of sustained tooth movement in monkeys and humans suggest that extensive osseous adaptation within the alveolar process is a characteristic feature of orthodontic translation.[1] Osteoclastic resorption is a bone surface phenomenon. It occurs as frontal resorption along the alveolar bone margin of the periodontal ligament (PDL) or as an undermining process. The velocity at which a tooth moves is limited by the linear rate of resorption at the PDL/bone interface.[2] It has been proposed that cortical bone is more resistant to resorption than trabecular bone because of a lack of internal vascularized spaces.[3]

The present research is a clinical study in adults comparing the rate of tooth movement over time with the apparent radiographic density of bone in the path of tooth movement. Use of osseointegrated retromolar anchorage to close large spaces (8 mm or more) is an effective experimental model for studying steady state skeletal physiology during a period of sustained tooth movement. The clinical methodology has been documented in two detailed case reports[4,5] and a clinical overview.[6]

Gross skeletal morphology (bone density) of the alveolar process is inversely related to the rate of tooth movement.[1,3,7] Although osteology of the human stomatognathic system is well described,[8-12] there is little information on skeletal adaptation in response to tooth movement. Most histological studies of human tooth movement

Abstract

Retromolar dental implants served as anchorage to close first molar extraction sites in five adult patients. Rates of unidirectional space closure for mandibular second molars were assessed with periapical radiographs superimposed on anatomical landmarks and retromolar anchorage implants. Regression analysis revealed that mesial displacement of the midroot area of the leading root was less variable (r=0.97) than for other landmarks on the same teeth: crown (r=0.83), alveolar crest (r=0.82) or apex (r=0.90). When mesial root movement (uprighting) was the principal feature of the initial mechanics (4 of the 5 patients), mesial movement of the apex was about 0.60 mm/mo for the first 8 months and then decreased to about 0.34 mm/mo as the trailing (distal) root of the second molar engaged the relatively dense bone formed by the leading (mesial) root. During the last year of space closure, radiolucent foci were noted 1-2 mm ahead of the distal root. These data suggest: (1) sustained orthodontic translation is a physiological manifestation of bone modeling and remodeling throughout the adjacent alveolar process, and (2) rate of mandibular molar translation is inversely related to the apparent radiographic density of the resisting alveolar bone.

Key Words

Orthodontics • Space closure • Rate of tooth movement • Implants • Anchorage • Radiographic analysis • Bone

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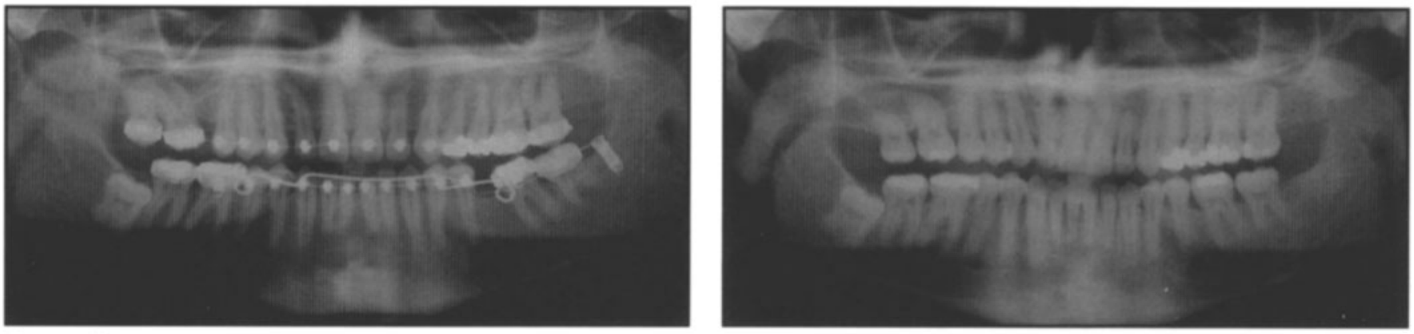
Figure 1A
Figure 1B

Figure 1A-B
A: Panoramic radiograph exposed during the initial stage of molar translation showing the anchorage implant and the two molars being translated mesially to close the first molar extraction site. The anchorage wire extends from the endosseous implant to a vertical tube in the bracket bonded to the first premolar.
B: At the end of treatment, all spaces are closed, restoring an intact dentition.

have focused on initiation of the orthodontic response in PDL[7,13] The differential components of osseous modeling (surface formation and/or resorption) and remodeling (internal turnover of cortical or trabecular bone) are integral components of the tooth movement process.[1,14] However, the relationship of bone modeling and remodeling to the actual rate of tooth movement is unknown.

Differential rates of tooth movement are manifest as orthodontic anchorage. Clinicians have long appreciated the excellent anchorage value of molars.[15-17] The theoretical explanation for molar resistance to tooth movement is the greater cross-sectional area of the roots compared with other teeth.[3,18] The use of root area as an index of anchorage value assumes that: (1) the resorptive mechanism for removing bone in the path of tooth movement is similar for all teeth during the course of tooth movement, (2) following a brief ($\leq$ 3 wk) phase of PDL hyalinization and undermining resorption, the rate of orthodontic tooth movement for all teeth is more or less linear, and (3) anchorage values of teeth are directly related to stress (force per unit area) at the PDL-alveolar bone interface. These assumptions are not consistent with the variable osseous morphology of the oral cavity.[8-12] In the posterior region, increased density of the alveolar process during sustained tooth movement may be an important factor in enhancing the anchorage value of mandibular molars.[1,4,14]

Studies of the rate of tooth movement in small animals[19-21] present special methodological problems. The results are often species- and/or technique-specific and can be difficult to extrapolate to humans. There are a few reports of sustained tooth movement in larger species (monkey and dog),[22-24] but the significance of the results is limited by mechanical approaches that are often clinically unrealistic. The rate of translation in buccal segments is difficult to assess because of the differential movement of anchorage teeth.[25,26] The most reliable evaluations of physiologic[27] and orthodontic[7] tooth movement in humans are clinical studies that have focused on the tipping of isolated teeth. Although this research is useful for defining functional mechanisms, its significance to more realistic clinical applications is limited.

No clinical assessments of mandibular molar movement, correction of axial inclination (uprighting) and/or translation have been reported. The present research describes a two dimensional method for assessing the rate of mandibular molar movement from routine periapical radiographs.

Materials and methods

A mandibular retromolar implant, a rigidly integrated titanium screw distal to the third molar, was used as anchorage for mesial translation of second and third molars to close a first molar extraction site (Figure 1). Detailed case reports of the diagnosis, treatment, and follow-up of the first two patients in the series have been published.[4,5]

The sample comprised five adults of northern European ancestry with missing mandibular molars. There were three males (34, 34, and 35 years) and two females (38 and 44 years). The younger female was premenopausal and the older female was postmenopausal. The first molar extraction sites were closed using indirect anchorage, i.e., a passive segment extended from the implant to the vertical tube of a premolar mesial to the extraction site. The stabilized premolar was then used as anchorage for mesial translation of the molars (Figure 1). As previously described,[1,4,14] these mechanics allow direct assessment of unidirectional space closure in the posterior region of the mandible. Routine sets of periapical radiographs, controlled for no more than ±5% elongation or foreshortening, were exposed in the premolar-molar-retromolar areas, at varying intervals from 3.5 to 24.5 months after initiation of space closure. Three time intervals were assessed for each subject (Figure 2).

Using x5 magnification, tracings were made of

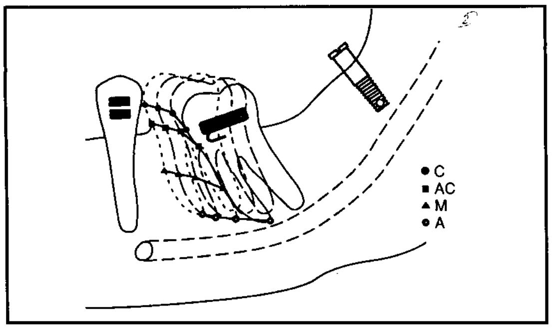

Figure 2

Figure 2
Superimposition of tracings from three sequential radiographs showing a typical path of tooth movement during a 24-month period of space closure. Linear segments connect the crown (C), alveolar crest (AC), midroot (M) and apical (A) landmarks.

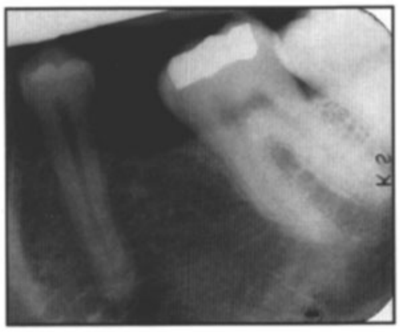

Figure 3A

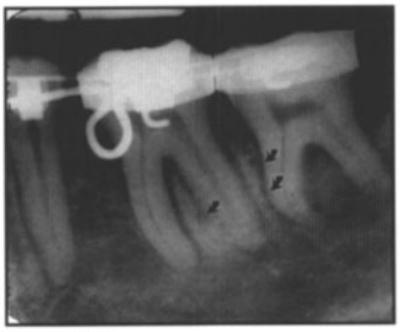

Figure 3B

Figure 3A-B
A: Pretreatment periapical radiograph of patient RG (34-year-old male shown in Figure 1) shows the edentulous first molar area and mesial tipping of the second and third molars. Note that relative bone architecture is similar on the mesial aspect of all molar roots prior to initiating space closure.
B: Periapical radiograph of the same area, exposed during the last half of space closure (20 months), shows an apparent increase in radiographic density (more bone mass and/ or increased degree of mineralization) in alveolar bone mesial to the distal root of the second molar. Note multiple foci of radiolucency (arrows) in the areas of dense bone as the distal root of the second molar and mesial root of the third molar are translated mesially (to the left).

each set of radiographs and then superimposed on the rigidly integrated retromolar implant with a best fit of internal skeletal landmarks, out of the path of tooth movement: (1) inferior alveolar canal, (2) external oblique ridge, (3) alveolar crest and (4) unique trabeculae. The same landmarks, visible in the premolar-molar view, were used for a best fit superimposition along with more mesial landmarks such as the mental foramen. Premolars, stabilized by the anchorage wire from the retromolar implants, were also used as landmarks.

For the detailed analysis of each subject, sequential premolar-molar views for all patients were traced with x5 magnification and the tracings were superimposed to determine the relative change in the positions of the molars as they were leveled and mesially translated. Four anatomical landmarks on the mesial surface of the second molar were defined: (1) apex of the mesial root, (2) midroot curvature as determined by bisecting the distance from the alveolar crest to the apex, (3) alveolar crest, and (4) crown (most mesial curvature of the interproximal surface). A caliper measuring to the nearest 0.1 mm was used to measure the displacement of each molar landmark over time in the vertical and sagittal planes. Overall tooth movement was a point-to-point measurement of landmark migration through bone (Figure 2).

Results

For each patient, superimposed mandibular tracings of sequential cephalometric radiographs[28] documented the path of tooth movement and demonstrated that the anchorage implants did not move relative to supporting bone. Histomorphometric examination of the recovered anchorage implants from three of the five patients sampled showed that the fixtures were osseointegrated.[29] Overall, the radiographic and histologic evaluations were consistent with rigid osseous anchorage.[4,29]

Detailed analysis of tooth movement for each case revealed the change in second molar position in the vertical plane (Y-axis) and sagittal plane (X-axis). Overall unidirectional movement (point-to-point) was plotted for each case. The four cases that had mesially tipped molars initially (Figure 3A) displayed the same pattern of tooth movement, i.e., mesial root movement to correct the axial inclination followed by translation to complete space closure (Figure 3B). The residual molar in the other case was not tipped mesially so initial mesial root movement was not required. A representative detailed plot for patients presenting with mesially tipped second molars is shown in Figure 4A-C.

The total sample, 15 time points for five patients, was plotted for the crown, alveolar crest (margin of alveolar bone on the mesial aspect of the second molar), midroot, and apical landmarks. Linear regression analysis of the overall rate of tooth movement revealed that mesial displacement of the midroot area was less variable (r=0.97) than crown (r=0.83), alveolar crest (r=0.82) or apical (r=0.90) measurements (Figure 5A-D). The overall rate of midroot movement for the entire sample (n=5) over 24.5 months was 0.32 mm/month.

All regressions had a Y-intercept greater than zero, suggesting a nonlinear rate of tooth movement over the course of treatment. Since the apex of the mesial root of the second molar was moved the greatest distance in all patients, the data were replotted for the four patients with initially tipped molars to assess the differential rate of apical movement during the uprighting and translation phases. Figure 6 is a two-part regression demonstrating the higher initial rate of tooth movement during the first 8 months and a slower rate of apical migration from 11.5 to 24.5 months. The mean rate of tooth movement (axial inclination correction and translation) for the four subjects with initially tipped molars was about 0.60 mm/month for the first 8 months. A highly consistent rate of translation of about 0.34 mm/month was observed over the last 12 months of space closure for all patients.

Figure 4A-C
A: Movement of the second molar in the vertical plane is plotted over time for RG, a 34-year-old male. Rates are given for each segment.
B: Movement of the second molar in the sagittal plane is plotted over time. Rates are given for each segment.
C: Overall movement (point-to-point) for the second molar is shown. Rates are given for each segment.

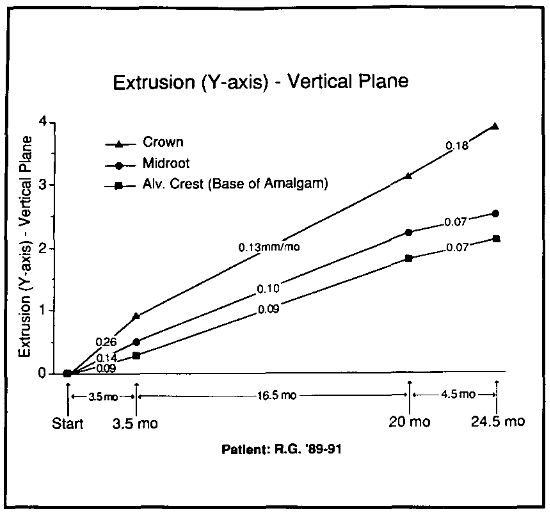

Figure 4A

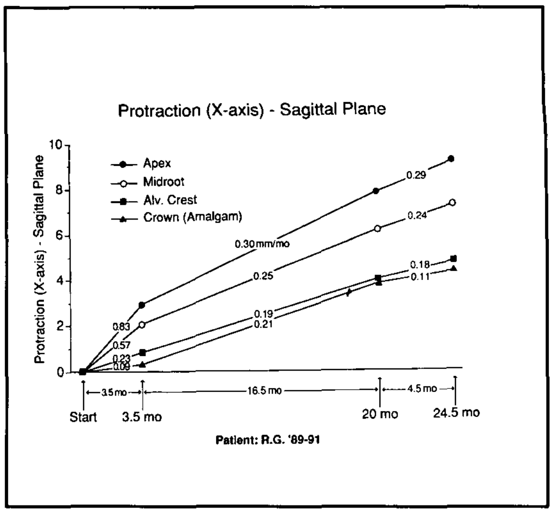

Figure 4B

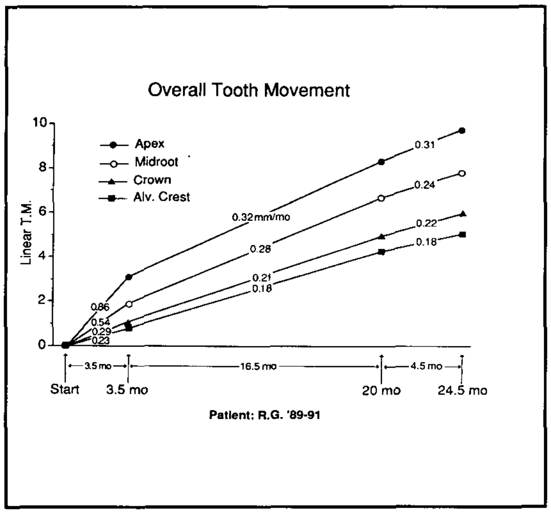

Figure 4C

Routine visual inspection of the radiographs revealed that the decrease in the rate of tooth movement after the first 8 months (Figure 6), was associated with the trailing roots engaging relatively dense bone formed by the leading roots. During the last year of space closure, pockets of porosity (radiolucency) were noted in the relatively dense alveolar bone resisting tooth movement (Figure 3B) suggesting there is an internal resorptive response ahead of the moving root.

Discussion

Measurement of tooth movement on routine periapical radiographs requires careful attention to technical details. Assuming no film bending, there are three parameters that can affect the measurement: translation, which is due to linear movement of the x-ray tube or patient; magnification, which is due to change in film-to-tooth or tooth-to-anode distance; and rotation, which is due to change in film angulation relative to the x-ray tube. Translation was controlled by superimposing on the implant and identifying stable landmarks within the bone, similar to the classical cephalometric approach of Björk.[28] Magnification between films was <5% as determined by sequential measurement of the size of the implant, metallic restorations, and tooth widths. Rotation varied <4° as calculated from sequential measurement of tooth length. To compensate for the relatively small magnification and rotation errors, relative landmarks (as defined in the methods section) were used.

Bone conservation and its therapeutic manipulation are important aspects of most dental procedures, particularly if rigidly integrated dental implants are part of the treatment plan.[30] As previously reviewed,[31] Linkow published the first clinical reports using blade implants for orthodontic anchorage. In the early 1980s, the prosthodontic appeal of osseointegrated[32] implant systems stimulated increased interest in bone physiology as a means of understanding skeletal atrophy, wound healing, maturation, and sustained function. By 1982, a series of animal studies, subsequently published,[29,31] resulted in a clinical trial of rigidly integrated titanium implants as a source of orthodontic anchorage.[4] Serial periapical radiographs from five typical cases in the series were used to provide a perspective on the rate of molar translation in the posterior mandible.

In a benchmark study, Smith and Storey[26] retracted mandibular canines with light (150-250 g) or heavy (400-600 g) forces for up to 8 weeks. Although heavy forces produced more mesial movement of the anchorage units, the rate of retraction of the canines was constant, i.e., they tipped distally about 2 mm/month with either light or heavy forces. Comparing these results

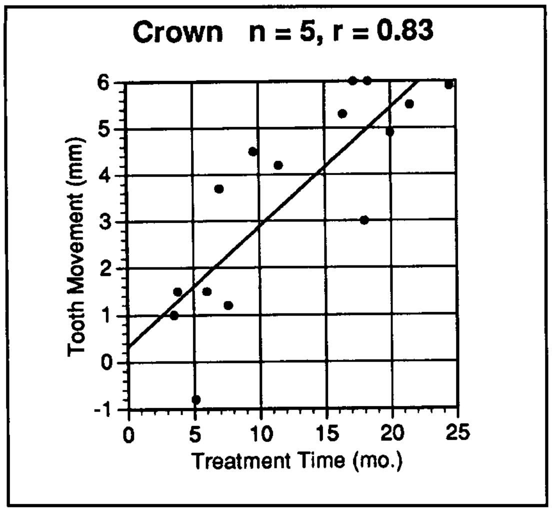

Figure 5A

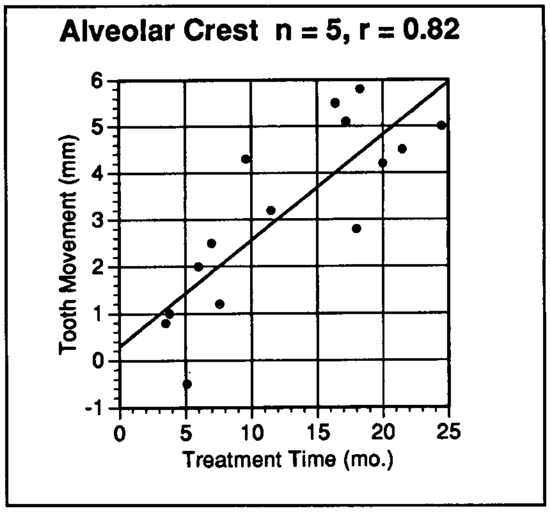

Figure 5B

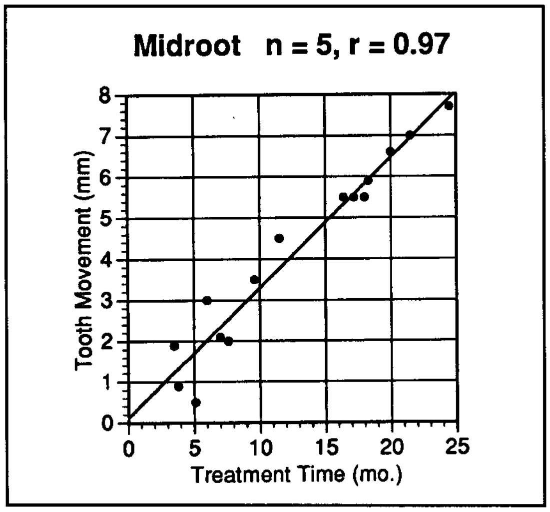

Figure 5C

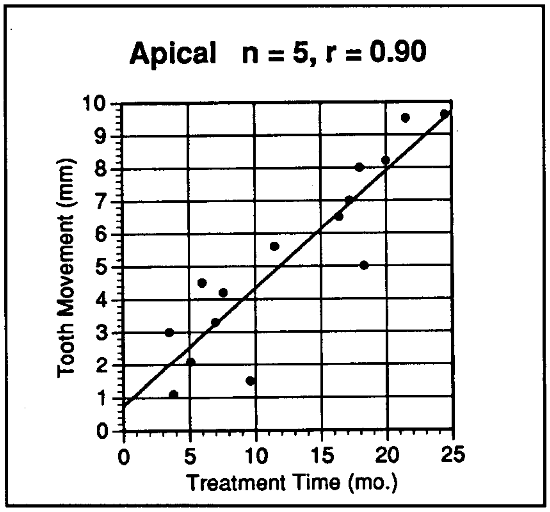

Figure 5D

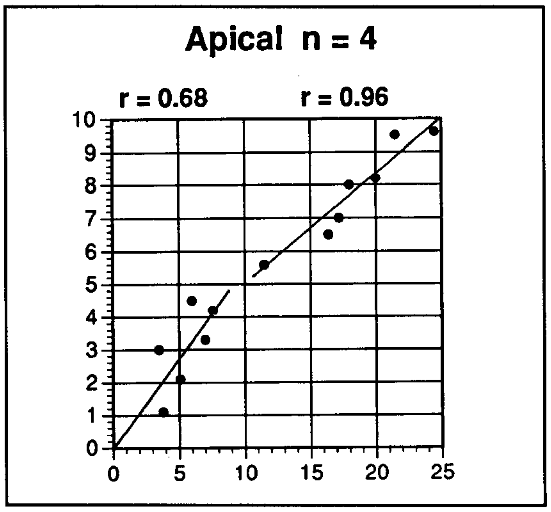

Figure 6

Figure 5A-D
A: Linear regression for crown movement plotted for all patients. B: Linear regression for movement of the alveolar crest margin plotted for all patients. C: Linear regression for midroot movement plotted for all patients. D: Linear regression for apical movement plotted for all patients.

Figure 6
Separate linear regressions plotted for tooth movement during the first 8 months compared with after about 12 months for the four patients in which mesial root movement was initiated at the start of treatment.

with the current data (about 0.33 mm/mo), it is evident that the rate of distal tipping of canines in growing patients is more than six times faster than mesial translation of mandibular molars.

This is the first report of the time course for sustained tooth movement of up to 8 mm in humans. Since the total duration of the study was about 24 months, a more complete evaluation of the initial and sustained phases of tooth movement was possible. It has been hypothesized that achieving a steady state of continuous bone adaptation takes at least 4 months.[33] However, the current data indicate the initial phase may last as long as 12 months in some patients (Figure 6).

Abrupt changes in bone physiology, such as endocrine problems, dietary deficiencies, and/or mechanical loading, elicit transitional modeling and remodeling changes that require more than a sigma (duration of the human remodeling cycle) to resolve into a new steady state.[34,35] Sigma in man was originally estimated to be

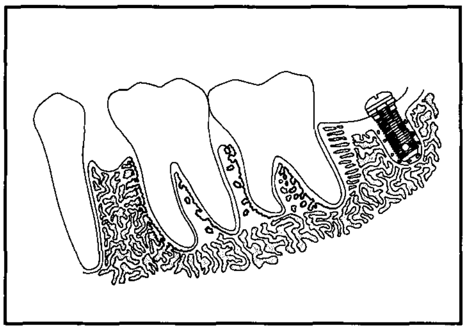

Figure 7A

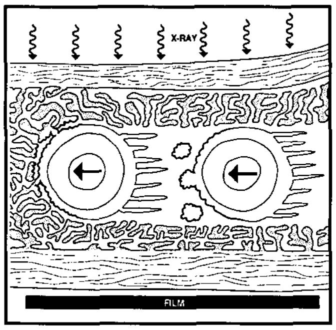

Figure 7B

Figure 7A-B
A: The mesial root of the second molar moves through the predominantly trabecular bone, leaving in its wake primary cortical bone. It is proposed that the distal root subsequently engages the more dense bone and the rate of tooth movement slows.
B: A horizontal cross-section through the roots of the second molar demonstrate the relationship of the mandibular cortex, internal trabecular bone, and the relatively dense primary cortical bone formed by the moving roots. It is proposed that this relationship results in the apparent increase in density of bone formed by mandibular molar movement.

about 4 months. However, more recent evaluations with larger samples of males and females over a wider age-range indicate sigma is closer to 6 months in iliac cortical bone.[36] Premenopausal females have a shorter sigma (about 123 days) than postmenopausal women (about 202 days).[37] Since the current sample is mixed (three males, a premenopausal female and a postmenopausal female) the range of sigma is about 4 to 6 months. Assuming this sigma is similar to that for the iliac crest, the 8-month initial period of more rapid tooth movement represents 1.5 to 2 sigma. This is well within the time frame defined by Frost[33-35] for the remodeling transient, which is the time necessary to establish a new steady state of bone remodeling following perturbation of the system, such as the application of a continuous orthodontic force.

Midgett et al.[24] described a 12-week sequence for tipping premolars in dogs. This is an interesting study because 12 weeks is about one sigma for normal dogs.[31,38] For the first 4 weeks, teeth moved only 0.25 mm/wk. From 4 to 8 weeks, the rate increased to 0.75 mm/wk, and from 8 to 12 weeks, tooth movement of 1.0 mm/wk was achieved. These results are consistent with the increased rate of tooth movement achieved for up to 8 months in the present study.

The induction of tooth movement is divided into three physiologic events: initial strain - PDL displacement and bone bending; lag phase - necrotic PDL zones associated with undermining resorption; and progressive tooth movement - frontal resorption within the PDL associated with enhanced remodeling in the direction of tooth movement.[1] The increased rates of tooth movement for the first 8 months (Figure 6) are consistent with a theoretical model based on histological studies.[1]

It appears the rate of tooth movement was maximal when the molars were penetrating the predominately trabecular bone around the roots of the molars at the start of space closure (Figure 3A). A dramatic decrease in the rate of tooth movement was noted after the second molars had moved mesially a few millimeters (Figure 6). Radiographic images suggest that the decreased velocity of tooth movement was related to the trailing (distal) root engaging the more dense alveolar bone formed by the leading (mesial) root (Figure 4). The rate of tooth movement appears to be related to the ability of the body to remodel the relatively dense, immature bone formed by the leading root.

As the molars moved mesially through the more radiodense alveolar bone, radiolucent foci were noted mesial to the alveolar bone/PDL interface (Figure 3B). This radiographic picture is consistent with the combined modeling and remodeling mechanism of tooth movement previously hypothesized based on primate histology.[1,14] Initiating remodeling events (resorption cavities) ahead of a moving tooth appears to be an important mechanism for decreasing the mass of cortical bone in the path of tooth movement.[2]

From a clinical perspective, the present data indicate that rigid implant anchorage is an effective means for mesially translating mandibular molars; sustained orthodontic translation is a physiological manifestation of mechanically-mediated bone modeling and remodeling events; and the rate of mandibular molar translation is inversely related to the apparent radiographic density of the resisting alveolar bone.

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