European Journal of Orthodontics 18 (1996) 329–339

Initial stress differences between tipping and torque movements. A three-dimensional finite element analysis

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SUMMARY The aim of this study was to analyse the distribution of the stress on dental and periodontal structures when a simple tipping dental movement or torque movement is produced. A tridimensional computer model based on finite element techniques was used for this purpose. The model of the lower canine was constructed on the average anatomical morphology and 396 isoparametric elements were considered. The three principal stresses (maximum, minimum and intermediate) and Von Mises stress were determined at the root, alveolar bone and periodontal ligament (PDL). It was observed how the distribution of stress is not the same for the three structures studied. In all loading cases for bucco–lingually directed forces, the three principal stresses were very similar in the PDL. The dental apex and bony alveolar crest zones are the areas that suffer the greatest stress when these kind of movements are produced.

Introduction

Dental movement can be considered as one of the basic pillars of orthodontic treatment. Over the years numerous studies have been carried out in order to obtain a greater knowledge of these mechanisms, by means of which, the biological processes may be controlled.

These processes have been studied from a histological point of view in both animals and humans (Oppenheim, 1911; Schwartz, 1932; Reitan, 1947, 1964, 1967; Storey, 1955; Gianelly and Goldman, 1971).

Other investigations have focussed on the use of physical–mathematical models to inter-relate the histological processes of the forces applied, as these are the reason for the biological processes of the movement, in terms of magnitude, direction and their point of application (Mulligan, 1979; Thurow, 1982; Smith and Burstone, 1984; Burstone and Koenig, 1985).

In addition, techniques of photoelastic stress analysis and laser holographic interferometry have also been used (Caputo *et al.*, 1974; Burstone and Pryputniewicz, 1980).

Many studies have been carried out in order to demonstrate that the stress generated on tooth, PDL and bone following application of a force on the dental crown was responsible for the histological changes, allowing dental movement (Oppenheim 1911; Reitan, 1947, 1964; Baumrind, 1969).

The finite element method (FEM) is a numerical method of analysis that allows the study of stress distribution in biological systems. In dentistry it has been used in studies of cranio-facial development, (Moss *et al.*, 1985) prosthetics (Kawasaki *et al.*, 1987) and implantology (Cook *et al.*, 1982).

This method enables the strain-stress in the interior of the structures to be calculated. It also has the potential for equivalent mathematical modelling of a real object of complicated tridimensional geometry. At the same time it permits the application of various force systems at a set point, and the study of the distribution of such forces through the following structures: alveolar bone, tooth and periodontal ligament. It also provides qualitative and quantitative results.

Materials and methods

A right inferior canine extracted for periodontal reasons was used to undertake the present study. A total of 14 transverse sections were sliced and standardized photographs of the sections were digitized using a Calcomp 9500 board (Calcomp España, Madrid, Spain), an IBM PS/2 80 microcomputer (IBM Corp., USA) and an Autocad

10 (Autodesk, Asicom, Barcelona, Spain) software. The tooth model consisted of 396 isoparametric elements. The same computer was used for the meshing process and a Cosmos/M.v. program was used (Structural Research and Analysis Corp., Santa Monica, CA, USA).

The periodontal membrane was simulated as a 0.2 mm thick ring around every tooth section (Tanne and Sakuda, 1983; Cobo *et al.*, 1993). Once the modelling of the three structures was obtained, the study of the distribution of stress when different forces were applied was carried out. The point of application of these forces was established on the midpoint vestibular face of the crown, which coincides with the point where the bracket is normally placed in clinical practice.

A force of 100 g in a labio–lingual direction, perpendicular to the axis of the tooth was applied to one side.

The second type of force applied was intended to produce a torque movement with a root vestibular direction. A pair of forces were applied on both nodal elements found in the centre of the vestibular face of the crown and separated from each other in a vertical direction. One of these forces was in a bucco–lingual direction and the other in a linguo–buccal direction. Both forces had the same magnitude of 50 g.

These loading conditions were measured for the alveolar bone, the periodontal ligament and the root dental surface at four different radicular levels, and selected in an occluso–gingival direction. These had been established at: A, B, C, and D (Fig. 1).

Different nodal points were chosen at each level in order to register stress levels. These nodes were placed in a mesial, distal, labial and lingual position for each of these structures (Fig. 2).

This information was later organized graphically for each structure (tooth, ligament and bone) and for each radicular zone (labial, lingual, mesial and distal) relating the amount of load suffered in g/cm^2 with each of the occluso–gingival levels.

The load was described as being the three principal stresses (PS) that determine the general tensional state of a body, namely: σ_1, maximum principal stress; σ_2 intermediate principal stress and σ_3 minimal principal stress. In some cases, the occurrence of principal stresses could mask the tensional state of the body at a certain point. Thus in these cases it is easier to use only a single number, i.e. that of Von Mises stress: σ_e which describes the proximity of the end of the elastic behaviour at this point. Von Mises tensile stress was also measured at the same points as the three principal stresses. The equation used was:

$$\sigma_e=\sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}}$$

where σ_e represents the Von Mises equivalent stress and σ_1, σ_2 and σ_3 are the principal stresses.

The mechanical properties of the model were standardized using values obtained from previous studies (Tanne and Sakuda, 1983) (Table 1).

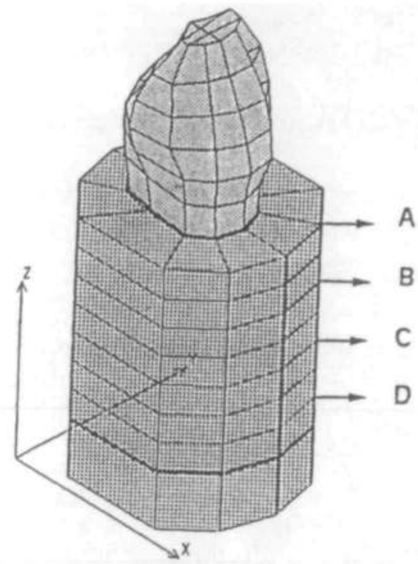

Figure 1 Oblique view of the three-dimensional finite element model of the inferior canine. The model comprises the tooth, periodontal ligament and alveolar bone. Occluso–gingival levels (A through D) where the principal stresses were determined.

Results

In Figures 3, 4, 5, for loading with a lingually directed 100 g horizontal force, the three principal stresses, are shown for only four points at the various occluso–gingival levels.

In the tooth, the greatest degree of stress appeared on the labial side, between levels B and C. On the lingual side the maximum degree

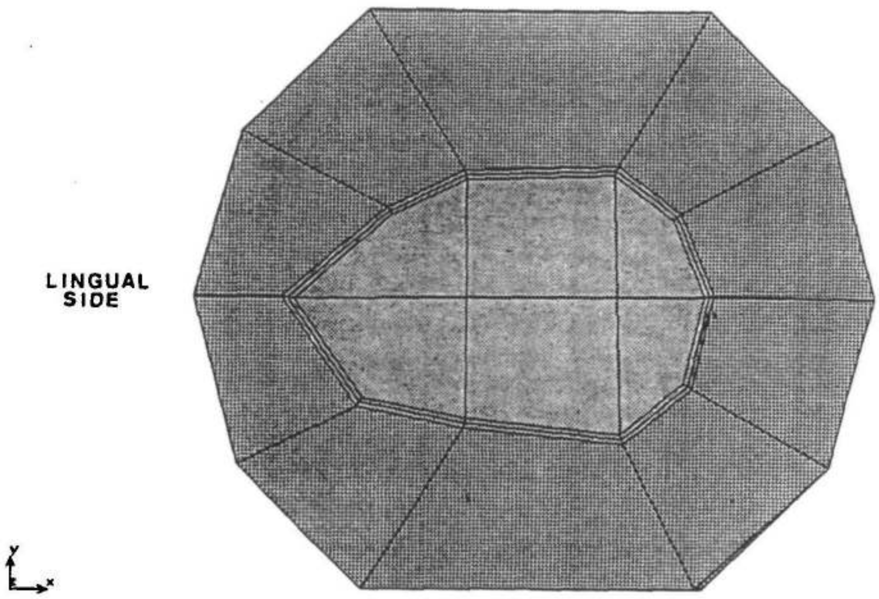

Figure 2 Horizontal points (mesial, distal, lingual and buccal) where the principal stresses were determined at each occluso–gingival level.

Table 1 Mechanical properties for the tooth, periodontal ligament and alveolar bone.

Material	Young's modulus (kg/mm²)	Poisson's ratio
Tooth	2.0×10^3	0.15
PDL	6.8×10^{-2}	0.49
Alveolar bone	1.4×10^3	0.15

of stress occurred between levels B and C and was determined by the minimum principal stress. These values were of a compressive nature on the lingual side and tensile on the labial side. The distal and mesial sides showed an almost symmetrical behaviour. The maximum, intermediate and minimum stresses of the periodontal ligament were very similar. Compressive values were found at level A on the lingual side and the distensive ones at the same level on the labial side. A zero level of stress was found between levels B and C. At the apical zone the values changed, being compressive on the labial side and distensive at the lingual side. A light distensive stress appeared at the mesial and distal zones, this being found at level C on both the lingual and labial sides. In the bone the maximum values of stress were registered at level A, where the lingual side was compressive and the labial side distensive.

For loading with a buccally directed crown couple of 100 g/mm., three principal stresses are shown for only four points at the various occluso–gingival levels (Figs. 6, 7, 8).

The maximum values of stress on the tooth were found at level A, these being compressive on the lingual side and distensive on the labial side. Something quite similar occurs when only one force acts, but the maximum degree of stress is seen towards the level of the crown. The periodontal ligament showed its highest level of stress at an apical level.

Zero value was nearer to A level when only a single force was applied, that is to say, the centre of rotation had moved towards a more occlusal position. The maximum level of stress in the bone was observed at level A, these recordings being found in a higher position than when a single force was applied. These are

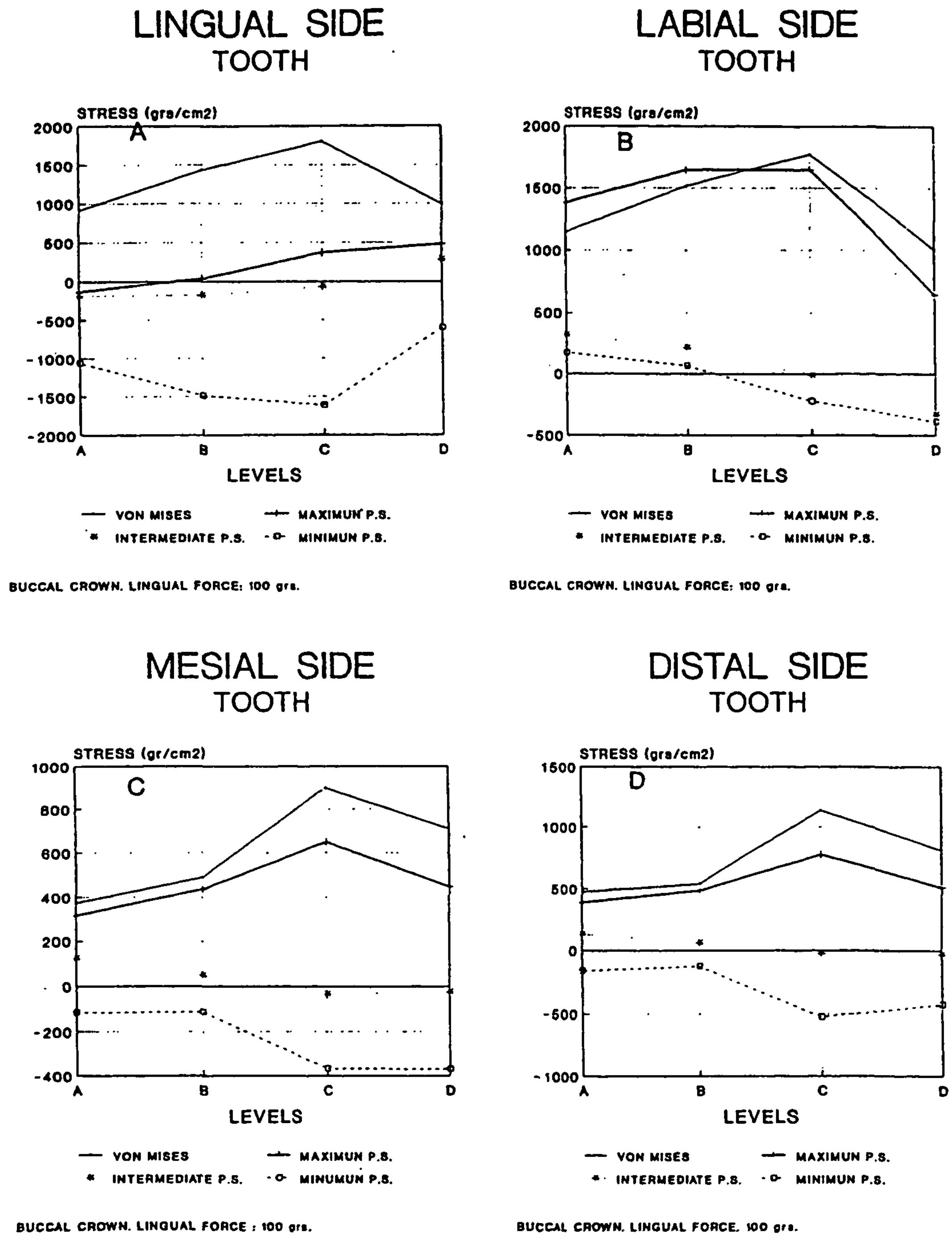

Figure 3 Stress distribution (g/cm^2) on the tooth in loading condition for a lingual force of 100 g. Three principal stresses (PS): (maximum, intermediate and minimum) and Von Mises stress are shown for four significant points (mesial, distal, lingual and buccal) and various occluso–gingival levels (A through D).

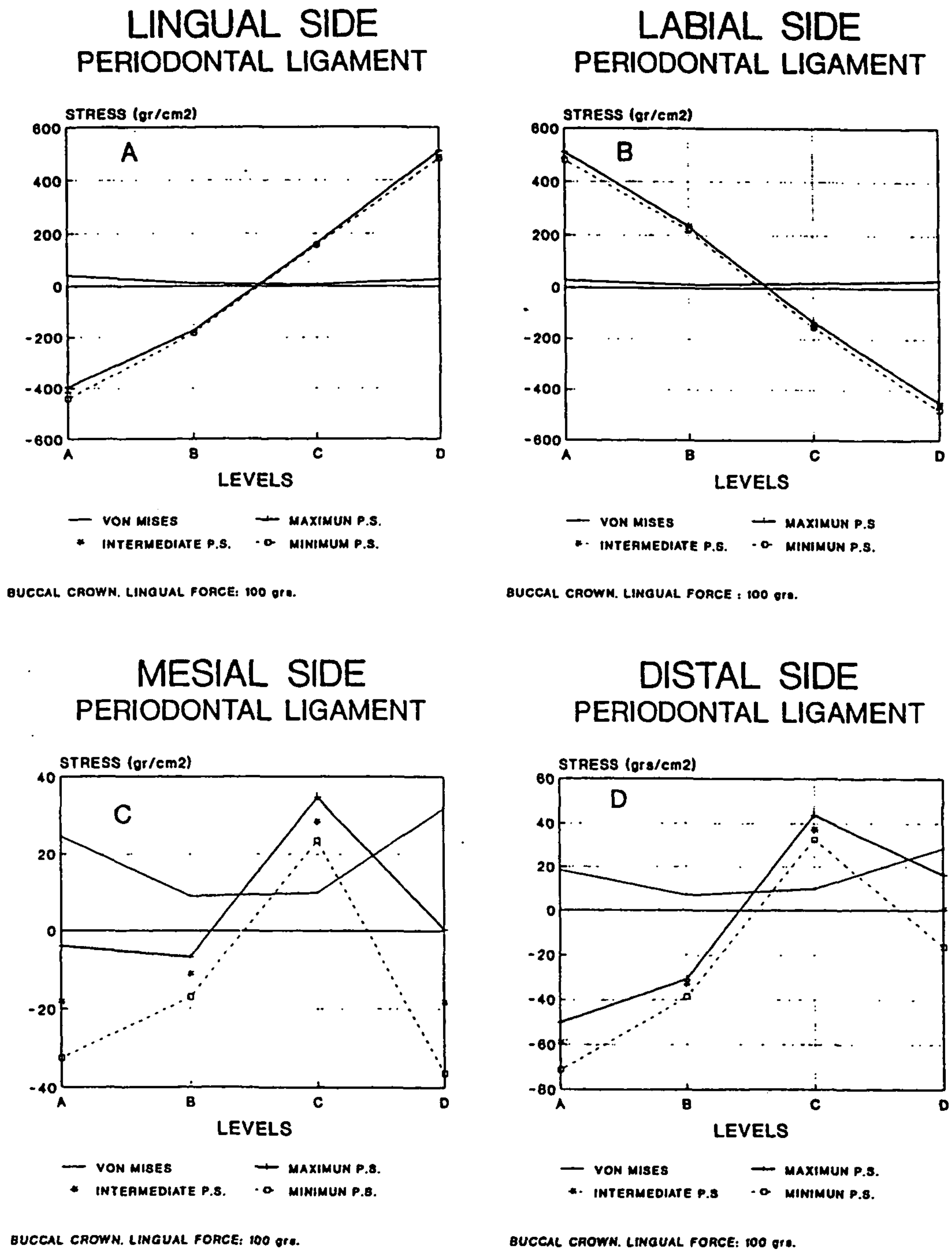

Figure 4 Stress distribution (g/cm^2) on the periodontal ligament in loading condition for a lingual force of 100 g. Three principal stresses (PS): (maximum, intermediate and minimum) and Von Mises stress are shown for four significant points (mesial, distal, lingual and buccal) and various occluso-gingival levels (A through D).

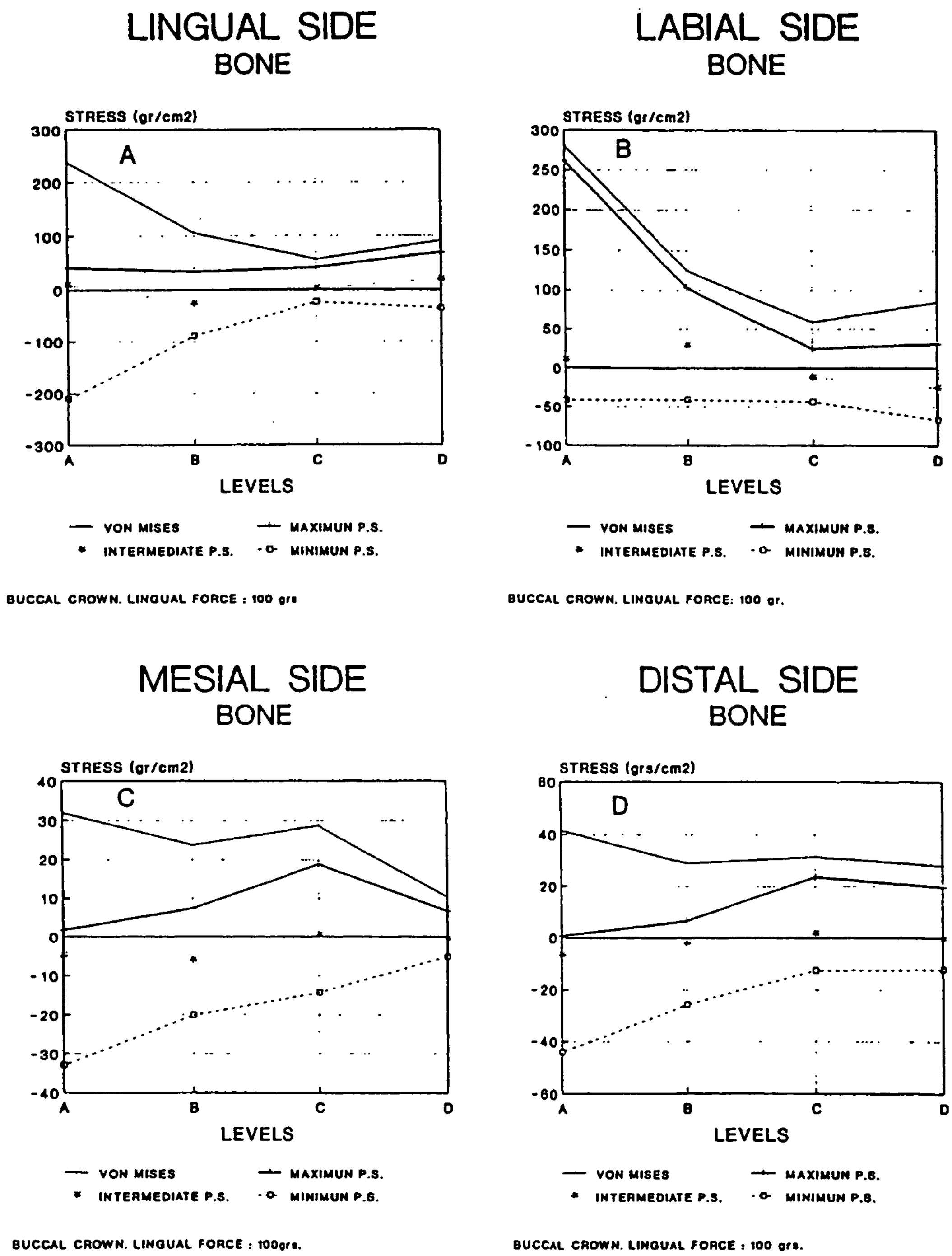

Figure 5 Stress distribution (g/cm^2) on the bone in loading condition for a lingual force of 100 g. Three principal stresses (PS): (maximum, intermediate and minimum) and Von Mises stress are shown for four significant points (mesial, distal, lingual and buccal) and various occluso–gingival levels (A through D).

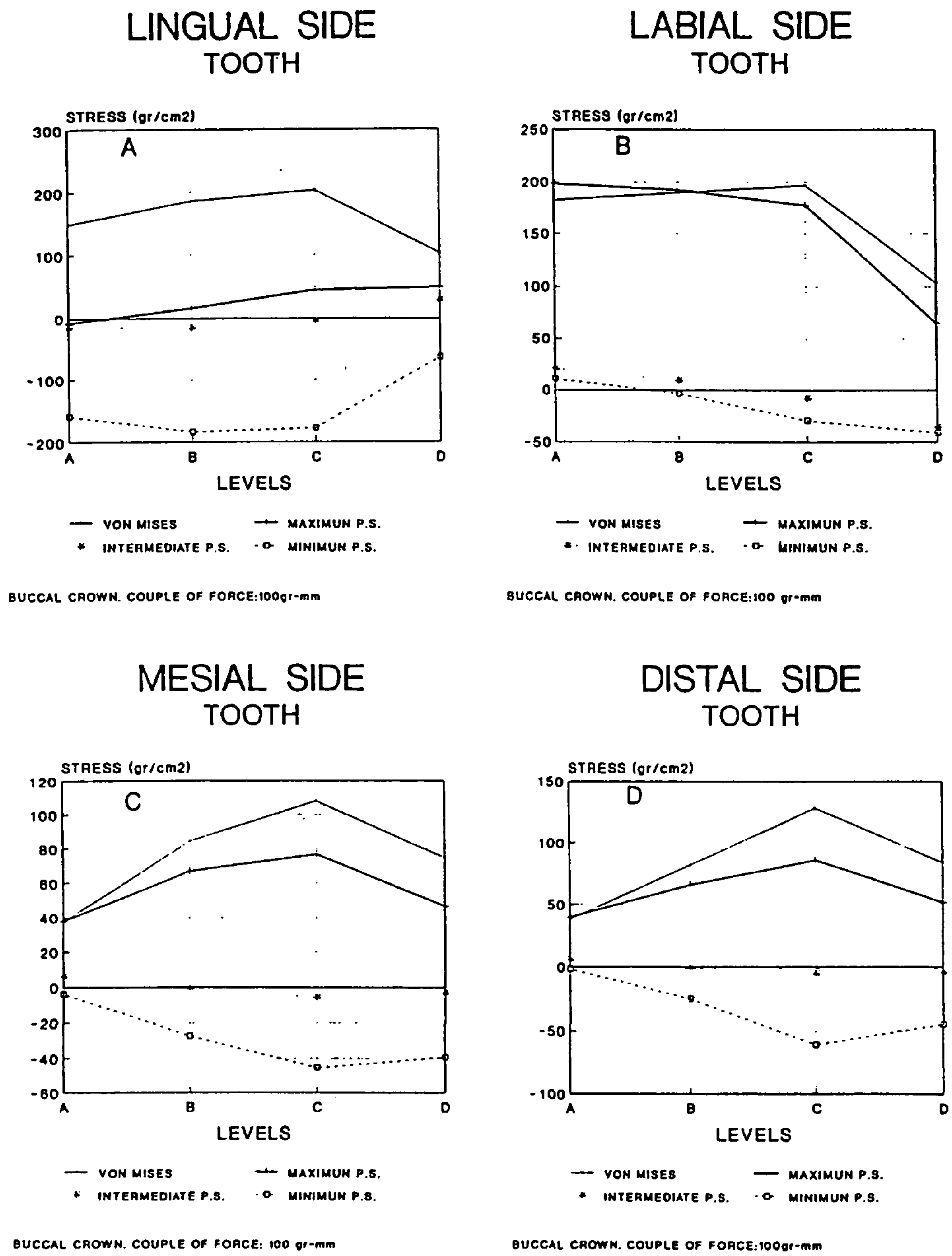

Figure 6 Stress distribution (g/cm^2) on the tooth in loading condition for a buccal crown couple of 100 g-mm. Three principal stresses (PS): (maximum, intermediate and minimum) and Von Mises stress are shown for four significant points (mesial, distal, lingual and buccal) and various occluso–gingival levels (A through D).

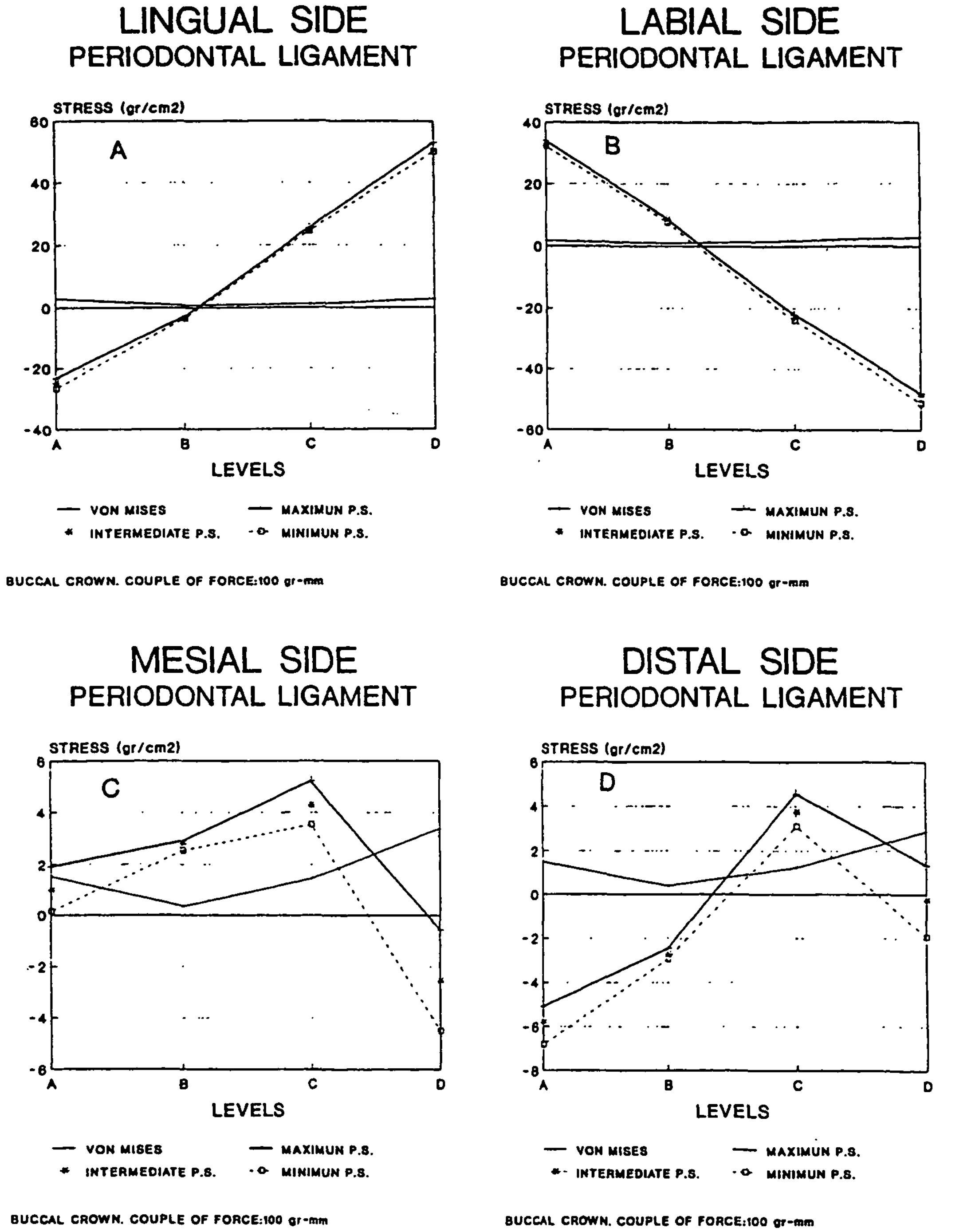

Figure 7 Stress distribution (g/cm^2) on the periodontal ligament in loading condition for a buccal crown couple of 100 g-mm. Three principal stresses (PS): (maximum, intermediate and minimum) and Von Mises stress are shown for four significant points (mesial, distal, lingual and buccal) and various occluso-gingival levels (A through D).

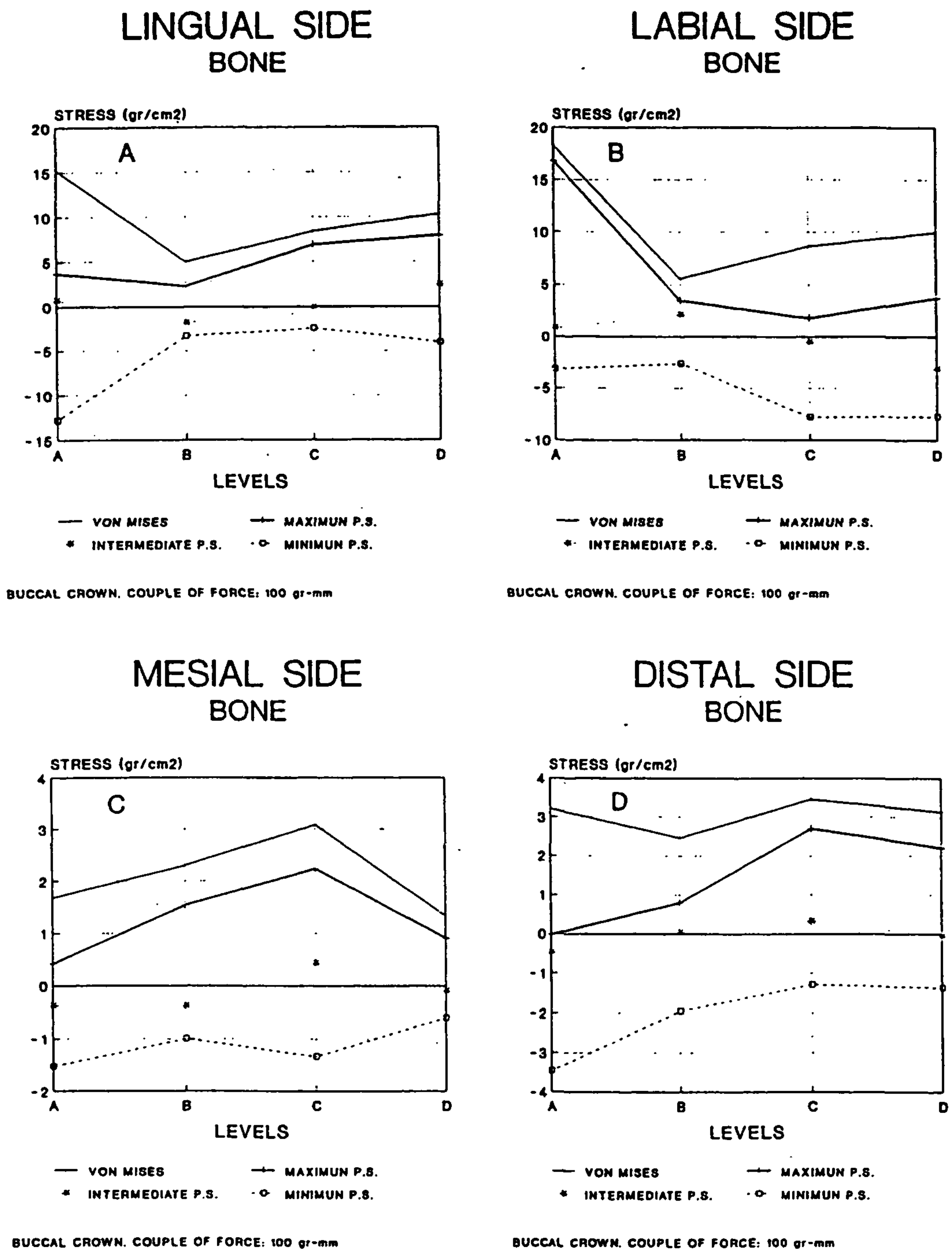

Figure 8 Stress distribution (g/cm^2) on the bone in loading condition for a buccal crown couple of 100 g-mm. Three principal stresses (PS): (maximum, intermediate and minimum) and Von Mises stress are shown for four significant points (mesial, distal, lingual and buccal) and various occluso–gingival levels (A through D).

compressive on the lingual side and distensive on the labial side.

Discussion

It has been demonstrated that the highest stresses were observed firstly on the root, secondly in the periodontal ligament and thirdly in the alveolar bone. These findings are due to the different mechanical properties of each structure: tooth, periodontal ligament and alveolar bone. Similar findings have been reported in other studies where the finite element method has been used (Tanne and Sakuda, 1983; Williams and Edmuson, 1984; Wilson *et al.*, 1991; McGuinness *et al.*, 1991). These studies are different from those mathematical models that have reached the conclusion that stress distribution was the same for every structure (Mulligan, 1979; Thurow, 1982; Smith and Burstone 1984; Burstone and Koenig, 1985). When a force or couple of forces are applied at a midcrown point, it can be observed how some zones of maximum stress are generated for the three structures. A zero stress level zone also exists among the previously described ones. The zones of maximum stress for both movements coincide with the dental apex and bony marginal crest. The zero stress zone is the same as the so-called rotation centre. In this study, this did not correspond to a particular point but to what is rather an unloaded radicular area around which the tooth could rotate. This rotation area will move towards level A when the load is a couple of forces producing torque movement.

These results coincide with some histological findings which show the hyalinization areas at levels A and D (Storey, 1955; Reitan, 1964, 1967). In the same way iatrogenic effects can be found whenever the forces used are not the correct ones such as: apical root resorption or irreversible resorption of the bony alveolar crest (Massler and Malone, 1954; Rygh, 1973, 1977). The same zones of maximum stress were found in other studies employing FEM techniques (Tanne and Sakuda, 1983; Williams and Edmuson, 1984; Wilson *et al.*, 1991; McGuinness *et al.*, 1991) and through the studies on physical-mathematical models (Mulligan, 1979; Thurow, 1982; Smith and Burstone, 1984; Burstone and Koenig, 1985). For the force values and their distribution on the structures, it can be said, that differences exist between the FEM models. We propose that this is due to different facts such as: the tooth chosen for study, the computer package and the number of elements used to design the model or Young's modulus and Poisson's ratio among others.

In the same way, this model assumes, as other authors have suggested (McGuinness *et al.*, 1991; Wilson *et al.*, 1991) that histological changes following application of a stress produced changes in the physical properties of the tissues, so that Young's modulus and Poisson's ratio would be different, and the model would change.

Finally, it can be concluded that this tridimensional model is a useful example to investigate the biomechanism of dental movement, keeping in mind that it is more valid as a qualitative study. On the other hand, it has served to show that the applied force is not equally distributed over the tooth, PDL and bone. In these types of movement, maximum tensional stresses are situated on the bony marginal crest and the dental apex, and the rotation centre is not a unique point, but a radicular area, situated between the B and C levels in our model.

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