Published in final edited form as:

J Biomech. 2009 August 25; 42(12): 1961–1966. doi:10.1016/j.jbiomech.2009.05.016.

Functional Cues in the Development of Osseous Tooth Support in the Pig, *Sus scrofa*

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Abstract

Alveolar bone supports teeth during chewing through a ligamentous interface with tooth roots. Although tooth loads are presumed to direct the development and adaptation of these tissues, strain distribution in the alveolar bone at different stages of tooth eruption and periodontal development is unknown. This study investigates the biomechanical effects of tooth loading on developing alveolar bone as a tooth erupts into occlusion. Mandibular segments from miniature pigs, *Sus scrofa*, containing M₁ either erupting or in functional occlusion, were loaded in compression. Simultaneous recordings were made from rosette strain gages affixed to the lingual alveolar bone and the M₂ crypt. Overall, specimens with erupting M₁'s were more deformable than specimens with occluding M₁'s (mean stiffness of 246 vs. 944 Mpa, respectively, p=0.004). The major difference in alveolar strain between the two stages was in orientation. The vertically applied compressive loads were more directly reflected in the alveolar bone strains of erupting M₁'s, than those of occluding M₁'s, presumably because of the mediation of a more mature periodontal ligament (PDL) in the latter. The PDL interface between occluding teeth and alveolar bone is likely to stiffen the system, allowing transmission of occlusal loads. Alveolar strains may provide a stimulus for bone growth in the alveolar process and crest.

Keywords

Alveolar bone; microstrain; periodontium

1. Introduction

Tooth movement from a developmental position in the dental arch to a functional position in the oral cavity coincides with development of periodontal tissue that will support the tooth in occlusion. Bone on the alveolar ridge heightens as the tooth erupts, forming an alveolar crest that encircles the root. Although tooth eruption is generally considered to be the stimulus for alveolar bone growth (Marks and Schroeder, 1996; Moss et al., 1967), the functional relationship of the tooth with the adjacent alveolar bone is unknown. This study investigates the biomechanical effects of occlusal loading on the developing bone during tooth eruption.

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Conflict of Interest Statement: The authors of this manuscript have no financial or personal relationship with other people or organizations that could inappropriately influence or bias the reported work.

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Teeth develop within bony crypts that protect the developing crown from external forces. Root growth corresponds with the intraosseous stage of tooth eruption in which resorption of bone overlying the crown provides an eruptive pathway. As the tooth emerges through bone, only the oral mucosa separates the crown from the oral cavity. Mucosal penetration occurs through apoptosis of overlying mucosal epithelial cells (Kaneko et al., 1997; Shibata et al., 1995). Low levels of periodontal ligament (PDL) attachment also characterize the mucosal penetration stage of eruption (Berkovitz and Moxham, 1990; Bernick and Grant, 1982), and without a firm tooth to bone linkage, the tooth is highly mobile in its developing alveolus. Although mucosa largely covers the tooth and the tooth has not yet reached the occlusal plane, pressure from the tongue or a food bolus could produce an occlusal load during mucosal penetration.

Our understanding of the deformation of alveolar bone during occlusion is derived from a few experimental studies and modeling of the loaded periodontium. Although strains in the maxilla and mandibular body have been measured during chewing in pigs (Herring et al., 2001; Rafferty et al., 2003), and macaques (Hylander, 1979; Hylander et al., 1987), these studies have not measured alveolar bone strain. Alveolar strain was measured on the mandibular surface in rabbits, and demonstrated large compressive strains on the chewing side (Weijs and de Jongh, 1977). *In vivo* alveolar strain in the central incisor region of a human subject established that tensile strains dominated in the cervical alveolar region but were reduced apically (Asundi and Kishen, 2000). The results of this latter study correspond with the findings of FEA modeling of human incisors in which cervical bone demonstrated high tensile stresses under occlusal load (Ona and Wakabayashi, 2006). Additional models note the role of the periodontal ligament and alveolar bone in distributing bite forces (Kaewsuriyathumrong and Soma, 1993) and find that variations in alveolar bone stiffness affect strain distribution within the mandibular cortex (Chen and Chen, 1998).

The above-mentioned studies provide insight into deformation of the tooth and periodontal tissues under load and its dependency on tissue mechanical properties, but lack information on strain distribution at different stages of periodontal development. This latter information is of critical interest because of the likely role of functional loads in promoting periodontal ligament growth and adaptation. This study therefore investigates *in vitro* alveolar strains with a view to understanding how occlusal loads distribute differently at different stages of tooth eruption. With an axially applied compressive load, minimum principal strains in the alveolar bone supporting erupting M_1 's are predicted to be less than that of occluding M_1 's, and demonstrate greater variation. The rationale for this hypothesis is that the immature periodontal ligament in erupting M_1 's is likely to impair transmission of occlusal loads to the adjacent bone and to introduce greater variability in the load transduction pathway.

2. Materials and Methods

In vitro alveolar bone strain was measured in left side mandibular segments of 7 miniature pigs with erupting first molars (M_1) and 6 miniature pigs with functional M_1 's. Pigs with erupting M_1 's were 12 weeks of age and pigs with functional M_1 's were 22 weeks. Lateral cephalograms and postmortem examination of the occlusal surface for wear were used to verify eruption and functional status. Tissues from pigs with erupting M_1 's were tested in the mucosal penetration stage, in which all cusps have progressed above the alveolar crest, but have not fully penetrated the mucosa.

Pigs were sacrificed and specimens were prepared, including M_1 and the posterior region of the deciduous third molar, dm_3 (Figure 1). Soft tissues were removed, including mucosa overlying the erupting M_1 . The occlusal surface of M_1 was ground flat with a dental drill in order to support even loading of the tooth, and the dm_3 was ground to a lower level for focused loading on M_1 . Mandibular segments were embedded in a base of dental acrylic that enclosed

the mandibular body but exposed the alveolar bone. Rosette strain gages were affixed posterior to M_1 on the anterior wall of the M_2 crypt (Fig. 1), and on the lingual cortex adjacent to the posterior M_1 cusps (Figure 2). The occlusal surface of M_1 was loaded in compression at 0.3mm/s until 440N using a materials testing machine (MTS/Sintech). This loading rate was selected to approximate the 2-3 Hz chewing rate of mini-pigs. The 440N endpoint was selected as a load level likely to occur in both erupting and occluding molar teeth. A saline drip was used to maintain specimen moisture. Occlusal tape was placed over M_1 and the locations that ink transferred from the tape to the specimen during compressive loading was checked between tests. The even appearance of ink markings on the M_1 occlusal surface verified that the M_1 bore the compressive load exclusively. A series of five tests were performed in order to precondition the specimen, and data from a subsequent sixth test was used for comparison of overall specimen stiffness and alveolar strain. Stiffness was calculated as the slope of the linear region of the stress-strain curve between 200-440N. Applied stresses were estimated by dividing compressive loads by the M_1 cross-sectional area. Overall specimen strains were calculated as the change in distance between compression platens divided by the pre-test distance. Strain gage measurements of alveolar strain were recorded simultaneously with occlusal loading, and principal strain magnitudes and orientations were calculated at 440N. Conventional statistics were used in the analysis of stiffness measurements and principal strain magnitudes, including normal and nonparametric tests. Minimum principal strain orientations were calculated relative to the horizontal occlusal plane and analyzed using circular statistics, including circular mean and circular standard deviation (C.S.D.; Oriana, Kovach Computing Services). Strain angles were compared with the Watson-Williams F-test when the concentrations of the two samples were similar and sufficiently large (>2); otherwise, the data were compared with the Watson's U^2 Test (Fisher, 1993).

Histology of the M_1 periodontium was performed on erupting ($N=3$) and occluding M_1 's ($N=3$). Specimens were cut from mandibles postmortem and decalcified in 8% EDTA. Tissues were paraffin embedded, and parasagittally sectioned at 7 μ m. Deparaffinized slides were stained with a Van Gieson stain (Sigma-Aldrich) to highlight collagen fibers. The orientation of the sections allowed visualization of periodontal tissues anterior and posterior to the root, but not on the lingual or labial sides.

3. Results

3.1. Total Specimen Deformation

Specimens with erupting and occluding M_1 's had similar M_1 cross-sectional areas (Table 1). Load-deformation curves show a linear region for all specimens, but greater deformation of specimens with erupting M_1 's than occluding M_1 's (Figure 3). The calculation of stiffness from stress-strain curves also shows the erupting M_1 specimens to be more deformable than specimens with occluding M_1 's (mean stiffness of 246 vs. 944 Mpa, erupting vs. occluding M_1 's respectively; 2 sample t-test, $p=0.004$).

3.2 Alveolar Bone Strain

Minimum principal strain (ϵ_2 , min) in lingual alveolar bone averaged -156 $\mu\epsilon$ with a standard deviation (S.D.) of 199 in erupting M_1 's and -260 $\mu\epsilon \pm 138$ (S.D.) in occluding M_1 's (Table 2). Except for #4718 all molars showed occlusal tape markings on buccal and lingual cusps. However, in #4718, markings were found only on buccal cusps, indicating that the load applied resulted in buccal tipping of the crown. For this reason, values from #4718 were omitted from statistical comparisons. Although ϵ_2 was lower in erupting specimens than occluding, the difference was not statistically significant. Coefficients of variation (C.V.) in ϵ_2 between erupting and occluding specimens also tended in the expected direction with younger animals showing greater variability than older, however, these differences were not significant.

Minimum principal strain angles averaged $63^{\circ} \pm 27$ (C.S.D.) in erupting specimens, with Min orientation showing minor deviations from axial in some specimens and tilting from postero-superior to antero-inferior in others (Figure 4). In specimens with occluding M_1 's, the average orientation of the minimum principal strain was $101^{\circ} \pm 30$ (C.S.D.), and showed minor deviations in the axial load direction that were opposite to the erupting specimens, i.e. antero-superior to postero-inferior. The orientation of ε_2 in #4134 was an outlier; however, these lingual strain magnitudes were also very low ($<100\mu\epsilon$). Differences in ε_2 orientation, the deviation from the axial load orientation or in angular variation were not statistically significant between groups.

Crypt gages in erupting M_1 's showed similar levels of ε_2 to lingual gages, but surprisingly high levels of ε_1 , averaging almost $900\mu\epsilon$ (Table 2). ε_1 was significantly larger than ε_2 (Wilcoxon signed rank test, $p=0.02$), and this difference remained significant even after exclusion of #4425 (Table 2). In two specimens (#4425, #5060), both values were tensile, suggesting a posterior bulging of the crypt bone. The lingual strain magnitudes in both specimens were low, suggesting that the alveolar crypt bone bore the majority of the load. Excepting #4718, which was tipped, ε_1 orientations were parallel with the occlusal plane, and ε_2 were perpendicular (Figure 4).

In specimens with occluding M_1 's, crypt strains were not predominantly tensile and no specimen showed principal strains with the same sign (Table 2). Compression ranged from -90 to $-730\mu\epsilon$ (Min) and tension from 128 to $367\mu\epsilon$ (Max). Similarity in strain magnitudes between ε_1 and ε_2 among some specimens suggested high levels of shear. Although the average orientation of ε_1 was nearly perpendicular (100°), this is because 2 specimens were buccal-oblique and three were lingual-oblique (Figure 4), but none were actually perpendicular. Comparisons of crypt strain magnitude and variation showed no significant differences between specimens with erupting and occluding M_1 's; however, variation tended to decrease in ε_1 and was similar for ε_2 (Table 2). Orientations of ε_2 differed significantly (Watson U^2 , $p < 0.05$), and the mean deviation of ε_2 orientation from 90° was significantly greater in older specimens (8° vs. 50° , Watson Williams F test, $p=0.0003$).

3.3. Histology

In erupting molars the horizontal, alveolar crest, and oblique PDL fibers show definition, however, the fiber density is sparser than in the PDL of occluding molars (Figure 5). The alveolar bone of erupting molars is lined with osteoblasts and thick fiber bundles protrude from the bone and cementum except in the apical 1/3 of the root where the fibers adjacent to the bone appear disorganized. Thick fibers protrude from the cementum, except in the root apex where fibers are less developed. A fibrous layer adjacent to the cementum is aligned with the tooth root, whereas other fibers appear to extend across the ligament space toward the bone. The roots of erupting molars appear shorter than those of occluding molars. The PDL of occluding molars appears narrower than erupting molars and features dense fiber bundles that extend obliquely across the ligament space. Fibers are embedded in cementum and bone throughout the PDL space, and appear more densely embedded in bone in occluding molars.

4. Discussion

Load transmission within the periodontium involves the fibrous and loose connective tissue of the periodontal ligament, as well as alveolar bone. As a unit these structures counter occlusal forces, although the respective role of each component is not well understood (Moxham and Berkovitz, 1995). Ligament fibers occur in bundles that traverse the space between bone and cementum obliquely toward the root apex, and are presumed to resist tooth displacement (Picton, 1989). PDL fibers are embedded in the alveolar bone proper, which in forming the interior of the alveolus bears the ligament stress and distributes these forces to cancellous bone.

Proteoglycan aggregates embedded in the ligament fibers support the ligament and exert a swelling pressure that resists compression. These hydrophilic molecules contribute to the viscoelastic properties of the ligament in that water is extruded from the loaded tissue. The proteoglycans rehydrate when the load is removed, restoring the tissue's shock absorption potential (Embery et al., 1995).

The load-deformation curves in this study correspond with previous studies of periodontal displacement under tooth load, and are consistent with individual mechanical testing of PDL and bone. Intrusive axial loading of teeth generally shows an initial phase of high displacement at low loads and a secondary phase of decreased displacement and increased load (Picton, 1989; Shimada et al., 2003). Both erupting and occluding specimens showed an early phase of high displacement that was reduced in a secondary phase; however, in specimens with erupting M_1 's the displacement was higher than in erupted M_1 's at both the early loading phase and secondary linear region of the curves (Figure 3). Mechanical testing of the PDL reveals high deformability, viscoelasticity, and a biphasic nature of the stress-strain curve (Driel et al., 2000; Komatsu et al., 1998), and these characteristics have been specifically established for pig PDL (Dorow et al., 2002, 2003). Bone is less deformable than the PDL, and behaves elastically as an instantaneous response to stress and viscoelastically under a persisting load (Linde, 1994; Robertson and Smith, 1978; Schoenfeld et al., 1974). Thus, the biphasic load-deformation curves in this study probably reflect the deformation of the PDL, with the alveolar bone contributing to the rigidity of the tooth support.

The greater deformation of the periodontal tissue in erupting versus occluding specimens corresponds with the lesser development of the periodontal ligament. Denser fibers were seen in the PDL from occluding M_1 's, as well as greater connectivity between root and bone. In an *ex vivo* study of continuously erupting incisors in rodents, regions of greater ligament development also demonstrated greater resistance to load (Komatsu et al., 1998). Greater *in vivo* mobility in erupting vs. fully erupted teeth has also been demonstrated in monkeys (Mühlemann, 1954) and ferrets (Moxham and Berkovitz, 1989).

Because the PDL in erupting M_1 's is immature, the ligament is unlikely to transmit occlusal loads. Instead, compressive loading of the erupting tooth may cause the mobile tooth to press against the adjacent bone and generate bone strains that are similar in magnitude to those transmitted by the PDL in the occluding M_1 . The lesser development of the PDL in erupting vs. occluding M_1 's was predicted to result in lower minimum principal strains in alveolar bone of erupting teeth. Although there was a trend in this direction for ϵ_2 , strains were too variable for statistical significance. Indeed, a post hoc power analysis indicated that only 60% power was achieved with the current sample.

More than influencing strain magnitudes, PDL development may direct strain orientation. During mucosal penetration the crown has emerged only partway from the developing alveolus and the PDL is immature, permitting mobility and providing little stability against occlusal loads. Because the anterior cusps of M_1 erupt prior to the posterior (Figure 1), the PDL of the anterior roots develops in advance of the posterior. Correspondingly, the less mature posterior PDL is likely to generate greater mobility in the tooth's posterior. In the lingual gage, the mean compressive strain angle of 63° may reflect greater periodontal fixation of the anterior versus posterior cusps (Figure 4A). At the crypt gage of erupting M_1 's, axial loading is directly reflected in posterior alveolar bone deformation with a mean strain orientation of 87° . Because the immature PDL is unable to absorb and direct occlusal loads to the bone, the crypt gage strain simply reflects the axial sinking of the tooth within the alveolus. The absence of a functional PDL suggests that the unexpected high magnitude horizontal tensile strains in the crypt gage are the result of the mobile posterior crown pressing directly against the crypt.

In occluding M₁ specimens, compressive strain orientations probably reflect the maturity of the PDL and its role in transmitting occlusal loads to adjacent bone and providing greater stability to tooth position. Lingual alveolar strains showed an antero-superior to postero-inferior orientation with a mean of 101°, indicating the posterior PDL was equal or superior to the anterior PDL in providing tooth support. The crypt gage never indicated direct contact of the tooth with alveolar bone, but showed a tendency to tip either lingually or buccally, shearing the bone.

Although in previous studies of skeletal development and functional adaptation variability in bone strains decreased with maturity (Bertram and Biewener, 1988; Herring et al., 2005; Main and Biewener, 2004), a reduction in strain variation could not be demonstrated between alveolar bone supporting erupting vs. functioning teeth. On the other hand, coefficients of variation (C.V.) do show a decreasing trend for all of strain magnitudes except the crypt min where the C.V. were similar (Table 2). Strain angles did not show a decrease in circular standard deviation between erupting and occluding specimens and this may be explained by the techniques employed. Occlusal surfaces were flattened to reduce load bearing variability and *in vitro* axial compressive loading of occlusal surfaces provided a more consistent orientation of applied load than did the chewing or locomotory cycles in the cited studies. Thus erupting M₁ specimens did not show the predicted greater variation in strain orientation because the orientation of applied load limited variation in bone strain orientation.

Overall these results do not refute the predictions of higher strains and lower variability in occluded molars, but neither do they provide support. Rather, the results reflect a change in strain pattern due to the maturation of the PDL. The ability of occlusal loads to deform bone surrounding both erupting and occluding M₁'s supports the idea that occlusal loads can influence bone formation. High bone strain is thought to stimulate apposition until the reinforced bone reduces strain levels (Frost, 1987; Turner et al., 1994). In erupting M₁'s, deformation of alveolar bone in association with tooth loads is likely to trigger apposition within alveolar processes and at alveolar crests. With increasing occlusal movement of the tooth, bone may be added at alveolar crests in order to counter the increasing deformation incurred by mechanical pressure in the oral cavity.

Acknowledgments

Supported by NIH/NIDCR DE015815. The study sponsors had no role in the study design, collection, analysis and interpretation of data, in the writing of the manuscript, or in the decision to submit the manuscript for publication.

References

- Asundi A, Kishen A. A strain gauge and photoelastic analysis of in vivo strain and in vivo stress distribution in human dental supporting structures. *Archives of Oral Biology* 2000;45:543–550. [PubMed: 10785517]
- Berkovitz BKB, Moxham BJ. The development of the periodontal ligament with special reference to collagen fibre ontogeny. *Journal de Biologie Buccale* 1990;18:227–236. [PubMed: 2254296]
- Bernick, S.; Grant, DA. Development of the periodontal ligament. In: Berkovitz, BK.; Moxham, BJ.; Newman, HN., editors. *The Periodontal Ligament in Health and Disease*. Pergamon Press; Oxford: 1982. p. 197-213.
- Bertram JEA, Biewener AA. Bone curvature: sacrificing strength for load predictability? *Journal of Theoretical Biology* 1988;131:75–92. [PubMed: 3419194]
- Chen X, Chen H. The influence of alveolar structures on the torsional strain field in a gorilla corporeal cross-section. *Journal of Human Evolution* 1998;35:611–633. [PubMed: 9929172]
- Dorow C, Krstin N, Sander FG. Experiments to determine the material properties of the periodontal ligament. *Journal of Orofacial Orthopedics* 2002;63:94–104. [PubMed: 12506782]

- Dorow C, Krstin N, Sander FG. Determination of the mechanical properties of the periodontal ligament in a uniaxial tensional experiment. *Journal of Orofacial Orthopedics* 2003;64(2):100–7. [PubMed: 12649706]
- Driel, WDV; Leeuwen, EJv; Von den Hoff, JW.; Maltha, JC.; Kuijpers-Jagtman, AM. Time-dependent mechanical behaviour of the periodontal ligament. *Proceedings of the Institution of Mechanical Engineers* 2000;214(H):497–504.
- Embery, G.; Waddington, RJ.; Hall, RC. *The Periodontal Ligament in Health and Disease*. Mosby-Wolfe; 1995. The ground substance of the periodontal ligament; p. 83-106.
- Fisher, NI. *Statistical analysis of circular data*. Cambridge University Press; Cambridge: 1993. p. 277
- Frost HM. Bone “Mass” and the “Mechanostat”: a proposal. *The Anatomical Record* 1987;219:1–9. [PubMed: 3688455]
- Herring SW, Pedersen SC, Huang X. Ontogeny of bone strain: the zygomatic arch in pigs. *Journal of Experimental Biology* 2005;208(23):4509–4521. [PubMed: 16339870]
- Herring SW, Rafferty KL, Liu ZJ, Marshall CD. Jaw muscles and the skull in mammals: the biomechanics of mastication. *Comparative Biochemistry and Physiology* 2001;131(Part A):207–219. [PubMed: 11733178]
- Hylander WL. Mandibular function in *Galago crassicaudatus* and *Macaca fascicularis*: an in vivo approach to stress analysis of the mandible. *Journal of Morphology* 1979;159:253–296. [PubMed: 105147]
- Hylander WL, Johnson KR, Crompton AW. Loading patterns and jaw movements during mastication in *Macaca fascicularis*: a bone-strain, electromyographic and cineradiographic analysis. *American Journal of Physical Anthropology* 1987;72:287–314. [PubMed: 3578494]
- Kaewsuriyathumrong C, Soma K. Stress of tooth and PDL structure created by bite force. *The Bulletin of Tokyo Medical and Dental University* 1993;40:217–232. [PubMed: 8275547]
- Kaneko H, Ogiuchi H, Shimono M. Cell death during tooth eruption in the rat: surrounding tissues of the crown. *Anatomy and Embryology* 1997;195:427–434. [PubMed: 9176665]
- Komatsu K, Yamazaki Y, Yamaguchi S, Chiba M. Comparison of biomechanical properties of the incisor periodontal ligament among different species. *The Anatomical Record* 1998;250:408–417. [PubMed: 9566530]
- Linde F. Elastic and viscoelastic properties of trabecular bone by a compression testing approach. *Danish Medical Bulletin* 1994;41(2):119–38. [PubMed: 8039429]
- Main RP, Biewener AA. Ontogenetic patterns of limb loading, in vivo bone strains and growth in the goat radius. *Journal of Experimental Biology* 2004;207(15):2577–2588. [PubMed: 15201290]
- Marks SC, Schroeder HE. Tooth Eruption: Theories and Facts. *The Anatomical Record* 1996;245:374–393. [PubMed: 8769674]
- Moss ML, Chase P, Kameros J. Trabecular bone structure of post-canine alveolar processes in adult American whites and negroes. *Acta Anatomica* 1967;67:399–423. [PubMed: 5639254]
- Moxham BJ, Berkovitz BK. A comparison of the biomechanical properties of the periodontal ligaments of erupting and erupted teeth of non-continuous growth (ferret mandibular canines). *Archives of Oral Biology* 1989;34(10):763–6. [PubMed: 2610611]
- Moxham, BJ.; Berkovitz, BK. *The Periodontal Ligament in Health and Disease*. 1995. The effects of external forces on the periodontal ligament; p. 215-241.
- Mühlemann HR. Tooth mobility: the measuring method. Initial and secondary tooth mobility. *Journal of Periodontology* 1954;25:22–29.
- Ona M, Wakabayashi N. Influence of alveolar support on stress in periodontal structures. *Journal of Dental Research* 2006;85(12):1087–1091. [PubMed: 17122159]
- Picton DCA. The periodontal enigma: eruption versus tooth support. *European Journal of Orthodontics* 1989;11:430–439. [PubMed: 2512176]
- Rafferty K, Herring SW, Marshall CD. Biomechanics of the rostrum and the role of facial sutures. *Journal of Morphology* 2003;257:33–44. [PubMed: 12740894]
- Robertson DM, Smith DC. Compressive strength of mandibular bone as a function of microstructure and strain rate. *Journal of Biomechanics* 1978;11:455–471. [PubMed: 730760]

- Schoenfeld CM, Lautenschlager EP, Jun PRM. Mechanical properties of human cancellous bone in the femoral head. *Medical and Biological Engineering* 1974;18:313–317.
- Shibata S, Suzuki S, Tengan T, Yamashita Y. A histochemical study of apoptosis in the reduced ameloblasts of erupting mouse molars. *Archives of Oral Biology* 1995;40(7):677–680. [PubMed: 7575241]
- Shimada A, Shibata T, Komatsu K, Chiba M. The effects of intrusive loading on axial movements of impeded and unimpeded rat incisors: estimation of eruptive force. *Archives of Oral Biology* 2003;48(5):345–351. [PubMed: 12711378]
- Turner CH, Forwood MR, Rho JY, Yoshikawa T. Mechanical loading thresholds for lamellar and woven bone formation. *Journal of Bone and Mineral Research* 1994;9(1):87–97. [PubMed: 8154314]
- Weijs WA, de Jongh HJ. Strain in mandibular alveolar bone during mastication in the rabbit. *Archives of Oral Biology* 1977;22:667–675.

Figure 1.

A. Lateral view of a pig mandible showing the location of cuts made to isolate the segment of the mandible containing the first lower molar, M_1 . B. Lateral radiograph showing the relationship of M_1 to last deciduous tooth, dm_3 and second molar (M_2) tooth crypt.

Figure 2.

Lingual view of the mandibular M₁ test specimen in position for compressive load application. Occlusal tape overlay the test specimen and transferred ink to locations on the specimen that received load. Rosette strain gages were applied to the lingual alveolar surface and the M₂ crypt distal to M₁ and strain recordings were made simultaneously with compressive loading.

Figure 3.

Load-deformation curves from compression tests of mandibular segments with erupting or occluding M₁'s. Loading of specimens with erupting M₁'s showed greater deformation than specimens with occluding M₁'s.

Figure 4.

Orientations of minimum principal strain (Min), compression. Strain orientations for the lingual gage (A) and crypt gage (B) in specimens with erupting M_1 's. The asterisk distinguishes specimen 4718 as an outlier. Strain orientations for the lingual gage (C) and crypt gage (D) in specimens with occluding M_1 's.

Figure 5.

Van Gieson stained parasagittal sections through the periodontium of erupting (A) and occluding M_1 's (B). Collagen fibers are stained red. A. In erupting M_1 's PDL fibers adjacent to cementum are oriented parallel with the tooth root (doubleheaded arrows). Fibers appear less dense than in occluding M_1 's and are embedded in bone to a lesser degree. Fibers protruding into cementum and bone are marked with arrowheads. B. The PDL fibers of occluding M_1 's are predominantly oblique. Dentin (D), cementum (C), periodontal ligament (PDL), alveolar bone (B).

Table 1

M₁ cross-sectional area and stiffness, mean $\pm$ standard deviation.

Tissue origin	M ₁ cross-sectional area (mm ²)	Stiffness (Mpa)
Younger pigs, M ₁ erupting	153 $\pm$ 18	246 $\pm$ 59
Older pigs, M ₁ occluding	154 $\pm$ 28	944 $\pm$ 341
<i>p</i> -value, younger vs. older	NS	<i>p</i> =0.004

Table 2
Alveolar bone microstrain adjacent to the erupting and occluding M₁.

	Pig #	Age (wks)	Lingual Strain ($\mu\epsilon$)			Crypt Strain ($\mu\epsilon$)		
			Max (ϵ_1)	Min (ϵ_2)	Min Angle (0°)	Max (ϵ_1)	Min (ϵ_2)	Min Angle (0°)
Erupting M _I	4292	12-15	97	-223	74	480	-234	102
	4298	12-15	-49	-530	50	817	-101	90
	4425	12-15	56	-24	40	2354	38	86
	4718	12-15	422 [*]	-993 [*]	160 [*]	287 [*]	-106 [*]	24 [*]
	4745	12-15	68	-47	91	318	-52	74
	5060	12-15	36	-9	25	629	263	81
	5061	12-15	367	-100	99	759	-127	86
	Mean		112	-156	63 ¹	892	-136	87 ¹
	S.D.		127	199	27 ²	739	94	9 ²
	C.V.		1.1	1.3		0.8	0.7	
Occluding M _I	3975	23	141	-287	124	353	-381	131
	4082	23	122	-479	105		no data (detached gage)	
	4119	23	-122	-293	84	367	-730	165
	4134	23	77	-57	40	140	-281	120
	5069	23	94	-238	120	285	-250	42
	5071	23	34	-205	122	128	-90	32
	Mean		98	-260	101 ¹	255	-346	100 ¹
	S.D.		39	138	30 ²	115	239	56 ²
	C.V.		0.4	0.5		0.5	0.7	

* values for 4718 omitted from statistics, see text.
¹ values represent circular mean.
² values represent circular standard deviation (C.S.D.).