THE DEVELOPMENT OF A VALIDATED MODEL OF ORTHODONTIC MOVEMENT OF THE MAXILLARY CENTRAL INCISOR IN THE HUMAN SUBJECT

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Abstract. A progressive approach to the modeling of orthodontic tooth movement is described. A novel method of experimental validation of a three dimensional model of a human maxillary central incisor is presented. By this approach an appropriate figure for the Elastic Modulus and Poisson's Ratio for the periodontal ligament (PDL) were determined to be 1.0 N/mm^2 and 0.45 respectively.

Key words: tooth movement, FEM modeling, experimental validation, periodontal ligament properties

Introduction

Orthodontics is a dental speciality concerned with the movement and alignment of teeth in reaction to the placement of a load, usually applied by some form of intra-oral appliance. The health gain of such measures relates to an improvement in occlusal function and dental health together with better aesthetics of the teeth and facial profile.

Although teeth are moved routinely in orthodontic practice little is known as to the precise mechanism of tissue response following the loading of a tooth crown. The remodeling of the load-bearing tissues within the human body has been considered for many years to be influenced by the loads they carry. This reaction is well known to orthodontists, however the association between loading and structure has proved difficult to quantify. A number of early investigators attempted to relate tooth movement to the applied force, developing theories based on very simple and imprecise experimental techniques on human subjects [1,2].

Most of the experimental work performed in the area since that time has been based on animal experimentation [3-12] which can only give a crude indication of the likely mechanical consequences in the human, since animal tissues, in this instance, are poor morphological reflections of the matching human tissues. More recently, tissue culture systems have been developed to examine the effects of stress on osteoblast cells [13]. Although of interest, this approach can only begin to reflect the complex stress patterns involved and it will be some time before results from these studies have any influence on clinical practice.

Other methods used to predict tissue response to load have included theoretical mathematical techniques [14], photoelastic systems [15], and laser holographic interferometry [16]. However, such techniques have the disadvantage of only examining surface stress whilst having the added problem of usually being supported by poor validation systems. In the last decade the application of a well proven predictive technique, originally used in structural analysis, the finite element method (FEM), has revolutionised dental biomechanical research.

Early work focused on the development of crude 2D models using existing information on the physical properties of dry/wet bone and other tissues, inevitably the validation systems were very limited in scope [17]. Since then 3D FEM models of the tooth, periodontal ligament and bone continuum have been produced [27], with simple time dependency and viscoelastic properties also being introduced [18,19]. Such predictive models have been found often to reflect existing, historical experimental data [20] on tooth displacement following load, although such information has been found to be sparse and the methodology employed in collection questionable.

Recently, some workers have developed computational models of tooth movement in animals, using animal experimental techniques for validation [21]. However, the current study describes a different approach where a new technique of measurement of tooth movement on humans is used to directly validate an initial finite element model. Since these models are of the human subject rather than of animals the results, when interpreted, are far more likely to be of direct relevance to clinicians.

Aims of investigation

- To develop an accurate and validated 3D FEM computer model of initial time dependent tooth movement in a typical human subject.
- Thus to have an appropriate model available to study the behaviour of teeth and surrounding tissues under load.

Initial objectives

- Establish the response of teeth to load and the material properties of the periodontal ligament (PDL) through direct measurement on human volunteers.
- Develop a 3D-computer simulation of maxillary incisor tooth movement applying the finite element method using both historical and experimentally derived data on the physical properties of the surrounding tissues.
- Examine, in detail, the stresses and strains in the surrounding tissues associated with tooth movement and, in particular, the nature of the displacement of the periodontal ligament (PDL).

Method and materials

Laser measurement equipment, that has been described in detail previously [22], was further developed and used in ten human volunteers to test the *in vivo* tooth response to load over time. A constant force was applied to the tooth under test by a stainless steel ball-ended probe, which was

Fig. 1: a) Volunteer in apparatus for measuring tooth displacement under constant load.
b) Calculated movement for maxillary incisor from experimentally derived displacement plots.

Accuracy of 0.001 mm – recording displacement every 0.01 seconds over 2 minutes in furst instance.
Measured in Microns.

Fig. 2a: Typical plot series of tooth displacement. (Axes as in 2b). Note initial immediate elastic behaviour followed by viscoelastic response of PDL. (The ‘oscillations’ in the plots are as might be expected in highly sensitive measurement of a biological system and are, in part, pulsatile in nature).

Fig. 2b: Six consecutive recordings of the one individual over 2 separate occasions (subject 2). Demonstrates level of reproducibility that can achieved in some individuals.

adjustable in three dimensions. A piston responding to air pressure regulated by a pressure sensor drove the probe. The displacement was measured by a laser beam trained at a target mounted at right angles and in a constant relationship to the probe. The laser was a Class 2 LAS-501V product with a 1 mega-watt maximum and a 680 nano-metre wavelength. The displacements plotted via this apparatus was also to be used to determine the properties of the periodontal ligament (PDL) and therefore was initially calibrated against a material of known dimensions and elastic modulus (a perspex rod beam).

In the experimental phase of the study the loading system was adjusted to achieve a low, well-defined and precise force on a maxillary incisor tooth. This force was of a continuous nature. Figure 1a shows the equipment in operation with one of the volunteers. An upper central incisor tooth’s displacement, measured in microns and calculated from the plots, is shown graphically in Fig. 1b. Such an approach facilitates the detailed examination of time dependent change in tooth

Fig. 3: Some of the Components of the FEM model.

Fig. 4: Plots of strain fields on incisor tooth, ligament alone on right. Note areas at neck and towards the ‘root apex’ of PDL.

displacement, there being the capacity in the apparatus to sample every 1/100th of a second. The accuracy has been previously confirmed [22] at 0.001 mm. Measurements in this current study were taken over a one-minute cycle, with the first 10 seconds pre-load (to achieve a steady baseline reading to the cycle), then 30 seconds under load, followed by a 20 seconds recovery phase.

Detailed load displacement plots were obtained for 10 patients who were judged to be typical of young healthy adults (a number of subjects had been previously examined, and it was found that age and periodontal health were important factors in the PDL response [24]). The mean age of the subjects was 30.7 years with a range of 24.7 – 36.5 years. The subjects involved in the study had to have, on clinical examination, good soft-tissue health with a minimal depth of gingival crevice (less than 2 mm). The mesial and distal contacts were evaluated according to the ease of passage of dental floss and those with 'tight contacts' were excluded. The dimensions of each tooth were recorded (mean mesio-distal width 9.95 mm) and the mid-point of the labial surface of the crown was consistently located for the application of load.

The data collected was to be used to establish PDL behaviour under orthodontic load (Fig. 2). To achieve a steady displacement recording, volunteers chewed a standard material (chewing gum) for 5 minutes prior to a load of 0.39 N being placed on the incisor tooth to be measured. This approach largely eliminated a variable 'fatigue' response that had been noted in the pilot studies and thus gave more consistent readings. Successive tests on individuals were performed with a rest period of no less than 3 minutes and no more than 5 minutes. Ten volunteers were measured 8 times (with the exception of subject 8) and showed significant inter- and intra-subject variability although 2 patients were able to give a very consistent, reproducible reading (Table 2). One difficulty with the measurement system was maintaining the point of force application and a method was developed to address this difficulty, which involved attaching a glass ionomer (GIC) cemented 'female marker' to the enamel surface of the incisor. This received the rounded probe through which the load was applied.

Fig. 5: Sectioning of the FE computer model facilitates a detailed analysis of strains within the PDL.

The experimental results were used to assist in the derivation of an accurate 3 dimensional finite element method model. This was designed to reflect the anterior maxillary teeth and jaws of a typical human subject (Fig. 3). In parts of the model modules were included for automatic adaptive mesh refinement, and since it was anticipated from previous work by the authors [23] that the PDL was particularly important in tooth movement, considerable effort was committed to modeling this area in detail. The PDL was designed to be initially elastic then basically visco-elastic and non-linear based on the experimental data.

The finite element model was developed on a main frame computer equipped with MSC/PATRAN[1] software. The basic mesh was formed using existing data[2].

A mesh of 15,000 elements was constructed, the element used being of the four-noded linear tetrahedral type. This element was chosen since it is good at meshing arbitrary geometries - a prerequisite in this project. The tooth was divided into two basic materials: dentine and enamel. The surrounding alveolar bone (with compact and cancellous layers) and the periodontal ligament was also included in the model. The basic material properties used are shown in Table 1 and a graphical sample from the model is shown in Fig. 1.

Using the FEM model the predicted response to load was initially validated against previous data form earlier models [18], historical data and then the experimental results obtained in the parallel experimental study. This was achieved by adjusting the physical properties of the PDL in the FEM model until the computed displacement matched the experimental clinical results; thus the Elastic Modulus and Poisson's Ratio could be deducted.

[1] MacNeal-Schwendler Co. Ltd. MSC House. Frimly. Surrey. UK.
[2] Viewpoint Data. 625S State, Orem. USA.

Results & discussion

The results are summarised in Fig. 2 – 5 and in Table 2.

The values for total displacement of the PDL over a one minute cycle for the 10 subjects ranged from 0.012 - 0.134 mm (or 134 microns) but showed coefficients of variation which ranged from 7 or 9% in subjects 7 and 10, to 59 or 64% in subjects 6 and 4. This was a not unexpected variation but nonetheless demonstrated that appropriate average values are best applied to this type of FE model. Having said this, reasonable consistency could be achieved in certain individuals partly due to their ability to relax within the apparatus. The mean maximum displacement was 87.7 microns (SD (standard deviation) = 50.71). The mean elastic modulus for a typical ligament was calculated for the PDL through identification of the elastic phase of the tooth displacement on the plots. This was applied to the FE model. A typical plot of an incisor tooth under load is shown in Fig. 2a. The six consecutive plots taken over two separate occasions and shown in Fig. 2b demonstrate the reproducibility possible in some subjects.

Table 1.

Some of the Historical Material Properties used in FEM model. (After Wilson, 1992 [19]).

MATERIAL	YOUNG'S MODULUS (N/mm^2)	POISSON'S RATIO
Enamel	84100	0.2
Dentine	18600	0.31
Cancellous bone	345	0.31
Cortical bone	13800	0.26
Periodontal ligament	50	0.45

Table 2.

Maximum recorded tooth displacements on nine volunteers measured 8 times (subject 8 was only measured on one occasion).

Subject No.	Maximum displacement (μm)				Coefficient of variation (%)	Rank Order
	Mean	Min	Max	S.D.		
1	89.9	12	205	50.71	56	5
2	134	97	166	24.79	19	3
3	132.6	82	186	47.54	36	4
4	99.6	43	205	63.79	64	9
5	80	39	159	46.79	58	6
6	73	33	133	43.51	59	8
7	12.4	12	14	0.89	7	1
8	117	--	--	--	--	--
9	103.6	90	112	9.01	9	2
10	103.6	90	112	9.01	9	2
All	87.7	12	205	50.71	58	--

The detail of the model is discussed elsewhere [25], but it comprised of a basic 15,000 x 3D trihedral elements. The tooth movement analysed on the model was found to basically follow rigid body motion with an initial instantaneous centre of rotation at the apical third of the root (Fig. 1b). The movement of the root of the tooth was comfortably within the PDL space and stresses were found to be within Lee's maximum for physiological movement [2]. However, the stress patterns within the modelled PDL were found to be very complex.

The maximum displacement occurred at the cervical margin (the neck of tooth at the junction between crown and root). This is the area where one might expect greater stresses, leading to a potential for cell hyalinisation in the ligament. Such stresses may also lead to local undermining resorption of the bone of the socket wall as part of a pathological response. Such a localised reaction can have a significant effect on the predictability of the tooth movement. In this area the strains noted were largely shear across the PDL.

The maximum principal strains in the periodontium were concentrated in two areas, at the alveolar crest on the buccal aspect and at the palatal side closest to the incisor root apex. The magnitude of these strains was greatest at the alveolar crest reaching a peak of 4.77×10^{-3} while the largest value of apical strain was 1.55×10^{-3}. By comparison, the maximum principal strains seen in the alveolar bone adjacent to the ligament were at least 35 times less (1.4×10^{-4}). Elsewhere in the bone strains approached zero.

Interestingly, large strains were found to be localised to the periodontal ligament but only negligible strains were found at the surface of the tooth root and bony socket. This data, together with that obtained from a largely theoretical previous model [23], suggests that initial orthodontic tooth movement must be largely mediated via the periodontal ligament rather than by any cellular remodeling response originating in the local bone. Only in the PDL did the strains recorded exceed the minimum threshold previously established [26] as being necessary to activate a local bone resorption process.

Finding an absolute value for the elastic value of the periodontal ligament based on the experimental data proved difficult and is in any case probably inappropriate since there are large variations between individuals. A good working assumption is that in a young adult with a healthy PDL, the elastic modulus is likely to be under 0.18 N/mm^2, most probably usually in the region of N/mm^2.

The experimental work on human volunteers examining tooth displacements with the laser displacement has been established as a valid approach and the apparatus has provided a number of interesting findings. Firstly, the initial elastic and then basic visco-elastic behaviour of the ligament has been confirmed. Secondly, it is apparent that in order to determine the physical properties of the ligament by back calculation that the apparatus needed significant modification to be able to place accurate light load over time. This gives a slower initial displacement and gives a clearer picture of early response ligament behaviour under load.

When a series of loading and recovery procedures have been performed on the teeth of volunteers, it has been very interesting to accurately chart, on occasion, a 'fatigue-like' behaviour in the periodontal ligament. The findings have relevance to the development of the computer model and indeed, are of significance in the variable behaviour of teeth to continuous and intermittent loading in the clinic. This will be investigated in more detail in the future.

Conclusion and summary of findings

- A computer based three dimensional finite element model of a maxillary left incisor tooth together with its neighbouring teeth and surrounding tissues was created. A novel laser displacement apparatus to measure the movement of teeth under a constant load on a series of human volunteers was constructed. It underwent extensive testing and modification to support this study. Detailed accuracy trials at low loading levels were performed.
- Displacements from in-vivo testing showed much variation between subjects and greater consistency within subjects.

- The PDL demonstrates an initial elastic response followed by a viscoelastic phase when subjected to a continuous load.
- The experimental results acquired from this apparatus were fed into the finite element model and thus the time dependent computer simulation of tooth movement was validated.
- The material properties of the periodontal ligament, a notoriously difficult material to quantify, were calculated from the experimental data. An early finding not previously reported in the current context was a «fatigue response» of the periodontal ligament on initial repetitive loading. A method of overcoming this response and of achieving a stable reading was developed and parameters established for the behaviour of the periodontal ligament under load in a number of individuals.
- An appropriate estimate of the Elastic Modulus of the PDL is 1 N/mm^2 whilst the Poisson's Ration is 0.45 as confirmed by the experimental results.
- An important incidental finding was an inter-subject variability of response, which could, in part, be related to early disease of the ligament. The apparatus described could form the basis of a non-invasive early detection mechanism for this common disease process.
- The FEM model demonstrated that only the PDL demonstrated any strain levels of significance. This supports the contention that the periodontal ligament is central to the tissue response to load and subsequent tooth movement.
- This initial FEM computer model has demonstrated that such an approach can be valid in the detailed study of orthodontic biomechanics. The movement of a tooth was charted, validated and the centre of rotation was described in detail.

Such computer models may be used to study both the biomechanics of tooth movement whilst accurately assessing the effect of new appliance systems and materials without the need to go to animal models. In effect, they could be used for research and development of new dental materials whilst reducing the need for animal experimentation or prolonged clinical trials.

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References

1. Storey E., Smith R. Force in orthodontics and its relation to tooth movement. **Aust J Dent**, 56: 11 –18, 1952.
2. Lee B. Relationship between tooth movement rate and estimated pressure applied., **J Dent Res**, 44: 1053, 1965.
3. Sandstedt C. Nagra bidrag til tandregleringens teori. Pub. P.A. Nordstedt & Stoner. Stockholm.1901.
4. Reitan K. Some factors determining the evaluation of force in orthodontics, **Am J Orthod**, 43: 32 – 45, 1957.
5. Picton D.C.A., Davies W.I.R. Dimensional changes in the periodontal membrane of monkeys due to horizontal thrusts applied to teeth. **Arch Oral Biol**, 12: 1635 – 1643, 1967.
6. Rygh P. Elimination of hylanized periodontal tissues associated with orthodontic tooth movement. **Scan J Dent Res**, 82: 57 – 73, 1974.
7. Davidovitch Z., Shanfield J.L.. Cyclic AMP levels in alveolar bone of orthodontically treated cats. **Arch Oral Biol**, 20: 567 – 574, 1975.
8. Wills D.J., Picton D.C.A., Davies W.T.R. An investigation of the visco-elastic properties of the periodontium in monkeys. **J Perio Research**, 7: 42 – 51, 1972.
9. Rygh P. Orthodontic root resorption studied by electron microscopy. **Angle Orthod**, 47: 1 – 16, 1977.
10. Chiba M., Ohkawa S. The response of the tensile strength of the rat periodontium in the rat mandibular first molar. **Arch Oral Biol**, 25: 569 – 572, 1980.
11. Yamasaki K. The role of cyclic AMP, calcium and prostaglandins in the induction of osteoclastic bone resorption associated with experimental tooth movement. **J Dent Res**, 62: 877 – 881, 1983.

12. Hong R.K. Effect of experimental tooth movement on the mechanical properties of the periodontal ligament in the rat maxillary molars. **Am J Orthod Dentofac Orthopaed**, 98: 553 – 543, 1990.
13. Sandy J. DNA changes in mechanically deformed osteoblasts: a new hypothesis. **Brit J Orthod**, 20: 1–11, 1993.
14. Steyn C.L., Verwoed W.S., Van der Merwe D., Fourie D.L. Calculations of the position of the axis of rotation when single rooted teeth are orthodontically tipped. **Brit J Orthod**, 5: 153 – 156, 1978.
15. Caputo A., Chaconis S.J., Hayashi R.K. Photoelastic visualisation of orthodontic forces during canine retraction. **Am J Orthod**, 65: 250 – 259, 1974.
16. Burstone C.J, Pryputniewicz R.J. Holographic determination of centres of rotation produced by orthodontic forces. **Am J Orthod**, 77: 396 – 409, 1980.
17. Williams K.R., Edmondson J.T., Morgan G., Jones M.L., Richmond S. Orthodontic movement of a canine into an adjoining extraction site. **J Biomed Eng**, 8: 115 – 120, 1986.
18. McGuinness N.J.P., Wilson AN., Jones M.L., Middleton J. A stress analysis of the periodontal ligament under various orthodontic loadings. **Eur J Orthod**, 13: 115 – 120, 1992.
19. Wilson A.N., Jones M.L., Middleton J. The effect of the periodontal ligament on bone remodeling. **Proc.Methods in Biomech. & Biomech.Eng.**, Pub, BJI. Oxford: 150 – 158, 1992.
20. Ross C.G., Lear C.S., De Lour R. Modeling the lateral movement of teeth. **J Biomech**, 92: 723 – 734, 1976.
21. Tanne K., Sakuda M., Burstone CJ. Three-dimensional finite element analysis for stress in the periodontal ligament by orthodontic forces. **Am J Orthod Dentofac Orthopaed**, 92: 499 – 505, 1987.
22. Volp C.R., Weston B.J., Knox J., Williams K., Jones M.L. A method of evaluating dynamic tooth movement, **Computer Methods in Biomechanics and Biomedical Engineering**, Pub. Gordon & Breach., 461 – 470, 1996.
23. Middleton J., Jones M.L., Wilson A.N. The role of the periodontal ligament in bone remodeling - the initial development of a time dependent finite element model. **Am J Orthod Dentofac Orthopaed**, 109, 155 – 162, 1996.
24. Tanne K., Yoshida S., Kawata T., Sasaki A., Knox J., Jones M.L. An evaluation of the biomechanical response of the tooth and periodontium to orthodontic forces in adolescent and adult subjects. **Brit J Orthod**, 25: 109 – 115, 1998.
25. Hickman J. A validated finite element method study of maxillary incisor tooth movement. MScD Thesis. University of Wales., 1997.
26. Frost H.M. A determinant of bone architecture: the minimum effective strain. **Clin Orthop Rel Res**, 175: 286 – 292, 1983.
27. Nyashin M.Y., Pechenov V.S., Rammerstorfer F.G. Determination of optimal orthodontic forces. **Russ J Biomech**, 1-2: 84 – 96. 1997.

Развитие разработанной модели ортодонтического движения верхнего центрального резца человека

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Приведено описание теоретических и экспериментальных методов, позволяющих описать поведение зуба под нагрузкой при ортодонтическом лечении. В данной работе описано применение трехмерного метода конечных элементов, описывающего движение зуба. Экспериментальная проверка проведена с помощью установки, содержащей лазер. Измерения перемещения передних резцов in vivo проведены на 10-ти добровольцах со средним возрастом 30,7 года (в диапазоне 24,7 – 36,5 лет). При расчете учтены упругие свойства (модуль Юнга и коэффициент Пуассона) эмали, дентина, окружающей решетчатой и кортикальной костной ткани. Сравнение расчетных и экспериментальных результатов по перемещениям зубов позволило оценить упругие параметры периодонтальной связи. Модуль Юнга равен 1,0 Н/мм^2 и коэффициент Пуассона –0,45. Библ. 27.

Ключевые слова: ортодонтия, движение зубов, метод конечных элементов, эксперимент, свойства периодонтальной связи.

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