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An Evaluation of the Biomechanical Response of the Tooth and Periodontium to Orthodontic Forces in Adolescent and Adult Subjects

K. TANNE, D.D.S., PH.D.

S. YOSHIDA, D.D.S., PH.D.

T. KAWATA, D.D.S., PH.D.

A. SASAKI, D.D.S.

Department of Orthodontics, Hiroshima University School of Dentistry, 1-2-3 Kasumi, Minami-ku, Hiroshima 734–8553, Japan

J. KNOX, B.D.S., M.SC.D., M.ORTH., F.D.S.R.C.S.

M. L. JONES, B.D.S., M.SC., PH.D., D.ORTH., F.D.S.R.C.S.

Department of Dental Health & Development, Dental School, University of Wales College of Medicine, Heath Park, Cardiff, CF4 4XY, U.K.

Abstract. *This study was designed to quantify the magnitude of tooth mobility in adolescents and adults, and to investigate the differences in the biomechanical response of tooth and periodontium to orthodontic forces. The initial displacement of the maxillary central incisor was measured in 50 adolescent and fifty adult patients and the biomechanical properties of the periodontium were examined using the finite element method (FEM) and supporting experimental data. The magnitude of tooth mobility was significantly greater in the adolescent group than in the adult group. By integrating the differences in tooth mobility in both subject groups with analytical tooth displacements, the Young's modulus of the periodontal ligament (PDL) was demonstrated to be greater in the adults than in the adolescent subjects. The differing biomechanical properties of the PDL in adults were demonstrated to result in almost equivalent or somewhat increased stress levels in the PDL in adult subjects. It is suggested that this might produce a reduction in the biological response of the PDL and thus lead to a delay in tooth movement in adults.*

Index words: Biomechanical Properties of Periodontium, FEM, Orthodontic Tooth Movement, PDL Stress, Tooth Mobility.

Introduction

Recent advances in clinical techniques and changes in patient's awareness of malocclusion have resulted in an increased demand for orthodontic treatment amongst adults. In the treatment of such patients, the differences in the anatomic structure and tissue response between young and mature (adult) periodontium should be considered (Kyomen and Tanne, 1997). Moreover, the potential problems of TMJ disorders and periodontal disease in adult patients demand that orthodontic mechanotherapy be accurately prescribed.

Histological changes in the periodontal tissue during experimental tooth movement have been studied extensively (Reitan, 1957; Norton, 1988; Reitan and Rygh, 1994). Orthodontic tooth movement is dependent on the magnitude, direction, and duration of the force applied. However, it has been suggested that considerable variation exists in the periodontal tissue reaction between the younger and more mature patients in terms of the cell population, and vascularization of the periodontium (Jensen and Toto, 1968; Stahl *et al.*, 1969). These differences in the periodontium result in a longer hyalinisation phase and, subsequently, an often extended treatment time in adult patients.

These phenomena have been recognized histologically and also clinically, but have not been quantified biomechanically. The biological reaction of the periodontal ligament is determined by the stress-strain levels induced by mechanical forces applied to the tooth (Burstone, 1989; McGuinness *et al.*, 1990; Tanne *et al.*, 1992; Tanne and Sakuda, 1983, 1994). Measurement of tooth displacement in response to applied force would give an insight into the stress distribution within the periodontium and, thus, subsequent tooth movement.

This current study was designed to quantify tooth mobility in adolescent and adult groups of subjects, and then by using these data, to accurately develop a validated computer model of tooth loading, by application of the finite element method (FEM). Such an approach allows the

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opportunity to evaluate the effect, in detail, of the various biomechanical factors involved in tooth movement.

Materials and Methods

Tooth Mobility

Two groups of patients were selected for this section of the study. The first group consisted of 50 adolescents (20 males and 30 females) with a mean age of 11·6 years (range: 9–13 years). The second group consisted of 50 adults (20 males and 30 females) with a mean age of 22·5 years (range: 19–29 years).

Criteria for inclusion were that the maxillary central incisors should not be severely malpositioned, should have complete root formation, no deformation of crown or root, no obvious gingival inflammation or bone resorption, and no history of caries or root canal treatment.

Measurement of tooth mobility was carried out by use of a previously described 'Periotest' method (Shulte *et al.*, 1983; Kaneko, 1994; Siemens Co., Bensheim, Germany). The 'Periotest' is designed to precisely measure periodontal function and quantify pathological alterations. An electronically controlled rod percusses the tooth at a rate of four times per second. The contact time per impact between the rod and tooth, within the range of a millisecond, represents the measuring parameter proper. Since periodontal structural changes in the alveolar bone and/or PDL influence the contact time, the time recorded during 16 trials by the microcomputer of the Periotest unit can be averaged and thus represent the Periotest value ranging from –8 to +50 for each tooth.

Tooth mobility was measured for each tooth five times and was calculated as the mean Periotest value for both of the upper central incisors.

Three-dimensional Finite Element Analysis

A three-dimensional finite element model was developed for the maxillary right central incisor. Average anatomic data for the upper central incisors were based on the dimensions given by Takahashi (1989). Variable periodontal ligament (PDL) widths were defined for different apicogingival levels from the data of Coolidge (1937). Sixteen horizontal planes were made perpendicular to the long axis of the tooth. Each plane, which included the tooth and/or PDL and alveolar bone, was divided into a finite number of nodes and rectangular elements, maintaining geometric equivalence to the real object. Nodal coordinates were digitized on each plane and elements were described with node numbers. All of the planes perpendicular to the tooth axis were then built up three-dimensionally. Finally, a three-dimensional finite element model was constructed, comprising the tooth, PDL, and alveolar bone.

The model consists of 1205 nodes and 920 solid elements (Fig. 1). Details of the modelling procedures, including the validity of the model, have been described previously by Tanne *et al.* (1988). In the present analysis, all the materials in the model were assumed to be isotropic and elastic. Table I shows the material constants for the tooth, PDL and alveolar bone used in this analysis (Cook *et al.*, 1982).

TABLE I *Material constants of tooth, periodontal ligament, and alveolar bone*

Material	Young's modulus (Mpa)	Poisson's ratio
Tooth	$1·96 \times 10^{4}$	0·3
PDL	$6·66 \times 10^{-1}$	0·49
Alveolar bone	$1·37 \times 10^{4}$	0·3

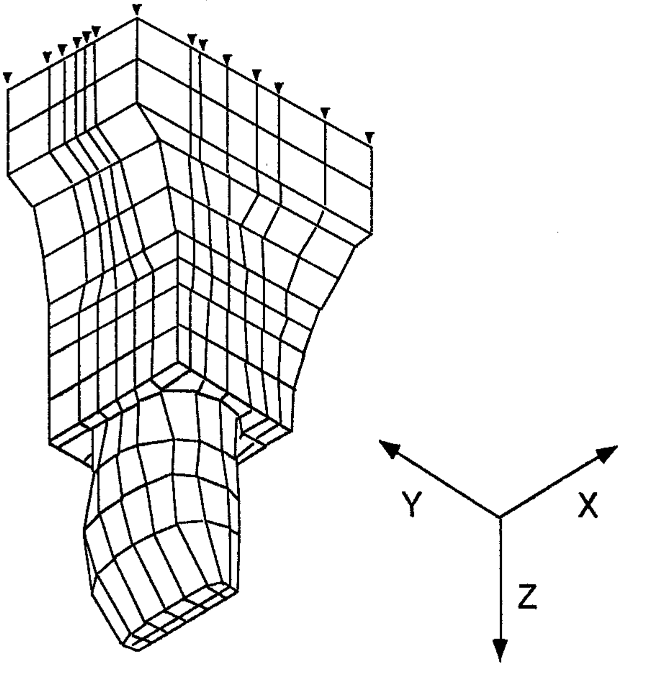

FIG. 1 A three-dimensional finite element model of an upper central incisor. The model is restrained at the maxillary basal bone area as indicated by solid triangles.

The constitutive behaviour of the PDL is based on previous studies (Tsutsumi *et al.*, 1977; Tanne, 1983) relating force and initial tooth displacement in human subjects.

The computer program used for the analysis was ISAP (NEC Corp., Tokyo, Japan). A lingually-directed force of 0·98 N (100 g) was applied analytically at the midpoint of the labial surface of the tooth crown, 4·5 mm apical to the incisal edge, and the amount of tooth displacement was analysed at the same point. Three principal stresses in the periodontal tissue were analysed and the converted volumetric principal stresses were evaluated for seven apicogingival levels (A–G) on both the labial and lingual aspects (Fig. 2).

Results

Tooth Mobility in the Adolescent and Adult Groups

The amount of tooth mobility is shown in Table II. No significant differences in the Periotest value were found between male and female subjects in the two groups. Therefore, the data of male and female subjects were considered together.

The mean adolescent Periotest value was 13·0 (SD 3·66). In the adult group, the mean value was 7·32 (SD 2·35). A

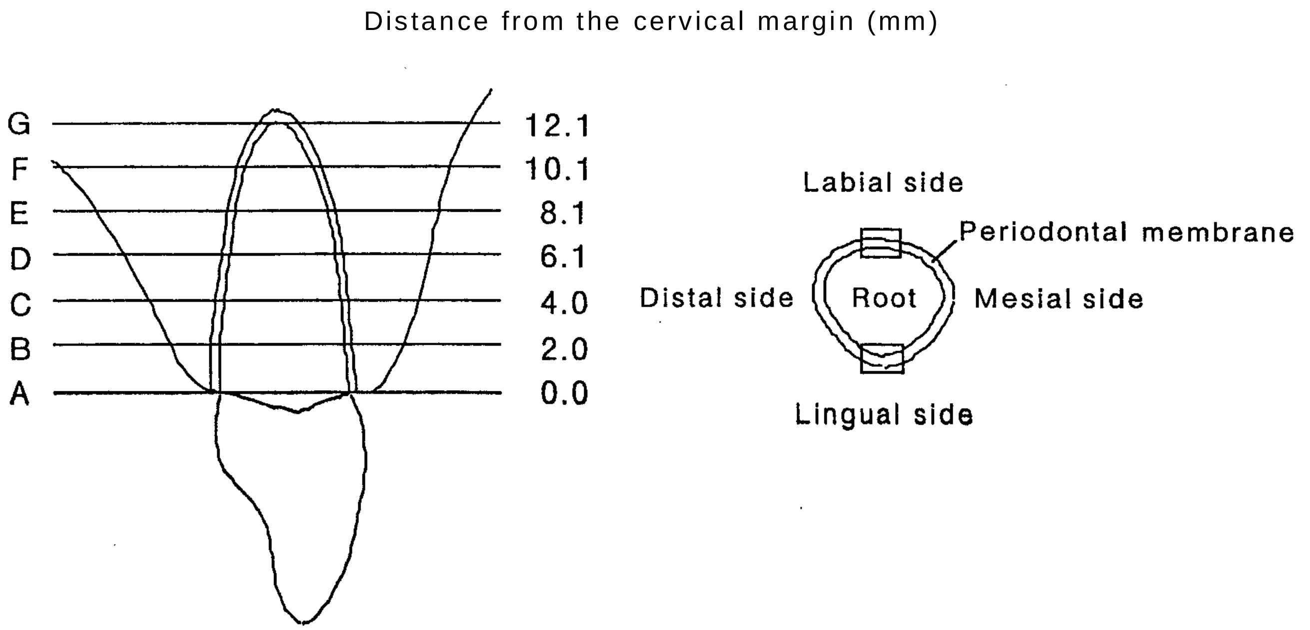

FIG. 2 Occlusogingival levels (A through G) and horizontal points (labial and lingual) where the principal stresses in the PDL were determined.

TABLE II *Means and standard deviations (SD) for recorded tooth mobility between adolescent and adult groups*

Periotest value		Mean ± SD			
Adolescent	Male	13·9 ± 3·52	NS	13·0 ± 3·66	*
	Female	12·4 ± 3·70			
Adult	Male	7·09 ± 2·81	NS	7·32 ± 2·35	
	Female	7·47 ± 2·01			

NS, not significant; * significant (P < 0·05).

statistically significant difference for the Periotest value ($P < 0·05$) was recorded between the adolescent and adult groups.

Tooth displacement and stress distribution in the PDL

Changes in tooth displacements with varying mechanical properties of the periodontal membrane are shown in Fig. 3. The amount of tooth displacement decreased substantially when the Young's modulus of the PDL was varied from 0·067 to 67·0 MPa. Changes in the Poisson's ratio of the PDL, ranging from 0·30 to 0·49, also had a significant influence on the amount of analytical tooth displacement and this was particularly true in the range of Young's modulus from 0·67 to 6·70 Mpa.

Changes in tooth displacements with varying mechanical properties of the alveolar bone are shown in Figs. 4 and 5. The amount of tooth displacement does not seem to be influenced by changes in the mechanical properties of the alveolar bone.

These results from the experimentally validated computer model would suggest that the Young's modulus of the PDL is the most important determinant of instantaneous tooth displacement.

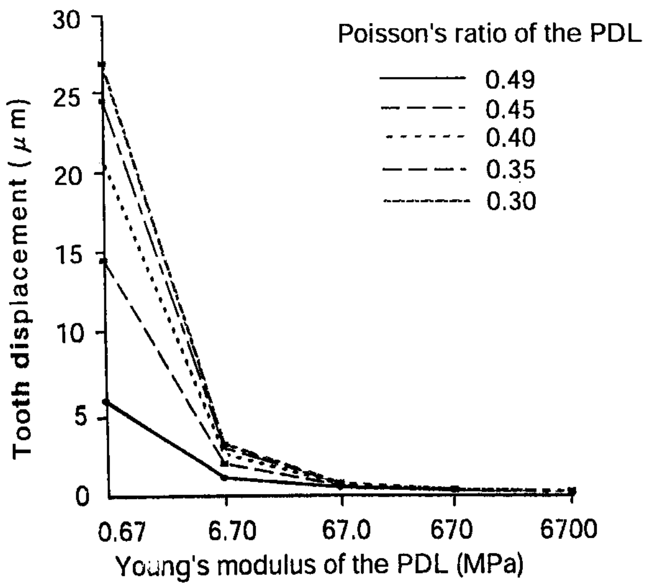

FIG. 3 Changes in tooth displacements with different Young's moduli and Poisson's ratios of the PDL.

Using the data generated from the Periotest, it can be seen that the Young's modulus of the PDL was significantly higher in adults than in adolescents. Therefore, the stresses in the PDL and on the surface of the alveolar bone were evaluated first using the Young's modulus values for adult (0·98 and 1·96 MPa) and then those for the adolescent (0·67 MPa) groups.

Figures 6 and 7 show three principal stresses in the PDL for each root level. Compressive stresses were produced at the margin, whereas tensile stresses were generated at the root apex. At the middle of the root, stress levels were substantially less.

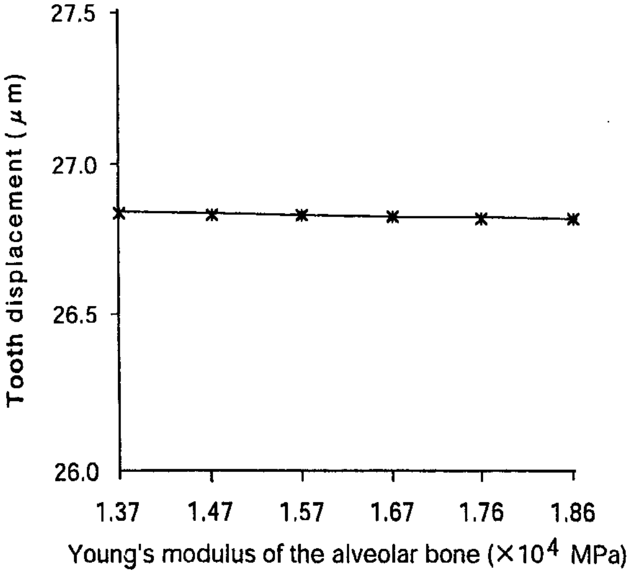

FIG. 4 Changes in tooth displacements with varying Young's moduli of the alveolar bone.

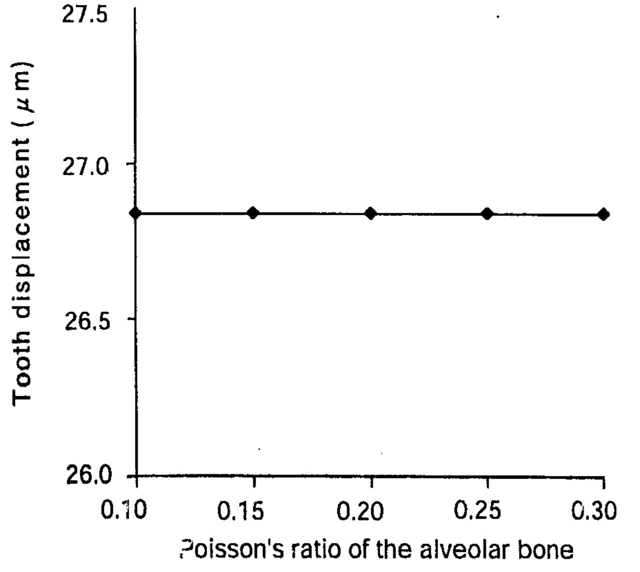

FIG. 5 Changes in tooth displacements with varying Poisson's ratios of the alveolar bone.

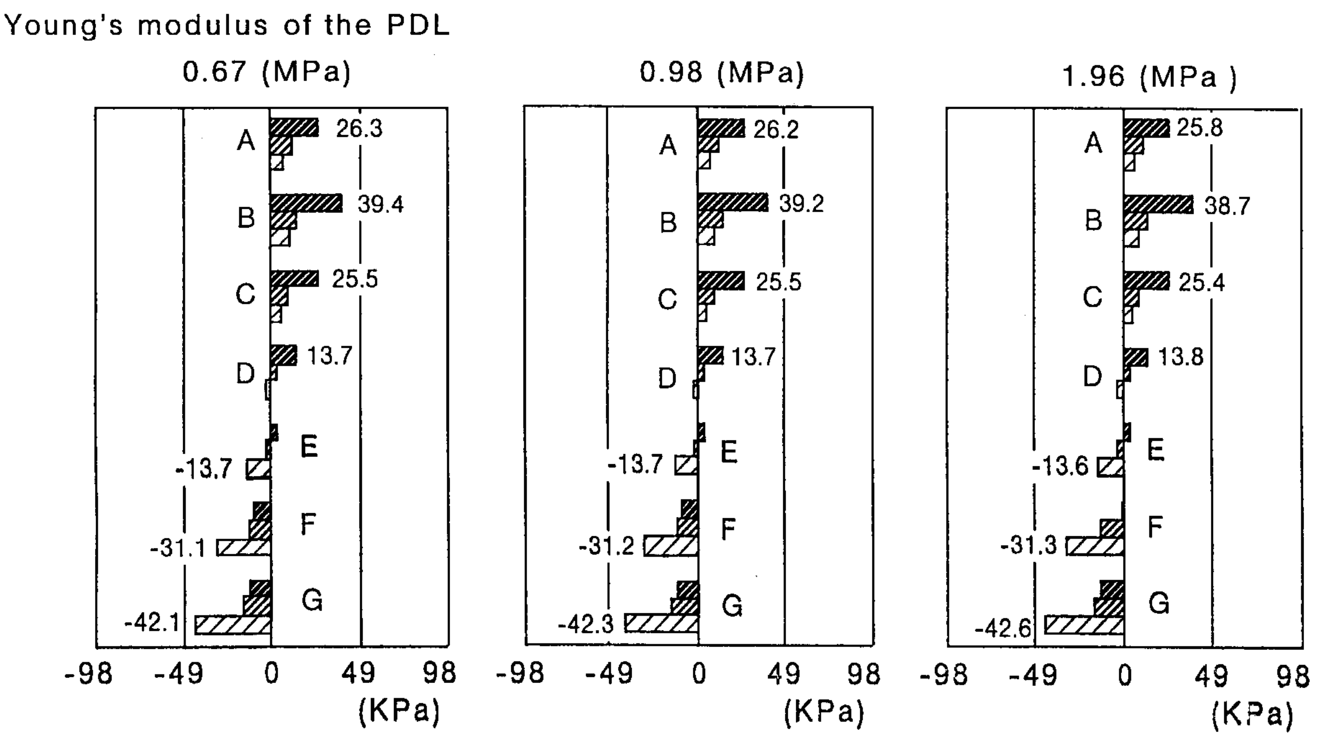

FIG. 6 Stress distribution in the PDL in loading condition for a lingual force of 100 g. Three principal stresses, maximum , intermediate , and minimum are shown for labial points at various apicogingival levels (A–G).

On the labial side of the root, tensile stresses were larger than the compressive stresses observed near the root apex. On the lingual aspect, compressive stresses were larger than those tensile stresses induced nearer the apex. A transition of stresses was observed at the centre of the root. Thus, the stress distributions coincided with the site specific dimensional changes expected in the PDL during tooth movement.

The patterns of stress distribution on the labial and lingual aspects were essentially similar in both the adolescent and adult groups. The compressive stresses at the alveolar crest on the lingual side were almost equivalent in the adult group with those in the adolescents. In a previous study (Kyomen and Tanne, 1997), it is described that significant differences in proliferative activity of the PDL cells were found between young and

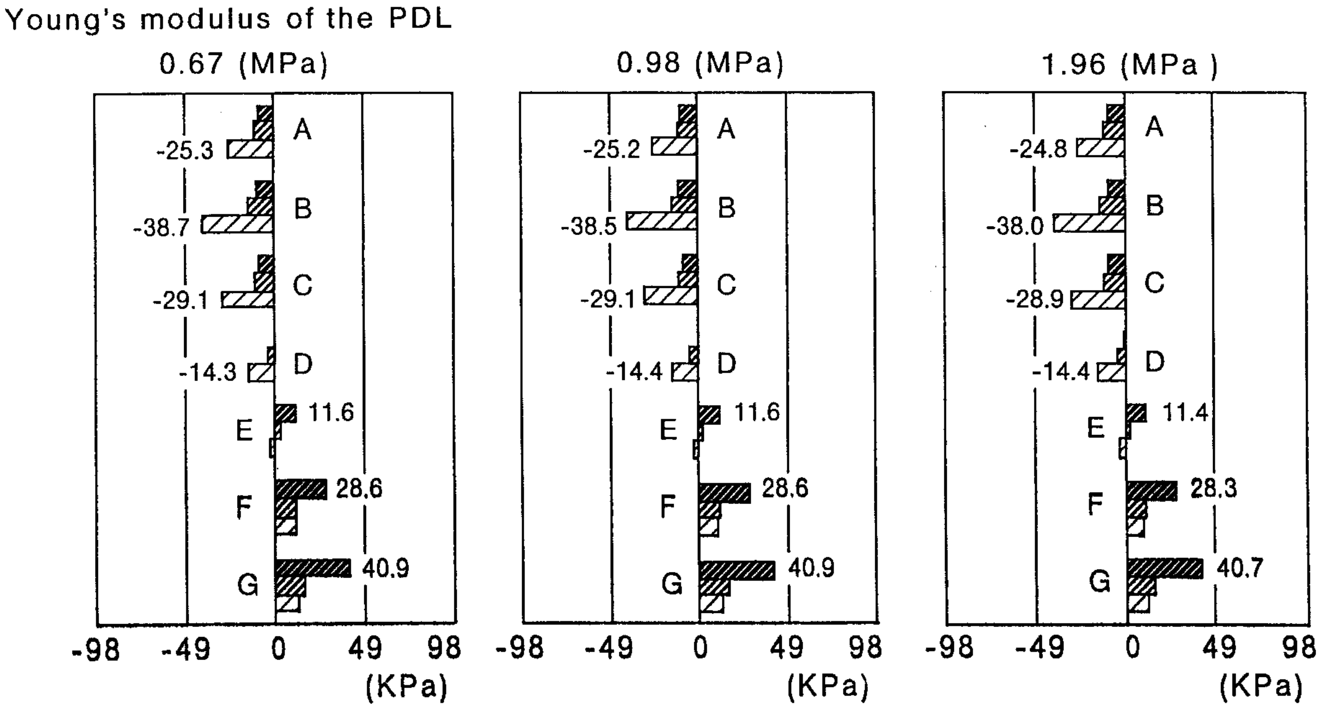

FIG. 7 Stress distribution in the PDL in loading condition for a lingual force of 100 g. Three principal stresses, maximum , intermediate , and minimum are shown for lingual points at various apicogingival levels (A–G).

adult groups during the initial phase of tooth movement. These findings emphasise that if an optimal PDL stress level exists, it should be substantially lower in adults than in adolescents. Therefore, the PDL stress levels demonstrated in adults in this analysis may be a factor in the induction of local bone change (i.e. resorption) and thus influence the nature of the tooth movement.

Discussion

Physiological tooth mobility is a product of the elastic attachment of the PDL between root and alveolar bone. This connective tissue provides tooth suspension, eruption, and repair of the periodontium.

The magnitude of tooth mobility has been used to evaluate the functional and pathological status of the periodontium. Measurement techniques for tooth mobility originally were developed by Mühlemann (1951), who used a 'dial gauge periodontometer' to measure lateral tooth displacements in response to digital pressure. Other methods of measuring tooth mobility have employed resistance-strain gauge (Kajii, 1967; Wills *et al.*, 1972), transducer (Parfitt, 1960; Kurashima, 1963; Yokota, 1975), laser hologram (Burstone *et al.*, 1978), non-contact sensor (Igarashi and Ai, 1980; Tanne *et al.*, 1986). More recently specific laser measurement systems have been developed to accurately record tooth movement to assist in FEM model validation (Middleton *et al.*, 1996a).

Most clinical studies of tooth mobility have employed large and complicated systems which are cumbersome in the clinical environment. Meanwhile, the Periotest, used in this study, offers a simple and accurate method of clinically determining the mobility of teeth with a coefficient of variation of the measured value of 4·3% on average. The mobility of teeth measured with Periotest is dynamic in nature, therefore, the quantity may be used for the evaluation of visco-elastic behaviour of the periodontium (Shulte *et al.*, 1983; Kaneko, 1994). Moreover, the absolute value may also be used for determining the amount of initial tooth displacement within the alveolar socket.

The pattern of tooth mobility is divided into three characteristic phases (Mühlemann 1951, 1954; Mühlemann and Zander 1954; Ishibashi, 1958); i.e. initial, intermediate, and terminal phases of tooth mobility. Within a range of force less than 0·98 N (100 g), the periodontal resistance against the tooth motion within the alveolar socket is very small, therefore, the initial phase is assumed to be due to the gradual unfolding of PDL fibre bundles without generating tension. In the second phase, with a force from 0·98 to 14·7 N (100 to 1500 g), mobility is a product of the deformation of the bony socket. Finally, as the force increases above 14·7 N (1500 g), terminal tooth mobility results due to a time-dependent interaction between the PDL fibres and alveolar bone. The force magnitude used in this current study was less than 0·98 N (100 g) and, therefore, the tooth mobility measured was assumed to reflect both quantitative and qualitative alterations in the PDL.

Looking more closely at the initial phase of tooth movement, Kurashima (1963) reported that visco-elastic distortion of the periodontium was produced by small forces around 0·49 N (50 g), whilst forces of about 4·9 N (500 g) gave rise to an additional elastic deformation of the alveolar bone. Upon removal of the load, the tooth returns to its original position in two phases. The first phase is a quick and substantial recovery of usually between 30 or 40 μ and the second phase is a slow recovery to its original position. From such results, it would appear a reasonable assumption that the periodontal tissues are essentially visco-elastic in nature.

In the present study, the tooth mobility was found to be significantly less in the adult group than in the adolescent group. In an adult, the PDL fibre bundles are more organized and the normal fibroblasts turnover is substantially reduced resulting in an alteration in the overall elastic properties.

Ishibashi (1958) investigated the mobility of the mandibular central incisor. He found that in erupting anterior teeth in young subjects, the tooth mobility is relatively high because of a difference in the arrangement and density of the PDL fibre bundles. After the completion of eruption, the tooth mobility became slightly less due to increased root formation and organization of the PDL. The differing tooth mobility found for adolescents as compared to adult patients recorded in the present study is in agreement with the findings of Ishibashi (1958).

The differences in the apparent biomechanical reactions of the PDL to external load in adult and adolescent groups would appear to be a product of the changes in PDL elasticity. In younger subjects, the periodontal membrane is rich in cellular components, the alveolar bone crest is lined with uncalcified osteoid tissue, and the cancellous areas are filled with loose fibrous tissues, these are not generally the case in the adult subject.

Although there have been numerous studies examining the histological basis of tooth movement (Reitan, 1957; Reitan and Rygh, 1994), there have been few biomechanical investigations. However, the biological reactions of the periodontal ligament are determined primarily by the stress-strain levels induced by applied orthodontic load, and thus, an evaluation of PDL stress distribution is essential to assist in the understanding of the mechanism of tooth movement (Burstone, 1989).

The stress distribution within the periodontium was determined in this study by the use of a specifically developed and carefully validated three-dimensional FEM computer model. With respect to the validity of the analytical model, geometrical equivalence of the model was precisely examined and mesh refinement was repeated until the requirements became satisfied by a preprocessing computer check (Tanne *et al.*, 1988).

The findings in this theoretical model would appear to suggest that the patterns of stress distributions in the PDL were not substantially varied by age changes in the periodontium. Meanwhile, it may be predicted that the stress levels in the PDL are varied according to the alteration in the mechanical properties of the periodontium, i.e. it is reasonably accepted that less tooth displacement revealed in adult population in this experiment leads to a smaller level of PDL stresses. Nevertheless, the results were somewhat different from that expected. An interesting finding in the adult model was that stress levels in the PDL appeared to slightly increase (or to be similar) in the compression areas close to the alveolar crest. The results of previous FEM studies (Middleton *et al.*, 1996b; Tanne and Sakuda, 1994) have suggested that the principal stress in the PDL is probably the most important determinant of the tooth socket alveolar bone remodelling. Furthermore, a previous study demonstrated a significant difference in proliferative activity of the PDL cells between young and mature rats with and without experimental tooth movement (Kyomen and Tanne, 1997), therefore, it is a reasonable assumption that the optimal force or stress levels in the PDL should be substantially lower in adults than in young patients. Given that the Young's modulus of the PDL is higher and that the stress values at the alveolar crest on the lingual surface of the root are similar in the adult in the current study, it may be predicted that in such patients, hyalinization of the PDL and undermining resorption is a more likely response to normal orthodontic loads than in adolescents. This could, in turn, explain the slower tooth movement and the increased pain experienced particularly during the initial phases of orthodontic treatment in adults (Jones and Chan, 1992).

A clinical implication may be derived from this study in that a considerably lower force is desirable for orthodontic tooth movement in adults particularly during the initial application of the load. In addition, a larger Young's modulus of the PDL in adult subjects may produce a higher risk of root resorption, although the association requires further detailed investigation.

Conclusions

1. A statistically significant lower Periotest value ($P < 0{\cdot}05$) for the PDL was found in adults than in a comparable adolescent group of human subjects.
2. Young's modulus of the PDL appears to be the most important determinant for instantaneous tooth displacement.
3. The pattern of stress distribution on the labial and lingual root surfaces appeared to be essentially similar in both the adolescent and adult groups.
4. The compressive stresses at the alveolar crest on the lingual side were almost equivalent in the adult and adolescent groups. Such stress levels in this area seem an important determinant in inducing transient PDL hyalinization. This could be a causative factor in delayed tooth movement and increased initial pain during orthodontic treatment in the adult.

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