Orthodontics & Craniofacial Research

ORIGINAL ARTICLE

R. F. Viecilli
*C. J. Burstone**

Ideal orthodontic alignment load relationships based on periodontal ligament stress

Authors' affiliations:
R. F. Viecilli, Loma Linda University School of Dentistry, Loma Linda, CA, USA
C. J. Burstone, University of Connecticut School of Dentistry, Farmington, CT, USA

Correspondence to:
R. F. Viecilli
Department of Orthodontics
159 W. Hospitality Lane
San Bernardino, CA 92408, USA
E-mail: rodrigoviecilli@gmail.com

Date:
Accepted 11 November 2014

DOI: 10.1111/ocr.12079

*Deceased.

Viecilli R. F., Burstone C. J. Ideal orthodontic alignment load relationships based on periodontal ligament stress
Orthod Craniofac Res 2015; **18**(Suppl.1): 180–186. © 2015 John Wiley & Sons A/S. Published by John Wiley & Sons Ltd

Structured Abstract

Objectives – To test the hypothesis that periodontal ligament (PDL) stress relationships that yield resistance numbers representing load proportions between different teeth depend on alignment load type.

Materials and Methods – Finite element models of all teeth, except the third molars, were produced. Four different types of loads were applied, and the third principal stresses of different teeth in standardized areas of most compression were calculated. Based on these results, resistance numbers, representing the load proportions for each tooth derived from PDL stress, were determined.

Results – The third principal stress values for typical alignment loads in the areas of most stress were very different for different load types for each tooth. Differences in resistance numbers between teeth also varied with different loads.

Conclusion – Resistance numbers, that is, load proportion numbers between teeth to achieve similar stress at the compressive PDL zone, depend on the type of applied load.

Key words: anchorage; finite element analysis; orthodontics; periodontal ligament; stress

Introduction

The clinical perception of resistance to tooth movement directly relates to the difference in relative speed of tooth movement between teeth that are supporting a force system. There is currently no literature available on the 3D estimation of possible resistance numbers during alignment that is based on scientific engineering methodology.

Here, we hypothesize that the resistance to movement associated with a tooth, based on their basic surrounding anatomy, position in the arch, and the generated periodontal ligament

(PDL) stresses, depend on the type of load applied. In this article, we focus on primitive loads that an orthodontic round alignment archwire routinely generates, that is, certain simple forces and couples.

The speed of tooth movement is the result of the interaction of intertwined basic scientific variables. Perhaps the most decisive is PDL stress because it is the initiating stimulus (1–3). Orthodontic tooth movement and the associated bone modeling can initiate only if PDL stress (active or residual) derived from a load exists. It has been shown that in a compressive environment the number of resorbing osteoclasts is, at least initially, proportional to the 3rd principal stress in the PDL, that is, the most compressive stress or most negative stress in the case of a compressive mechanical environment (3–5). It is a natural concept to orthodontists that, typically, larger teeth have more PDL and root support than smaller teeth, and hence, when the same load is applied the stress magnitudes in the PDL are smaller for larger teeth than for smaller teeth. Consequently, the resistance to tooth movement of larger teeth is larger compared to smaller teeth. With everything else being equal, within a certain stress threshold below that for necrosis, smaller stresses will tend to cause less tissue alterations and attract less osteoclasts so that tooth movement is slowed relative to larger stresses (4). Biological variables also affect resistance to tooth movement and act at the response level. These variables include differences between sites in bone turnover, quantity, or quality, as well as in the quantity or quality of the access of osteoclasts to the bone (1, 5–8). Additional variables that could theoretically affect the resistance to tooth movement are differences in the inflammatory responses due to local factors, such as differences in vascularity, presence of diseased tissue, or abnormal entities (9).

Recognizing the limitations that follow from the previous paragraph, we examine only PDL stresses to establish the resistance numbers. These may also serve as a load proportion factor between teeth to achieve similar levels of stress in areas where the most PDL compression exists.

Materials and methods

Finite element models

Using a computer-aided design program (Simpleware, Exeter, UK), a surface (STL) model of a human head digitally constructed from a cone beam computed tomography scan (Fig. 1) was scaled so that the dimensions of the teeth approximately matched average anatomical values. Then, the model was separated into the 14 different tooth structures (from central incisor to first molar) derived from the maxilla and the mandible. Subsequently, a PDL mask was digitally constructed to fill the space between the bone and the root. Finally, a mask model of each dentoalveolar site was meshed to generate from 348556 to 531357 10-noded tetrahedral elements (element type: SOLID92) as exemplified in Fig. 2. The resulting models were inputted into a finite element analysis program (ANSYS APDL, Cherry City, PA, USA). The material properties of the bone and tooth were typical and established at 12 and 20 GPa, respectively (2–5, 10). In this study, the PDL material properties were assumed to be linear at 0.05 MPa because only small loads that determine strains <7.5% were applied to all teeth and under this limit the PDL behaves linearly (10). Moreover, at higher loads, it is likely the resistance numbers can vary slightly according to the magnitude of loads, because M:F relationships for specific tooth displacements also do (3, 11).

Fig. 1. Surface model of the human head used for fabrication of the finite element models of the teeth. This model was digitally transformed into a solid model.

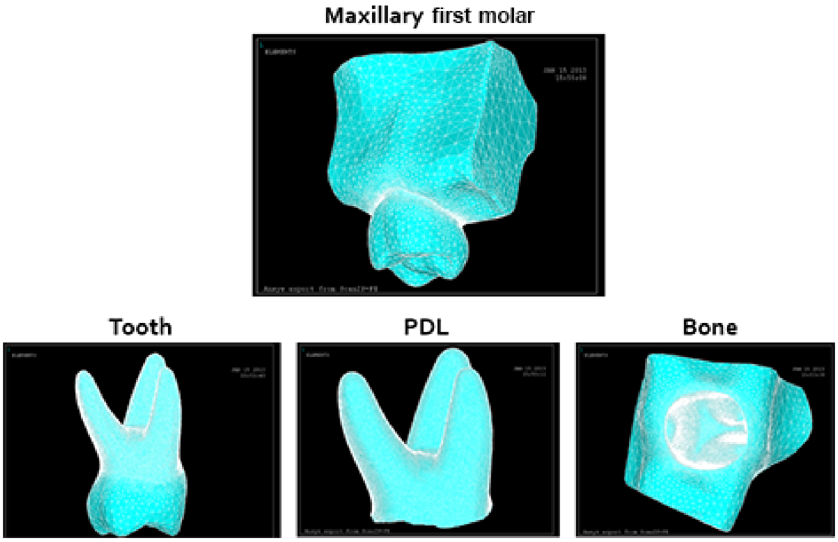

Fig. 2. Example of an assembled finite element model of a first maxillary molar (top) with the individual views of the tooth, PDL and bone models (bottom). PDL, Periodontal ligament.

Finite element analysis

Zero displacement was assigned to all nodes at the base of the maxilla and to all the lateral alveolar bone segment walls except the distal of the second molars. The mandibular central incisor was used to determine the target loads used to compare the stress fields within linear PDL material properties (<7.5% strain). Based on the analysis of this tooth, loads of 8 cN for vertical (extrusive/intrusive) and horizontal forces (labial/buccal or lingual/palatal) were applied to the approximate bracket position (centered on the labial/buccal side of the crown). In separate scenarios, 50 cN mm couples were applied to rotate the tooth (descriptions match the right hand rule). Figure 3 illustrates the loads applied, which are the most typical basic loads acting on teeth during alignment with a round wire.

Other studies have demonstrated that principal stress fields are variable along the root for different types of loads (3, 12). Because compressive stresses in the PDL lead to bone resorption as the initial limiting factor for tooth movement, we decided to adopt the following criteria when comparing predicted PDL stresses (Fig. 4):

a. The 3rd principal stress field (the algebraically minimum stress, or the most compressive stress in a compressive environment) was analyzed to yield the average stress in the zone of interest, determined as described below.
b. Each tooth root was divided in three equal areas vertically, and the region with the most compression within the 3rd principal stress field was chosen for analysis (Fig. 4).
c. Each tooth root was divided in four equal areas occlusally, and again the region with the most compression was intersected with the area described in 'b' to yield the area of analysis for each tooth root.
d. The 3rd principal stresses acting on the nodes of the PDL on the final intersecting regions were recorded and averaged to yield a stress number.
e. Each stress value was divided by the stress value of the lower central incisor, to yield a final resistance number for the specific tooth expressed relative to that of the lower central incisor.

Results

The stress results for load pairs in the same direction acting at the bracket (for instance labial or lingual/palatal forces and a labial or lingual/palatal moment vector) were symmetrical, and hence, only one of them is presented in Tables 1–5. The calculated resistance numbers in all load scenarios studied showed no consistent patterns of increase in resistance across different load types as the surface areas of the teeth increased (Tables 1–5). For example, the

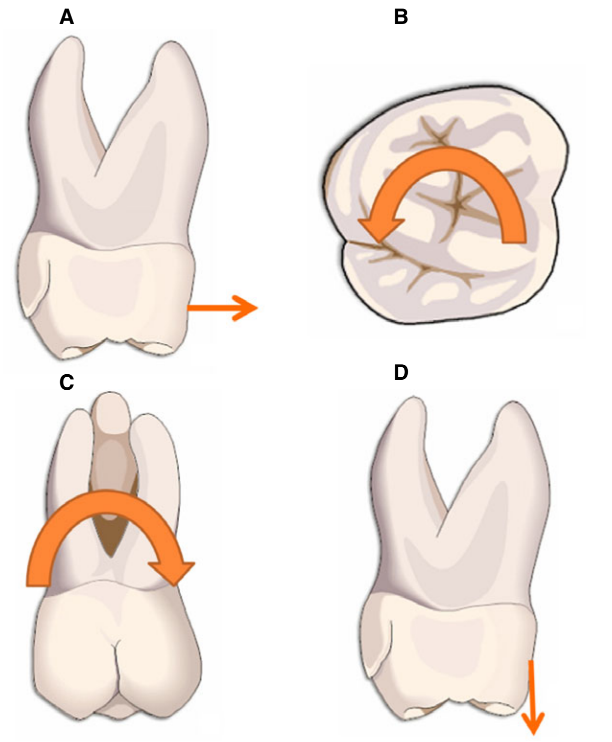

Fig. 3. Types of alignment loads applied to the finite element models illustrated relative to left maxillary first molar: (A) buccally oriented force parallel to the occlusal plane at the bracket level; (B) moment vector viewed occlusally, resulting from a couple applied about the vertical axis, which is perpendicular to occlusal plane; (C) moment vector viewed buccally, resulting from a couple applied about the buccal-palatal axis, which is parallel to occlusal plane; (D) occlusally oriented (extrusive) force perpendicular to the occlusal plane at the bracket level.

couple applied that generated rotation of the tooth around the tooth's vertical axis (Fig. 3b) showed differences in resistance to this rotation between some tooth types; however, the change in resistance did not vary simply according to root surface area (Table 2). The forces generated tipping-like PDL stress patterns where areas of stress concentration and the most compression in most scenarios studied were located near the alveolar crest.

Discussion

The current results demonstrated that the relationships between PDL stresses and the tooth resistance numbers vary depending on the type of load. These results suggest that it is a simplification to assume that only the projected surface area of the root is important to determine the PDL stresses. For instance, the presence of root curvature differences in wideness and the divergence and convergence of the roots in multirooted teeth can also contribute, that is, local root morphology is also important to determine load proportions between teeth. The results for the maxillary molars (Table 2) suggest that widely divergent roots will require higher loads (causing rotation about the vertical axis of the root) to achieve similar levels of stress, even if the surface area of the root is similar to other less divergent tooth roots. The reason is that the loads in the PDL that resist the application of the moment will be reduced in divergent roots that have a similar surface as convergent roots. The same concept applies to the analysis of root wideness.

Another example of how a general estimation of tooth surface area can be problematic to estimate resistance to tooth movement is differences in root shape. If the area limiting tooth movement is within the alveolar crest, the morphology of the root in that specific area will be more important than others when establish-

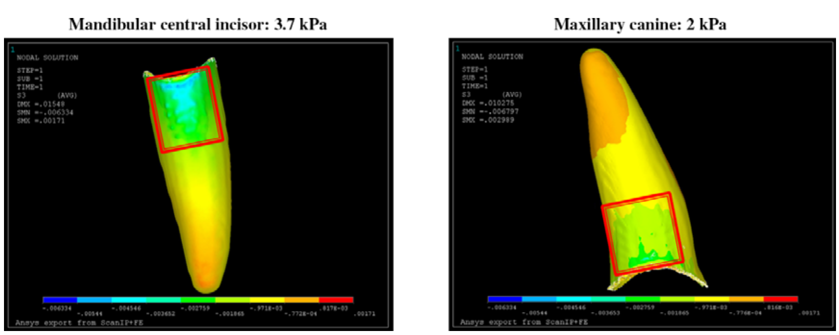

Fig. 4. Example of determination of the area of interest for calculation of the average 3rd principal stress (S3) and the corresponding results.

Table 1. **Results for approximate average 3rd principal stress (S3) affecting the region of interest, and the relative tooth resistance for a buccally (labially) oriented force, as seen in Fig. 3a**

	41	42	43	44	45	46	47	11	12	13	14	15	16	17
S3 (kPa)	3.7	3.8	2.2	2.1	2.3	1.6	1.7	1.7	3.2	2	2.1	2.3	1.3	1.1
Resistance number	1	1	1.7	1.7	1.6	2.3	2	2.2	1.1	1.9	1.8	1.6	2.8	3.4

Table 2. **Results for approximate average 3rd principal stress (S3) affecting the region of interest, and the relative tooth resistance for moment vector resulting from a couple applied about the vertical axis, which is perpendicular to occlusal plane, as seen in Fig. 3b**

	41	42	43	44	45	46	47	11	12	13	14	15	16	17
S3 (kPa)	2.3	2.3	2.2	2.1	2	0.9	0.9	1.2	2.3	2	1.7	2.1	0.8	0.6
Resistance number	1	1	1	1.1	1.2	2.6	2.6	1.9	1	1.2	1.4	1.1	2.9	3.8

Table 3. **Results for approximate average 3rd principal stress (S3) affecting the region of interest, and the relative tooth resistance for a moment vector resulting from a couple applied about the buccal-palatal axis, which is parallel to occlusal plane, as seen in Fig. 3c**

	41	42	43	44	45	46	47	11	12	13	14	15	16	17
S3 (kPa)	1.8	1.8	1.2	1.8	1.2	1	1.1	1	1.4	0.9	1.1	1	0.8	0.9
Resistance number	1	1	1.5	1	1.5	1.8	1.6	1.8	1.3	2	1.6	1.8	2.3	2

Table 4. **Results for approximate average 3rd principal stress (S3) affecting the region of interest, and the relative tooth resistance for an extrusive force at the bracket, as seen in Fig. 3d**

	41	42	43	44	45	46	47	11	12	13	14	15	16	17
S3 (kPa)	1.6	1.6	1.3	1.2	0.9	0.4	0.6	1.3	1.5	1	1.2	0.9	0.5	0.7
Resistance number	1	1	1.2	1.3	1.8	4.0	2.7	1.2	1.1	1.6	1.3	1.8	3.2	2.3

Table 5. **Average relative tooth resistance results for all load scenarios combined**

	41	42	43	44	45	46	47	41	42	43	44	45	46	47
Resistance number	1	1	1.4	1.3	1.5	2.7	2.2	1.8	1.1	1.7	1.5	1.6	2.8	2.9

ing the PDL stress in the area critical for initiation of tooth movement. That is, the stress fields and resistance numbers of roots of different shape and similar surface area can be different.

Although there are other variables important to determine the resistance to tooth movement of teeth within the same patient (such as bone quantity, vascularity, and quality), quantitative data on how these affect each tooth are unavailable. The results of the current study only consider PDL stresses. The number of active osteoclasts recruited, access of the osteoclasts to the bone and how much bone needs to be modeled for the tooth to move, will most likely also affect the true resistance to tooth movement. To analyze each biological variable separately, the stress needs to be controlled and the resistance numbers provided can assist the design of a study to do so.

The most important application of these numbers is to establish ideal proportions for loads on different teeth, so that the result is equalization of stresses in the PDL area where most bone modeling is occurring (near the area of most compression). That is, by applying the ideal proportions, tooth movement could be equally efficient for different teeth from the perspective of PDL stresses. For instance, if an orthodontist is comfortable applying a moment of 2000 cN $\times$ mm to rotate a first maxillary molar around its vertical axis, the equivalence for a lower central incisor would be approximately 1/3, or 690 cN mm. Another interesting application, albeit limited due to lack of consideration of bone features in these numbers, is to estimate the potential value of adding a tooth to an anchorage unit. For instance, a mathematical comparison of the resistance numbers suggests that adding a second molar can increase the buccal segment (maxillary second premolar and first molar) anchorage during alignment by approximately 50%. Another limitation of the current study was the utilization of linear PDL material properties for the models, due to the large number of teeth tested. We expect small differences in load proportions in teeth with more realistic, nonlinear PDL material properties. These may not be clinically important; however, this problem will be examined in a separate study with a limited number of teeth, because it is likely that load proportions could also vary with load magnitude.

Previous studies have shown that in rats and mice the necrotic threshold for compressive stress in the PDL is approximately between 8 and 10 kPa (3, 4). Although these studies are limited to rodents, the material properties of the human and rat PDL as well as the basic composition of the cellular structures are similar. Hence, once the effects of different types of stresses and different PDL material properties on PDL necrotic threshold values are better understood in rats, perhaps approximate intervals for optimal load values for ideal PDL response can be better estimated, and their biological response evaluated in human studies.

Typically, suggestions for optimal load values and tooth proportions published in books and literature from the beginning of the century have been based on estimations of root surface area and blood pressure. These estimations have scientific limitations compared to state of the art finite element methodology and actual histologic or tomographic analysis because they do not take into account different stress fields for different movements, and effects of root morphology in resistance loads and stress concentration. For instance, human values for blood pressure within the PDL and the different types of blood vessels that exist in it vary widely.

In the light of current findings, it is interesting to point out that the traditional design of fixed orthodontic appliances (brackets and archwires), within the model of the original Angle appliance, is still largely based on convenience and the anatomy of the crown, not the roots. Based on the numbers determined here and typical interbracket distances, no currently available orthodontic appliance, as a simple combination of archwire and bracket, can achieve the ideal load proportions between teeth during alignment. The loads acting on each tooth during alignment will depend on their malposition, and the stiffness of the archwire in that specific location. The stiffness of the archwire depends on the interbracket distances and material properties of the archwire. Orthodontists have typically limited the initial archwire dimensions and material properties to obtain lower forces in smaller teeth with small interbracket distances (such as lower incisors), and treatment efficiency may be somewhat reduced with this strategy because larger wires need to be used later to obtain better movement efficiency on posterior teeth. Certain nickel–titanium alloys with variable material properties currently exist on the market, but the variation in stiffness of the archwire does not consider the widely variable interbracket distances between each tooth, and thus, can result in unpredictable load relationships that do not match the ones presented in this study or the ones promised by manufacturers. The numbers published here could serve as references for the rational mechanical design for orthodontic alignment appliances that at least approximate optimal load proportions between the teeth.

Conclusions

Resistance numbers, that is, load proportion numbers between teeth to achieve similar stress at the compressive PDL zone, depend on the type of applied load. Differences between the resistance numbers in different teeth also vary with load type.

Clinical relevance

The orthodontic load proportions for different load types determined in this article can assist the clinician in planning how to vary loads between teeth, to better estimate anchorage needs and side effects for different types of movement. Moreover, it can facilitate design of orthodontic appliances to improve orthodontic treatment efficiency during alignment.

References

1. Katona TR, Paydar NH, Akay HU, Roberts WE. Stress analysis of bone modeling response to rat molar orthodontics. *J Biomech* 1995;28:27–38.
2. Kawarizadeh A, Bourauel C, Zhang D, Gotz W, Jager A. Correlation of stress and strain profiles and the distribution of osteoclastic cells induced by orthodontic loading in rat. *Eur J Oral Sci* 2004;112:140–7.
3. Viecilli RF, Katona TR, Chen J, Hartsfield JK Jr, Roberts WE. Three-dimensional mechanical environment of orthodontic tooth movement and root resorption. *Am J Orthod Dentofacial Orthop* 2008;133:791.e11–26.
4. Viecilli RF, Kar-Kuri MH, Varriale J, Budiman A, Janal M. Effects of initial stresses and time on orthodontic external root resorption. *J Dent Res* 2013;92:346–51.
5. Viecilli RF, Katona TR, Chen J, Hartsfield JK Jr, Roberts WE. Orthodontic mechanotransduction and the role of the P2X7 receptor. *Am J Orthod Dentofacial Orthop* 2009;135:694.e1–16; discussion 94–5.
6. Krishnan V, Davidovitch Z. Cellular, molecular, and tissue-level reactions to orthodontic force. *Am J Orthod Dentofacial Orthop* 2006;129:469.e1-32.
7. Melsen B. Tissue reaction to orthodontic tooth movement – a new paradigm. *Eur J Orthod* 2001;23:671–81.
8. Verna C, Zaffe D, Siciliani G. Histomorphometric study of bone reactions during orthodontic tooth movement in rats. *Bone* 1999;24:371–9.
9. Rygh P, Bowling K, Hovlandsdal L, Williams S. Activation of the vascular system: a main mediator of periodontal fiber remodeling in orthodontic tooth movement. *Am J Orthod* 1986;89:453–68.
10. Kawarizadeh A, Bourauel C, Jager A. Experimental and numerical determination of initial tooth mobility and material properties of the periodontal ligament in rat molar specimens. *Eur J Orthod* 2003;25:569–78.
11. Cattaneo PM, Dalstra M, Melsen B. Moment-to-force ratio, center of rotation, and force level: a finite element study predicting their interdependency for simulated orthodontic loading regimens. *Am J Orthod Dentofacial Orthop* 2008;133:681–9.
12. Tanne K, Koenig HA, Burstone CJ, Sakuda M. Effect of moment to force ratios on stress patterns and levels in the PDL. *J Osaka Univ Dent Sch* 1989;29:9–16.