A Study of the
Multiple Impulse Method of Tooth
Mobility Assessment

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Submitted by
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This thesis is dedicated to my wife Susan and my daughter Victoria.
Abstract

This study evaluates the multiple impulse method of tooth mobility assessment. For many years clinicians have sought a handheld means of evaluating tooth mobility for clinical use. This could provide data to aid in periodontal and restorative diagnosis and treatment planning and allow monitoring of the status of the supporting tissues of teeth and implants.

The Periotest device analyses the electronic signals produced by an accelerometer, mounted within a handpiece and attached to a percussion rod which is electromagnetically accelerated towards the tooth to produce a "moveability" value.

Bench and electronic testing evaluated the instrument signals and tooth displacement data. Initially this was carried out using an LVDT linked to an ultraviolet recorder and the data was collected from the teeth of anaesthetised Macaque monkeys. Ultimately a computerised recording system in conjunction with a non-contact displacement transducer were used to achieve this.

The factors affecting measurement were then analysed using the teeth in pig jaw models. The results are summarised as follows:

1. The percussion rod slows down as it travels away from the handpiece.
2. It is possible to control the position of the handpiece so that this deceleration is not a factor in measurement.
Abstract

3. Increasing the tooth mass affects signals and the Periotest values obtained. These changes are statistically significant.

4. Measured mobility values decreased as the application point was moved in an apical direction.

5. Significant changes in mobility values were produced by changing the angle of application in the horizontal and vertical plane by more than $10^\circ$ from normal for some of the test teeth.

6. The results of multiple impulse testing are, to some extent, comparable with traditional tooth mobility measurements.

7. When testing very loose teeth the system gives highly unpredictable results. This is explained by the method of analysis of the signals used by the microprocessor and could be modified to allow the instrument to function over a wider mobility range.

Based on the results of this work recommendations are made for the use and further development of this method.
The excellence of every art is its intensity, capable of making all disagreeables evaporate, from their being in close relationship with beauty and truth.

John Keats
List of figures

1. The Periotest instrument.

2. The Periotest in use.

3. Sectional diagram of the Periotest handpiece.

4. Histogram of Periotest values for a range of dental materials in order of decreasing elastic modulus.

5. Accelerometer signal from a high modulus specimen giving a Periotest value of -2.

6. Periotest signal from a low modulus specimen giving a Periotest value of 18.

7. Periotest value plotted against measured signal duration.

8. Periotest value plotted against calculated signal duration.

9. The modification of the trigger pulse.

10. The Sigavg parameter window set-up to capture data on 2 channels.
List of figures

11. Screen dump from Sigavg showing an example of the Periotest accelerometer signal.

12. Periotest signal showing slug retraction approximately 20 milliseconds after the primary peak.

13. Output voltage /time graphs for the unmodified slug driving signal and Periotest signal at 0 and 2.8 mm from the slug housing.

14. Periotest value plotted against measuring distance.

15. Distance/time graph for the Periotest slug.


17. Movement of the Periotest handpiece with and without a finger rest.

18. Handpiece movement over a two second period.

19. Simultaneous recording of handpiece position and Periotest signal.

20. Periotest value plotted against spring length of Voigt element model.

List of figures

22. Simultaneous recording of the tooth displacement and Periotest signal from a tooth mounted in rubber.

23. Simultaneous recordings of tooth displacement, Periotest signal; clock-on signal and clock-off signal.

24. Periotest signals for extracted teeth mounted in various materials.

25. Semistatic loading of a tooth in a pig jaw.

26. Displacement/time graph for a cheek tooth in a pig jaw during the sudden application and removal of a 400 gram load.

27. Histogram of Periotest values during bone removal from a tooth in a pig jaw.

28. A screen dump from Sigavg with voltage plotted against time.

29. Periotest value plotted against signal duration.

30. Signal amplitude plotted against signal duration.

31. The integral of the periotest signal plotted against signal duration.

32. Periotest value plotted against added mass for each of four test teeth.
List of figures

33. Signal duration plotted against added mass for each of four test teeth.

34. The effect of added mass on Periotest signals.

35. Signal amplitude plotted against added mass for each of four test teeth.

36. Mean Periotest values against distance from the cusp tip.

37. Mean Periotest value plotted against angle from the perpendicular varied in the horizontal plane.

38. Mean Periotest value plotted against angle varied in the vertical plane.

39. Non-contact transducer sensor.

40. Calibration rig made from a digital micrometer.

41. Example transducer calibration for the five levels of gain.

42. Example transducer calibration beyond the linear range of the transducer.

43. Experimental equipment for simultaneous signal capture.

44. Simultaneous tooth displacement and Periotest signals showing two bounces.
List of figures

of the Periotest slug on the tooth during one impact.

45. Simultaneous tooth displacement and Periotest signals showing oscillation of the tooth after impact.

46. The same data as figure 45 zoomed in to show the first 0.8 ms of the impact.

47. Simultaneous displacement and Periotest signals from a very mobile tooth.

48. The first impact in a series for a very mobile tooth.

49. The last impact in the same series for a very mobile tooth.

50. The displacements produced by the Periotest; 100 grams force and 200 grams force plotted against the Periotest value.

51. The displacements produced by the Periotest, 100 grams force and 200 grams force plotted against signal duration.

52. Displacement/time recording from a tooth of an anaesthetised macaque monkey.

53. The displacement produced by the Periotest plotted against Periotest value and signal duration.
List of figures

54. Simultaneous recording form the Periotest accelerometer and tooth displacement transducer; anaesthetised macaque monkey.

55. A comparison of accelerometer traces from healthy and Periodontally diseased teeth.

56. Peak force plotted against Periotest value.

57. Loading rate plotted against Periotest value.

58. Periotest value plotted against time after occlusal adjustment for five teeth.

59. Periotest value plotted against time for each pair of abutments for five bridges.

60. An example of Periotest value plotted against time during initial periodontal therapy.

61. Six point probing pocket charts from patient 1 taken at time 0 and 10 weeks later, before and after initial periodontal therapy.

62. Periotest values plotted against time for eight teeth during initial periodontal therapy.

63. Tooth displacement and Periotest signals from a human tooth.
List of tables.

1. Mean Periotest value and elastic modulus for various materials.
2. Mean Periotest value given by two instruments tested against seven surfaces.
3. Distance from the slug housing tabulated against mean time (ms), mean velocity so far and mean velocity over the previous 0.2mm.
4. Load (grams) applied with a corex gauge tabulated against displacement produced (microns).
5. The effects of bone removal on mean Periotest value and standard deviation of Periotest values.
6. Periotest value tabulated against means of contact time (ms), signal amplitude (volts) and signal area (vsec).
7. The effects of mass addition on Periotest value.
8. Bonferroni groupings for significant differences between Periotest means for tooth M1.
9. Bonferroni groupings for significant differences between Periotest means for tooth M2.
10. Bonferroni groupings for significant differences between Periotest means for tooth M3.
11. Bonferroni groupings for significant differences between Periotest means for tooth M4.
12. Significance table for Wilcoxon T-test comparison of Periotest value means at
no mass addition with pooled data from all levels of mass addition.

13. Mean signal duration (ms) and signal amplitude (volts) for each of the four teeth for each level of mass addition.

14. Bonferroni groupings for significant differences between signal duration means for tooth M1.

15. Bonferroni groupings for significant differences between signal duration means for tooth M2.

16. Bonferroni groupings for significant differences between signal duration means for tooth M3.

17. Bonferroni groupings for significant differences between signal duration means for tooth M4.

18. Bonferroni groupings for significant differences between signal amplitude duration means for tooth M1.


20. Bonferroni groupings for significant differences between signal amplitude means for tooth M3.


22. Means and standard deviations of Periotest values for each tooth at each distance from the cusp tip.

23. Bonferroni groupings for the significance of differences between Periotest means for each application point for tooth M1.

24. Bonferroni groupings for the significance of differences between Periotest
List of tables

25. Bonferroni groupings for the significance of differences between Periotest means for each application point for tooth M2.

26. Bonferroni groupings for the significance of differences between Periotest means for each application point for tooth M3.

27. Bonferroni groupings for the significance of differences between Periotest means for each application point for tooth M4.

28. Bonferroni groupings for the significance of differences between Periotest means for each application point for tooth M5.

29. Means and standard deviations of Periotest values for each tooth for each of the four angulations.

30. Bonferroni groupings for the significance of differences between Periotest means at each angle of application for tooth M1.

31. Bonferroni groupings for the significance of differences between Periotest means at each angle of application for tooth M2.

32. Bonferroni groupings for the significance of differences between Periotest means at each angle of application for tooth M3.

33. Bonferroni groupings for the significance of differences between Periotest means at each angle of application for tooth M4.

34. Bonferroni groupings for the significance of differences between Periotest means at each angle of application for tooth M5.

35. Mean Periotest value for each tooth for each of the seven angles tested.

36. Bonferroni groupings for the significance of differences between Periotest means for each of the angulations for tooth M1.

37. Bonferroni groupings for the significance of differences between Periotest means for each of the angulations for tooth M2.
List of tables

37. Bonferroni groupings for the significance of differences between Periotest means for each of the angulations for tooth M3.

38. Bonferroni groupings for the significance of differences between Periotest means for each of the angulations for tooth M4.

39. Bonferroni groupings for the significance of differences between Periotest means for each of the angulations for tooth M5.

40. Example calibration with displacements tabulated against the output voltages for the five gain levels.

41. Periotest values and the displacements produced by 100 grams force and 200 grams force for each of the five teeth.

42. Periotest value tabulated against displacement produced (microns) and signal duration (ms).

43. The Miller tooth mobility scale with the corresponding Periotest ranges.

44. Periotest values tabulated against the corresponding calculated values of signal duration (ms); peak force (Newtons) and loading rate (Newtons/sec).
CONTENTS

Abstract 3

List of Figures 6

List of tables 12

Chapter 1  Introduction, Aims & Evolution. 20

Section
  1.  Introduction. 20
  2.  Aims of study. 22
  3.  Evolution of the study. 23

Chapter 2  Indices and instrumentation for the measurement of
            the tooth support system, literature review. 24

Section
  1.  Clinical mobility indices. 24
  2.  Mechanical measurement. 25
  3.  Electronic measurement. 27

Chapter 3  The nature of tooth mobility, literature review. 32

Section
  1.  Early models of the mechanical behaviour of
      the periodontium. 32
  2.  The response to horizontal loads. 34
  3.  The response to axial intrusive loads. 40
  4.  The response to axial extrusive loads. 47
5. Conclusions. 48

Chapter 4 Review of clinical studies of tooth mobility. 51

Section
1. Normal tooth mobility. 51
2. Bridgework. 52
3. Splinting. 54
4. Occlusion and occlusal trauma. 56
5. Periodontal treatment. 58
6. Conclusions. 61

Chapter 5 The Periotest. 62

Section
1. The Periotest and its use. 62
2. Chronological review of the literature relating to the Periotest. 65

Chapter 6 Preliminary evaluation of the Periotest. 71

Section
1. Bench testing. 71
2. Estimation of slug velocity. 73
3. Comparison of two instruments. 74
4. Electronic testing. 75

Chapter 7 Computerised recording system. 79

Section
1. The system 79
2. Variation in slug velocity with measuring distance. 85
3. Handpiece movement. 91

17
## Contents

### Chapter 8 Modelling.

Section

1. Mechanical.
   1. Voigt element model. 96
   2. Extracted tooth mounted in rubber. 98
   3. Extracted teeth mounted in various materials. 102
2. Cadaveric.
   1. Pig jaw model. 104
3. Mathematical 106

### Chapter 9 Pig jaw model.

Section

1. Post mortem changes in tooth mobility, literature review. 107
2. Pig jaw model experiments.
   1. Incremental bone removal. 110
3. Factors affecting the Periotest signal.
   1. Tooth mass. 118
   2. Enamel modulus. 135
   3. Application point. 135
   4. Angle of application varied in the horizontal plane. 140
   5. Angle of application varied in the vertical plane. 145
4. Displacement measurement.
   1. Comparison with traditional tooth mobility measurements. 157

### Chapter 10 Animal model studies.

Section

1. Monkey studies. 169
2. Minipig studies. 178
## Contents

Chapter 12. Conclusions and Discussion.  
Chapter 13. The value of the Periotest as a tool & The Future.  
Chapter 15. Bibliography.  
Chapter 16. Appendices  

### Appendix 1: Calculation of slug velocity.  
### Appendix 2: Calculation of peak force and loading rate.  
### Appendix 3: Human clinical studies.  
#### 1. Occlusal adjustment by selective grinding.  
#### 2. Provisional bridgework.  
#### 3. Initial periodontal therapy.  
#### 4. Illustrative human data.  

Acknowledgements.
Corrigenda

Page 46. Line 18. "Embury" should read "Embery".
Page 63. Line 1. "mm" should read "centimetres".
Page 92. Line 11. "300 microns (0.3 mm)" should read "200 microns (0.2 mm)".
Page 93. Figure 17. The final figure on the abscissae of both graphs should read 20.
Page 96. Line 15. "series" should read "parallel".
Page 104. Line 5. "immediatly" should read "immediately"
Page 109. Line 6. "intruded" should read "extruded".
Page 113. Figure 28. In the caption "tims" should read "time".
Page 119. Figure 32. The abscissa units "Gms" should read "Grams".
Page 124. Table 12. Tooth notations have been transposed; for "M1" read "M4", for "M2" read "M3", for "M3" read "M2" and for "M4" read "M1"
Page 133. Line 1. "with mass" should read "with no mass".
Page 157. Line 15. "diameter" should read "radius".
Page 174. Line 21. "phenomena" should read phenomenon".
Page 180. Table 43. "+19- +35" should read "+21- +35".
Page 185. Line 15. "centimetres" should read "millimetres".
Page 186. Line 13. "periodotium" should read "periodontium".
Page 187. Line 11. "developement" should read "development".
Page 196. Line 15. "EMBURY" should read "EMBERY".
Page 208. Line 11. "STEPPLER" should read "STEPPELER".
Line 24. "7:14-150" should read "7:144-150".
Page 210. The reference "Wills DJ and Manderson RD (1977)" should be deleted from the bibliography.
Page 228. Figure 6. In the caption "lower second premolar" should read "lower left second molar".
Introduction

1.1 Introduction

For many years clinicians have been seeking a method of assessing the mechanical status of the tooth supporting tissues that is suitable for routine use. Periodontists and restorative dentists measure pocket probing depth and recession and take intraoral radiographs in an attempt to quantify attachment loss. Tooth mobility data would provide more pertinent information on the state of the attachment apparatus.

Clinical assessment of tooth mobility currently uses the Miller index which involves a visual estimation of the amplitude of horizontal tooth movement produced by a pair of manually applied mirror handles. This method has a zero to three scale with zero representing firm teeth and three representing extremely loose teeth. This index has poor reproducibility and although this can be improved with training the resolution remains poor.

Determination of changes in tooth mobility is not a realistic possibility using the Miller scale and thus it is not possible to assess the functional significance of the progression of attachment loss caused by periodontal disease or the mechanical improvements produced by regenerative periodontal therapy. It is also not possible to monitor periodontal healing after acute trauma.

It is frequently necessary to assess the suitability of teeth as bridge abutments. It is
difficult to determine if a tooth is capable of supporting additional teeth if it is not possible to measure how well it is supported itself.

The introduction of implant systems has led to the need for a method to evaluate the mechanical status of tooth root analogues. A non-invasive test of osseointegrated fixtures would allow for long term routine measurement of fixture stability.

At the planning stage the initial aim of this work was to design, build and test a clinical instrument for tooth mobility measurement suitable for routine clinical use. During the early stages of reviewing the literature on tooth support physiology and measurement a commercially produced instrument came to light. This instrument, the Periotest*, functions quite unlike anything previously described and, on initial examination, appeared to fulfil some of the criteria necessary for such an instrument.

Despite discussions with the manufacturer and a visit to the University where the Periotest was conceived very little technical information was available.

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*Siemens, Sierex dental division, Siemens House, Walsall
1.2 Aims of this study

The general aims of this study are to:-

1. Provide an in-depth explanation of the function of the Periotest.

2. Evaluate the factors affecting Periotest measurements.

3. Use the Periotest system to improve understanding of tooth support physiology.

4. To develop the use of a computer based system for recording and measuring tooth movement.

5. Make recommendations for the further development and improvement of the Periotest instrument.
1.3 Evolution of the study

The experimental sections of this study are presented in logical order starting with bench testing followed in sequence by model systems, live animal work and human studies. This does not however, reflect the actual chronology of events. The first experiments after basic bench testing were the live animal studies using anaesthetised Macaque monkeys.

Throughout the period of study understanding of the function of the Periotest system was gradually improving as new information came to light. At the same time the experimental equipment was evolving. The monkey studies used an LVDT linked to an ultraviolet recorder to record tooth movement and a recording oscilloscope with a pen recorder to produce output of the Periotest accelerometer signals. Bench tests and experiments on model systems performed at a later time used a computerised signal capture system to record data from a non-contact displacement transducer and the Periotest accelerometer.

Following development of the computerised system utilising the pig jaw model it would have been useful to be able to return to the live animal model but this was not possible.
Chapter 2

Indices and instrumentation for the measurement of tooth support

2.1 Clinical mobility indices

O'Leary (1974) states that Miller (1938) is acknowledged to have made the first attempt to classify the mobility of teeth. In this method the tooth is held firmly between two instruments and moved back and forth. Mobility is scored from 0 to 3 with 0 representing no distinguishable movement. A score of 1 indicates barely distinguishable movement; a score of 2 is used for movement up to 1 mm in any direction and 3 for movement of more than 1 mm. Teeth which may be rotated or depressed in their sockets are also given a score of 3.

Laster et al (1975) compared the clinical mobility assessments of several periodontists and found them to be effective at ranking mobilities within individual patients. Comparison from patient to patient showed a lesser degree of consistency. Laster et al also reviewed modifications of the clinical scale recommended by Lovdal et al (1959), Glickman (1972), Grant et al (1972), Prichard (1972) and Wasserman (1973).

Selipsky and Erickson (1975) determined the reproducibility of clinical tooth mobility
assessments utilising the Miller scale and compared these with objective evaluations using an O’Leary-Rudd periodontometer (Described later). They found that interoperator agreement of subjective assessment was good but bore no relationship to the defined scale of movement. Operators tended to score teeth based on the ease and rate of movement rather than the amount of movement.

Stoller and Laudenbach (1980) reviewed clinical mobility indices and tested a model containing five teeth with mobilities objectively set using an O’Leary-Rudd periodontometer. This model was used to aid clinical scoring by direct comparison and the authors claim that a relatively untrained examiner may be capable of quickly measuring tooth mobility with a maximum error of 0.1 mm.

2.2 Mechanical measurement

In a review of methods for measuring tooth mobility Yankell (1988) describes early attempts to quantify tooth mobility by Elbrecht (1939) and Werner (1942). The equipment used by Elbrecht consisted of a chin/forehead support and a dial indicator attached to a tripod in front of the patient. Movement was induced by digital pressure. Forces could not be measured and only movements greater than 0.75 mm could be measured. The equipment used by Werner consisted of a scale attached to a rod held on the front teeth. Forces of 700 grams were applied but displacements of
less than 0.25 mm could not be measured.

Muhlemann (1951, 1954a) developed two instruments for assessing tooth mobility; the macro and micro periodontometers. These consisted of a dial gauge to measure movement and a handheld spring dynamometer to apply the load. The macroperiodontometer utilised an impression tray for fixation and could only be used on anterior teeth. The microperiodontometer used a rubber dam clamp for fixation and was designed for use on posterior teeth. These instruments had the disadvantage of requiring custom made fixation for each tooth.

O'Leary and Rudd (1963) described an instrument which used the same principles and was fundamentally a refinement of the instrument described by Muhlemann. A jointed carrying vehicle was cemented to one side of an arch and a dial gauge to measure displacement was set up against the chosen test tooth. Forces were applied with a handheld spring dynamometer.

The instruments of Muhlemann and O'Leary and Rudd have been widely used for research purposes and these studies have significantly added to knowledge of the tooth support system. Subsequent research has shown that measurements of tooth displacement are sensitive to changes in loading rate and to the magnitudes of the applied loads. Accurate control of these factors is not possible using the handheld load applicators employed by Muhlemann and O'Leary and Rudd. In addition to this shortcoming no permanent record of tooth displacement could be made.
2.3  Electronic measurement

Displacement transducers

Picton (1957) reported on the use of resistance wire strain gauges to measure the vertical movements of teeth under pressure from the opposing arch. Resistance changes in the strain gauges were measured on a Wheatstone bridge circuit and calibrated extraorally using the eyepiece micrometer of a moving stage microscope.

This apparatus was developed (1962a) such that resistance changes were detected by a mirror galvanometer or recorded by an oscillograph. Applied load was measured using strain gauges in the load application rod. Thus a true dynamic record of displacement and load against time was made possible. This was output to a pen recorder. This apparatus had the advantage of accuracy but the disadvantage of requiring customised clutches for each tooth to be measured.

Parfitt (1960) described an instrument to measure axial mobility using inductive transducers to measure displacement and applied load. The displacement transducer was calibrated using a micrometer and Parfitt claimed an accuracy of 0.001 mm± 7%.

Parfitt (1961) adapted this apparatus to measure horizontal tooth movement.

Korber and Korber (1967) and Korber (1970, 1971) reported on the use of an inductive transducer to measure displacement. This functions using the principle of
Indices and instrumentation

eddy currents set up in a 3mm diameter magnetic disc cemented to the test tooth. This non-contact measuring method has the advantage of having no effect on that which is being measured. This equipment was used to examine many loading regimes including the impulse loading caused by dropping a glass bead onto a tooth.

Eddy current transducers were subsequently used by Bazirgan and Bates (1986) to measure the displacement of partial denture abutments.

deBoer (1987) used non-contact transducers set up in three planes to measure tooth displacement to provide data for a highly complex mathematical analysis of tooth dynamics.

Lear and Mackay (1972) and Lear et al (1972, 1974) reported on methods of generating force waveforms to produce accurately controlled tooth loading. Displacement measurement was achieved using a linear variable displacement transducer with a claimed resolution of 0.25 microns. This equipment was used to measure threshold levels of force required to move human teeth.

Matthews and Berkovitz (1972) and Searle et al (1973) used variable capacitance transducers in which the capacitance between two metal surfaces varies as the separation between them varies. Variable capacitance transducers were subsequently used by Matthews and Berkovitz (1972) and Moxham (1779a, 1979b) to study the eruption of rabbit incisors. Moxham and Berkovitz (1979, 1981 and 1984) also used them to study the effects of axially directed extrusive loads.
Persson and Svensson (1980a) developed a system for examining tooth movements. Loads were applied using a rod driven by compressed air and monitored using strain gauges. Displacement was measured using a linear variable differential transformer. This system has the disadvantages of requiring customised clutches and producing a variable loading rate.

Piezoelectric transducers.

Piezoelectricity is produced by some crystals when subjected to mechanical stress. An electric charge occurs across opposite faces due to displacement of ions within the crystal. This effect is used in accelerometers, the signal from which is proportional to acceleration. Velocity and displacement may also be derived.

Korber (1963) used a piezoelectric crystal in the root canal of an incisor tooth in vivo to examine the bending of the tooth under load.

Manley et al (1964) described a single impulse method of assessing tooth mobility. A spring driven mallet containing a piezoelectric accelerometer was used to impact gold strips of varying stiffness. Stiffer objects produced greater deceleration and less time for completion of the first half of the cycle. The system was tested on two subjects having clinical mobilities up to 3. "Yield ratios" were calculated by dividing the duration of the first half of the cycle by maximum deceleration. Yield ratios of less than 2 were obtained for mobilities of 0-1; 8-11 for mobilities of 1-2; and 14-30 for mobilities of 2-3. For mobilities over 3 the yield ratio decreased to below 10. The
Authors conclude that this instrument shows promise of offering a quantitative measure of lesser degrees of mobility.

Piezoelectric accelerometers have also been used by Noyes et al (1968), Noyes and Solt (1972) and Inoue (1977).

Aars and Linden (1982) used the ultrasonic transmit time between two piezoelectric crystals to monitor the position of the canine tooth of a cat.

Other attempts to quantify tooth movement

Manley et al (1951) described an instrument to measure the amplitude of vibration induced in a test tooth by a frequency oscillator at 100 to 10,000 Hz. This system to test the hypothesis that tooth mobility might be measured from the amount of vibration at a particular frequency was tested on an in vitro model and human subjects. A correlation was found between amplitude of induced movement and clinical mobility measurements. This was only true if teeth were separated into type groups. Molars gave lower readings than canines and premolars which gave lower readings than lower incisors. Presumably the results produced by this method are highly dependant on the tooth mass.

Kurashima (1965) used vibratory forces on human teeth over a range of 180 to 7000 Hz.
Noyes et al (1968) used sinusoidal forces over a frequency range of 60 to 5000 Hz to measure the mechanical input impedance of teeth in models and two human teeth.

The results of the vibratory or sinusoidal force methods described above are highly dependant on tooth mass and are thus of limited value.

The response of teeth to torsional loading was studied by Daly et al (1974) using extremely complex apparatus and techniques including a stereoscopic x-ray method of locating the central axis of the test tooth. The results are difficult to interpret or compare with other work and thus add little to knowledge of tooth support physiology.

Complex optical methods of tooth displacement measurement have been described by Wedental and Bjelkhagen (1974 a, b, c, d), Burstone et al (1978), Ryden et al (1974, 1975, 1979, 1982) and Liljeborg et al (1985). These studies have provided little useful data.

Browning et al (1987) used stereophotogrammetry to measure the displacement of partial denture abutments. There is little to commend this method.

For further information on this subject refer to the major reviews of Moxham and Berkovitz (1982) and Picton (1990).
Chapter 3

The nature of tooth mobility

3.1 Early models of the mechanical behaviour of the periodontium

Synge (1933a) proposed a two dimensional model which assumed the periodontal ligament to be incompressible and bounded by rigid bone and tooth. This wedge model was extended to three dimensions on publication of the cone model (Synge 1933b).

Boyle (1938) hypothesised that teeth are designed such that occlusal forces are chiefly dissipated in the coronal part of the periodontium with the apical portion subjected to "relatively minute forces". The author stated that the first force of occlusion is exerted as hydraulic pressure on the walls of the alveolus and that subsequent escape of fluid allows gradual extension of the periodontal fibres such that the full force of the occlusion is ultimately transmitted as tension to the alveolar bone.

Gabel (1956) extended the theories of Synge (1933a and 1933b) to include the function of the periodontal ligament fibres which were thought to act as a mattress in zones of compression, such that periodontal ligament fibres tangential to the applied load become involved in resisting the load. Gabel stated that movement of the root away from the opposite alveolar wall would produce a subatmospheric pressure
The Nature of tooth mobility

resulting in the adjacent bone being drawn towards the tooth rather than being pulled by tension in the fibres.

Subsequent to these hypotheses several mechanisms have been suggested as being contributory to resisting displacement of a tooth when force is applied to it. These are:

1. Tension.

2. Compression.

3. Hydrodynamic damping.

4. Viscoelasticity.

5. Thixotropy.

Evaluation of theories of tooth support is best done by examination of the experimental data.
3.2 Response to horizontal loads

Muhlemann (1951) loaded teeth with a range of forces from 100 to 1500 grams force. The relationship between load and displacement was not linear but in three phases; initial, intermediate and terminal. The resistance to movement increased from phase to phase but is seen to be linear within each phase. Thus in the intermediate phase the load/displacement relationship is linear between 100 grams and 1500 grams force. Muhlemann realised that in reality the apparently separate phases are a function of discontinuous measurement.

Muhlemann (1954a) made 2000 tooth mobility measurements on anaesthetised Rhesus monkeys to produce tooth mobility curves from 50 to 500 gram loads. The experiment showed that initial tooth mobility was not purely related to the width of the periodontal ligament.

Muhlemann (1954b) found that removal of interdental contact points led to an increase of tooth mobility of 0.05mm and that repeated measurements also caused an increase of 0.05 mm [500 grams force]. The increase caused by repeated measurement was referred to as "activated tooth mobility". Recovery from this activated state occurred within half an hour.

Muhlemann (1954c) measured the displacement at two points on the crowns of teeth to determine the centre of rotation. The centre of rotation was found to move apically with increasing force.

Measurements of movement of the alveolar bone crest were made while applying
The Nature of tooth mobility

semistatic horizontal loads to the tooth. In young monkeys alveolar movement began at forces above 100 grams. The author concluded that initial tooth mobility represented the changing intraalveolar orientation of the periodontal ligament fibres. During the secondary phase of tooth mobility there is distortion of the entire periodontium with compression and tension of the tissues. It is important to stress that the combination of a measuring method with low sensitivity and the use of semistatic loading gives the false impression of two clear phases of tooth mobility.

Parfitt (1961) measured horizontal tooth movement and found that movement was proportional to the log of the force for loads from 10 grams to 1000 grams.

Continuous displacement/time recordings were made from a central incisor tooth during eating and clenching. Peak displacements of 0.05 mm and 0.04 mm were recorded for eating and clenching corresponding to force levels of approximately one kilogram and 500 grams respectively.

Picton (1964b) studied the recovery of teeth on removal of horizontal loads of 10 Newtons applied at rates of 10 and 60 per minute. Recovery was found to be in two phases with an initially fast return towards the starting position. This was followed by a second phase during which the rate of recovery gradually decreased.

Using the time interval between thrusts gleaned from a comparable group of subjects it was concluded that teeth habitually occupy a tilted position during chewing because recovery between thrusts is incomplete.

Picton (1965) examined the role played by the socket in tooth support by measuring
The Nature of tooth mobility

The displacement of the alveolar crest during loading of the teeth of adult cynomologous (sic) monkeys. Displacement of the alveolar bone was frequently seen at or below 50 grams force. The mean displacement of the labial plate was greater than for the lingual plate but there were no differences between displacement under compression and tension for either plate. The character of the records indicated linear displacement and recoil of the socket under compression or tension.

On the basis of these results it is concluded that the initial fast phase of recovery on removal of a load is due to elastic recoil of the socket. The final phase is probably due to the gradual return of fluid to the membrane.

Muhlemann et al (1965) recorded the movements of teeth over periods of approximately 15 minutes when subjected to constant loads of 500 grams. They reported continued gradual displacement after the initial displacement which they referred to as "flow". Total buccal and lingual mobility at 500 grams force was always greater after a sustained period of loading.

Picton and Davies (1967) measured the displacement of the root and overlying alveolar bone of 15 anterior teeth of 4 adult Macaca irus monkeys. Two phases of root movement were usually seen. Bone movement was in the same direction as the force when measured above the axis of rotation and in the opposite direction when measured below the axis of rotation. This suggests that both compression and tension of tissues are involved in resisting horizontal loads. The axis of rotation was found to move in an axial direction as the force levels increased. This is in agreement with the findings of Muhlemann (1954c).
The Nature of tooth mobility

Picton (1967) measured the mobility of upper incisors and canines of 4 adult Macaca irus monkeys before and after cutting the mesial and distal gingival and transseptal periodontal fibres. Significant increases in displacement were produced by the trauma when applying labially directed loads but not palatally directed loads. It is clear from this that the mechanical properties of the periodontium are not homogenous.

Christiansen and Burstone (1969) studied the centres of rotation of teeth at various loads. Their results showed that the displacement/load relationship is parabolic up to approximately 150 grams force and linear from 150 to 700 grams force. Movements of the axes of rotation with increasing load were generally in an apical direction but frequently complex. This is in agreement with the results of Muhlemann (1954c) and Picton and Davies (1967).

Korber and Korber (1967) and Korber (1970 and 1971) used non-contact displacement transducers to demonstrate periodontal pulsation and to record the movements of teeth loaded with a variety of impulse loads. The reaction to a "needle shaped" impulse produced by dropping a glass bead onto a tooth is of particular interest as the impulse load must be similar to the load delivered by the Periotest. This impulse produced oscillation either side of the rest position followed by a slower recovery from the initial direction of displacement. Utilising a piezoelectric transducer within the tooth they demonstrated that at very high loading rates of this type considerable bending of the tooth occurs. Unfortunately no displacement/time data or details of the glass bead mass or velocity are given to allow for comparison with the Periotest.
Picton and Slatter (1972) measured horizontal tooth mobility before and after severing mesial or distal periodontal ligament fibres to the bone crest and after severing the coronal one third. Significant increases in mobility were produced following disruption of the gingival fibres only on the side of compression. Extending the trauma into the periodontal ligament resulted in a small additional increase in mean mobility on compression and tension but neither increase was significant.

It would be interesting to compare these results with the effects of cutting buccal and lingual periodontal fibres as these are parallel with rather than at right angles to the applied load.

The patterns of tooth displacement during simulated chewing were examined by Behrend (1974). Both horizontal and vertical tooth movements were recorded for one human canine and biting forces of 2 to 3 kilograms were measured but not simultaneously with the displacement measurement. Horizontal tooth movement of 30 to 60 microns and vertical movement of 10 microns were produced and this is consistent with rotation of approximately 15° about an axis in the apical third of the root. Recovery was in two phases and restoration of position was completed in one to one and a half minutes. This finding is in agreement with the work of Picton (1962b) which suggests that teeth remain displaced during function.

The same techniques were used again (Behrend 1978) to make over 250 recordings from 6 subjects however no useful information was produced.

Gillespie et al (1979) measured tooth mobility before and after cutting the supracrestal periodontal fibres of three groups of 20 human teeth with minimal, moderate and
severe bone loss. The minimal bone loss group demonstrated no significant difference between preincision and postincision recordings, however, moderate and severe bone loss groups demonstrated significant differences between preincision and postincision measurements.

Other factors affecting horizontal tooth mobility.

O'Leary et al (1967) reported that chewing caused a reduction in tooth mobility. This is presumed to be because the teeth are depressed in their sockets and is in contrast to Muhlemanns finding of "activated tooth mobility" where repeated horizontal loading led to increased tooth mobility, presumably caused by extrusion of the teeth from their sockets.

Rateitschak (1967) reported increases in tooth mobility in pregnancy while Friedman (1972) reported no changes in mobility during the female hormonal cycle or with the use of anovulatory drugs.

Son et al (1971) reported no changes in tooth mobility during a 17 day experimental gingivitis study in humans while Bernimoulin and Curilovic (1977) reported no correlation between tooth mobility and gingival recession.
3.3 Response to axial loads

Parfitt (1960) recorded the physiological mobility of teeth loaded in an axial direction. When the load was gradually and evenly increased the tooth displacement showed an initially rapid rise to approximately 25 microns at loads of one Newton. With increasing load the displacement increased in a logarithmic manner. Removal of the load led to recovery in two phases and reloading before complete recovery led to reduced displacement with each force application. Retention of a small load retarded recovery of tooth position.

When loads of 5 Newtons were maintained the initial tooth displacement was followed by a second phase of displacement at a constant rate of approximately 2 microns per minute until a limit was reached. The greatest tooth movement occurred after periods of sleep, splinting and injections of atropine or ephedrine. Parfitt concluded that the tooth was supported by tension and compression of the periodontal ligament fibres and fluids of the vascular and tissue fluid systems of the periodontal ligament.

Picton (1962a) recorded axial tooth movement in humans using forces up to 20 Newtons. Tooth movement occurred in two phases with an initial sharp rise in displacement followed by a slower rise. The change from first to second phase was variable but tended to occur at 300 to 600 grams. Patients with periodontitis showed increased axial mobility in comparison to healthy subjects and this effect was most marked on the phase up to 600 gram loads. The placing of an inlay in supraocclusion caused large increases in axial mobility and these increases were again seen at the lower levels of load.
Picton (1962b) reported that posterior teeth tilted mesially and intruded during biting. When interproximal contacts were present teeth mesial to those being loaded also tipped mesially. He also (1962c) measured movement of test teeth produced by force applied to the contralateral side. Movements were produced in 13 out of 14 mandibular teeth and 5 of 8 maxillary teeth tested. It was concluded that the jaws distort during biting.

Picton (1963a) computed the vertical movements of teeth from measurements from two transducers resting on adjacent teeth. Vertical mobility was studied in 40 cheek teeth in 10 human subjects. The load/mobility curves revealed a phase of relatively free movement up to loads of 300 to 400 grams and a phase of less movement as the load increased to 2 kilograms. A load of 2 Kilograms produced less movement of premolars than molars. The author suggested that the rate of thrust may have affected the character and amount of movement in this study.

Studying the effect of rate of thrust and time interval between thrusts on axial tooth mobility Picton (1963b) employed upgraded equipment with the next but one tooth on each side of the test tooth used as reference teeth. Load application point and direction of thrust were also standardised. Variation in the rate of thrust in the range of 0.8 to 40 Newtons per second produced no consistent effect on the load/mobility curves. Reduction of the time interval between thrusts at a standardised loading rate caused a progressive reduction in displacement. A time interval of 1 to 1.5 minutes between thrusts is necessary to ensure repeatable load/mobility curves.

Picton (1964a) examined the effect of time interval between thrusts on normal axial
The Nature of tooth mobility

mobility. Series of 20 thrusts of 2 kilograms with intervals of 5 seconds produced a gradual reduction in mobility with the tooth failing to return to its rest position between thrusts. Twenty thrusts at 2 minute intervals caused a gradual increase in mobility associated with progressive extrusion of the tooth from its socket.

Bien (1966a and 1966b) reviewed concepts of tooth support in the light of experimental data. The author states that the multiphase intrusion and recovery of teeth indicates that instantaneous and delayed elasticity occur and that such a viscoelastic system shows complicated rate dependant responses that can be explained using the Maxwell and Voigt models.

The Maxwell model of viscoelasticity is a spring and damper in series in which the spring goes into action with instantaneous elasticity followed by the damper giving delayed elasticity. The Voigt model is a spring and damper in parallel with the damper acting continuously to slow the instantaneous elasticity of the spring.

Bien explained damping in the periodontium in terms of the squeeze film effect and the formation of cirrroid aneurisms in periodontal blood vessels. The author also believed that fluid diffusion through the socket walls under high pressure acts as a further fluid damper.

Wills et al (1972) reviewed the mechanical properties of the Hookean spring, the Newtonian damper, the Maxwell element and the Voigt element. The recovery of teeth on sudden removal of axial forces was recorded and these data were analysed using the complex mathematical technique of exponential curve fitting. It was concluded that the tooth support system certainly behaves in a viscoelastic manner
The Nature of tooth mobility

and that the periodontium may be represented by at least three and possibly five Voigt elements.

Slatter and Picton (1972) examined the effect of local injection of 1:10,000 noradrenalin on the intrusive movements of the incisor teeth of Macaca irus monkeys. It was found that mobility decreased over a period of one to one and a half hours after injection whereas no comparable alteration was detected when physiological saline was injected. On the basis of these results it was concluded that the vascular system plays an important part in the resistance of the membrane to intrusive tooth movement and in the subsequent recovery after the load has been removed.

Picton et al (1974) reviewed the physiology of the tooth support system and compared it to the mechanisms of implant support. Although implants were seen to have a "pseudo periodontal ligament" they behave as if ankylosed. Osseointegration techniques were not in widespread use at this time. Horizontal pinning of teeth to bone eliminated the physical properties of tooth support. (Picton and Wills 1975) The remaining displacement of crowns was elastic in character. Three endosseous implants behaved in a similarly elastic manner.

Wills et al (1976) studied the role of the fluid systems in tooth support by local injections of noradrenalin and saline, intravenous angiotensin and exsanguination. Systemic angiotensin and local noradrenalin both resulted in reduced displacement, probably due to reduced blood volume in the periodontal ligament. Injections of saline resulted in increased tooth movement due to increases in extracellular fluid volume or extrusion of the tooth. The fluid systems were seen to be more important
The Nature of tooth mobility

at forces below one Newton than at higher loads when the fibrous components are
more directly involved in force transmission.

When the intrusive displacements produced by loads applied at varying rates to the
teeth of 5 Macaca irus monkeys were compared, rapid application of force
consistently resulted in less movement of the tooth at a specific load level than when
the load was more gradually applied. (Wills and Picton 1978) It was suggested that at
high loading rates blood and extracellular fluid are trapped whereas they are free to
move at low loading rates. At high loading rates all components of the periodontal
membrane remain in place and act as a single entity to transmit load.

Wills and Picton (1978) examined the changes in mobility and resting position of
incisor teeth in macaque monkeys. They also re-examined the effects of local
injections of water and saline. The teeth tended to extrude with time and there was an
equal probability that this extrusion be associated with increased or reduced mobility.
A more intruded position was more likely to result in an increase in mobility than a
reduction. Injections of water tended to produce extrusion and saline to produce
intrusion. The effects of this movement on mobility were inconsistent but water
tended to cause increases in mobility. The authors concluded that separate
mechanisms are involved in positioning and supporting the tooth under load. Changes
when water is injected may be due to a volume effect while saline may cause a
competitive effect between volume of saline and effects on proteoglycans which hold
fluid in the ground substance.

Picton and Wills (1978) compared the physical properties of the periodontal ligament
The Nature of tooth mobility

of groups of teeth linked with acrylic splints to those of mucous membrane in 3
Macaca irus monkeys. The linked teeth displayed viscoelastic behaviour which the
authors summarised as follows:

1. The displacement and recovery of the teeth with the load applied as a ramp
   function corresponds with the force/displacement relationship of a typical
   viscoelastic material.

2. Loads sustained for many seconds caused creep.

3. There is an inverse relationship between rate of loading and displacement.

4. The higher the rate of loading, the less is the distinction between early and late
   phases of displacement.

5. If loadings are repeated at intervals of less than 1.5 minutes, the recovery becomes
   progressively more incomplete.

6. The rate of recovery is directly related to the loading rate and indirectly related to
   the duration of the load.

Kardos and Simpson (1979 and 1980) proposed that eruption, orthodontic tooth
movement and tooth support mechanics may be interpreted to mean that the
periodontium behaves in a thixotropic manner. While there are some similarities
between viscoelastic and thixotropic behaviour there is no biochemical or physical
evidence supporting the concept that biological tissues are thixotropic.

When the changes in the force-intrusion relationship of the tooth with changes in its
The Nature of tooth mobility

resting position in macaque monkeys were re-examined, thrusts of 4 Newtons were applied either once every 30 minutes or as a sequence of 16 thrusts at 10 second intervals once every 30 minutes. (Wills and Picton 1981) For the single thrust changes in the slope of the log displacement against log force curves above the discontinuity (0.8 to 4 Newtons) correlated with changes in the position of the tooth within its socket. This did not occur over 30 minutes for groups of 16 thrusts but between the first and sixteenth thrust there was an almost constant reduction in slope.

The reasons for a lack of consistent relationship between intrusion under load and position within the socket are difficult to explain but it is possible that several positioning mechanisms are at work.

Picton and Picton (1987) studied the effects of excision of the root apex on the intrusive mobility of anterior teeth of Macaca fascicularis monkeys. Reflection of the labial mucosa caused a significant increase in mobility at 4 Newtons when the loading rate was slow (1Ns\(^{-1}\)) but not when fast (100Ns\(^{-1}\)). No significant increases in mobility were demonstrated after the apices were removed. The authors concluded that compression in the fundus of the socket is not important in supporting the tooth against small compressive loads.

Embry et al (1987) studied the biochemistry of the ground substance of the periodontal ligament after intrusive loading in Macaca fascicularis monkeys. The authors concluded that changes in polymerisation of the ground substance could partly explain changes in tooth mobility.

Coelho and Moxham (1989) measured intrusive mobility of the incisor teeth of the
guinea pig and reported a significant time-dependency of the response. The authors state that this confirms the view that the periodontal tissues behave as a viscoelastic system.

For further information on this subject please refer to the major reviews of Muhlemann (1967), Picton (1969), Rygh et al and Moxham and Berkovitz (1982) and Picton (1990).

3.4 Response to extrusive loads

Extrusive loads are applied to teeth by the oral soft tissues, sticky foods and some oral hygiene procedures.

Tractional forces of approximately 0.15 Newtons and 0.3 Newtons caused a human maxillary incisor to extrude by 6 microns and 8 microns respectively (Parfitt 1960).

Continuous recordings of the movements of the mandibular incisors of rabbits caused by axially directed extrusive loads of between 0.5 and 200 grams were made by Moxham and Berkovitz (1979). The response to loading is biphasic, with an initial rapid phase followed by a second phase of more gradual extrusion. Removal of the load lead to a biphasic but incomplete recovery. The authors did not emphasise the importance of incomplete recovery after loading, however, this finding supports the view that teeth have a range of resting positions rather than one resting position. Thus any measurements of tooth displacement should be made with reference to this
resting range. Tooth movements were measured on application of loads as small as 1 gram.

A qualitative study of the effects of axially directed extrusive loads on the rabbit mandibular incisor was subsequently undertaken by Moxham and Berkovitz (1981). They reported that both first and second phases of extrusive and recovery cycles are force dependant but that the force/displacement relationship is not linear. This supports the argument that the periodontal tissues behave in a viscoelastic manner. The same animal model and experimental equipment were used to study the effects of a lathyritic agent on the response to axially directed extrusive loads (Moxham and Berkovitz 1984). Compared with the controls, lathyritic teeth showed a similar pattern of displacement but markedly reduced resistance to extrusive loading.

While this work adds to the body of knowledge, extrapolation from studies using an animal model with curved roots and lacking apical fundi must be made with great care.

3.5 Conclusions from the review of tooth support physiology literature.

Displacement on application of semistatic loads is seen to be in two phases; primary or initial and secondary. The change from primary to secondary phase for a particular tooth occurs over a range of load levels. The evidence indicates that the primary phase represents changing intraalveolar orientation of periodontal ligament fibres and movement of fluid out of the periodontium while in the secondary phase there is distortion of the entire periodontium.
Recovery on removal of a load is also biphasic with the first fast phase representing elastic recoil of the socket and the slower second phase representing return of fluid to the periodontium.

The periodontium behaves in a viscoelastic manner such that displacement at a particular load level is inversely proportional to the rate of loading. The elastic portion is provided by the combination of the periodontal ligament and alveolar bone. Tension and compression of these tissues occurring to varying degree depending on the direction and magnitude of the applied load.

The viscous behaviour is mainly produced by tissue fluid and blood in the periodontal ligament blood vessels and may be modified by locally acting drugs. The fluid systems play a more important role in tooth support at low levels of load and low loading rates.

The physical properties of the periodontium are not homogenous. The mechanisms controlling vertical tooth position are not purely mechanical and are, as yet, not fully understood.

The contribution to tooth support of the supracrestal gingival and interdental periodontal ligament fibres is relatively small for a fully supported tooth and relatively greater for a tooth with significant bone loss.

The majority of tooth support physiology research has been done at physiological
levels of tooth mobility and very little has been done using teeth with reduced support. This may be due to the difficulties of performing such work.
Chapter 4

Review of clinical studies of tooth mobility

Introduction

The study of tooth mobility has frequently been separated into clinically based research and tooth support physiology. While the two subjects are inseparable this section of literature review focuses on mobility studies relevant to clinical subjects. The studies quoted below utilised objective methods of assessing horizontal tooth mobility.

4.1 "Normal" tooth mobility

Muhlemann (1951) made 690 measurements of total buccal and lingual displacement produced by 500 gram horizontal loads applied for 2 seconds to human upper central incisors. The displacements ranged from 0.1 to 0.5 mm. The author stated that pathological mobility begins when $T_{500} > 0.2$ mm.

Muhlemann (1960) reported that the correlation between intraalveolar root length and tooth mobility was poor. The author stated that qualitative changes in the periodontium produced more profound effects than quantitative changes.
Rudd et al (1964) measured horizontal tooth mobility in subjects carefully screened for periodontal and occlusal abnormalities using 500 gram loads and found mobilities ranging from 0.025 mm to 0.18 mm.

Persson and Svensson (1980a) used small loads of 20, 50 and 80 grams force to measure horizontal tooth mobility in two groups of patients. The mean displacements produced were 12, 20 and 26 microns respectively in the periodontally healthy group and 28, 42 and 55 microns respectively in the periodontally diseased group.

Khoo and Watts (1988) studied tooth mobility in 124 upper anterior teeth of 21 patients with untreated periodontitis and found a strong correlation between tooth mobility and attachment level. The correlation between radiographically estimated intraalveolar root length and tooth mobility was weak. This is in agreement with the findings of Muhlemann (1960). Tooth mobility was independent of inflammation as assessed by bleeding on periodontal probing.

4.2 Bridgework

Chayes (1910) vehemently denounced fixed bridgework stating that it was intrinsically and inevitably harmful. In 1915, 1917 and 1920 he discussed the influence of teeth moving in different directions when subjected to occlusal stresses. He believed that the rigid splinting of teeth was damaging and would cause blood congestion and stagnation leading to increased mobility of the abutments. He recommended the use of movable connectors to join sections of bridgework to allow for independent movement of teeth.
Chayes observations were made at a time of poor understanding of the pathogenesis of periodontal disease and little knowledge of occlusion, however, he was correct in believing that independent physiological movement of teeth may be a significant factor in restorative dentistry.

Subsequent studies by Morrant (1956) and Roberts (1970a, 1970b) found higher failure rates for fixed-fixed bridges than fixed-movable designs.

Glickman et al (1970) used photoelastic stress analysis to show that linking teeth with fixed bridges changes the stress distribution within the entire periodontium. This type of study is two dimensional and the model only represents the elastic components of the system.

The work of Nyman and Lindhe (1979) in human subjects has shown beyond doubt that fixed bridgework is not inherently damaging to the periodontal ligament. In this study teeth with dramatically reduced bone support were linked with long span fixed bridges with no demonstrable deterioration of the periodontal ligaments. However, the most favourable design for bridgework does depend on the mobility of the abutment teeth. While short span bridges with complete periodontal support are best treated with fixed-movable designs the long span bridges of Nyman and Lindhe are necessarily rigid to minimise stresses on individual abutment periodontal ligaments.

Managing situations with large differences in abutment mobility is a complex problem. It is recognised clinically and has been shown in vitro (Jacobi et al 1985) that if a relatively tight tooth is rigidly linked with a fixed bridge to a loose tooth one of two situations will arise. Either the tight tooth will become loose or the bridge will fail.
mechanically.

The same situation arises when considering joining natural teeth to implants. Opinions as to the advisability of this action vary. A resilient joint between an implant fixture and abutment may offer a possible solution (Richter et al 1990).

4.3 Splinting

It has been suggested that splinting teeth during various periodontal procedures would improve healing. Muhlemann (1960) measured tooth mobility over a period of 20 months after initial periodontal therapy in two groups of splinted and unsplinted patients. Mobilities increased for the splinted group for 8 months before beginning to decrease while mobilities for the unsplinted group decreased for 20 months. Mobilities for the splinted group did not reduce to the levels of the unsplinted group during the period of the study.

In this paper Muhlemann also presented his corrective formula for the calculation of percentage changes in tooth mobility which is designed to allow for physiological levels of tooth mobility. Prior to this percentage changes were calculated by subtracting the second value from the first, dividing the result by the first and multiplying by 100. i.e. Percentage change = \( \frac{x_2 - x_1}{x_1} \times 100 \)

Muhlemann believed that if tooth mobility returned to physiological level the change should be 100 percent. When percentage changes are calculated as follows this will
be the case: Percentage change = \frac{x_1 - x_2}{x_1} \times 100. \text{ Where } a = \text{Physiological mobility.}

Renggli and Schwiezer (1974) used removable bridges to splint clinically mobile teeth. They found no changes in tooth mobility after 1 and 12 months.

Kegel et al (1979) studied the effects of intracoronal wire and acrylic splints during initial periodontal therapy using a split mouth design. They found reductions in tooth mobility in both groups but no significant differences between groups during a 17 week period.

Galler et al (1979) compared the mobilities of two groups which were splinted and unsplinted before and after periodontal surgery including bone recontouring. They found no significant differences between the two groups. They reported that mobility increased for approximately 3 weeks after surgery and then decreased to baseline values after a further 9 weeks.

Renggli et al (1984) splinted teeth with removable telescopic bridges and measured mobility at 0, 4 and 10 weeks. They found no significant changes in tooth mobility.

Mandel and Viidik (1989) compared the effects of splinting on healing two weeks after extrusive luxation of the incisor teeth of vervet monkeys. Tensile testing of transverse sections of the periodontal ligament showed little difference between the two groups although unsplinted teeth demonstrated a higher failure energy.

Thus it appears that there is no evidence in favour of splinting teeth during periodontal treatment.
4.4 Occlusion and occlusal trauma

Muhlemann (1954e) studied the tooth mobility changes caused by artificial trauma to 70 teeth of 30 children using various orthodontic appliances. All methods produced increases in mobility and removal led to immediate reduction of mobility. No conclusions could be drawn as to the possibility of the production of irreversible traumatic periodontal lesions.

Hirt and Muhlemann (1955) recommended the use of tooth mobility measurements to aid the diagnosis of bruxism. They demonstrated increases in tooth mobility between 6PM and 8AM due to nocturnal bruxism which did not occur after use of a bite plate.

Muhlemann et al (1957) measured tooth mobility before and after selective grinding of the occlusal surfaces of teeth. Prior to selective grinding hypofunctional teeth were reported to be of greater mobility than hyperfunctional teeth. The explanation for this finding is unclear. Selective grinding significantly reduced tooth mobility on both sides.

Lovdal et al (1959) examined 8,039 teeth and categorised 1421 of these as "heavily loaded". They found significantly more teeth with increased mobility among the heavily loaded teeth than the normally loaded teeth. Details of categorisation criteria were not provided and thus it is unclear whether categorisation was independent of mobility.

Muhlemann and Herzog (1961) placed an inlay in supraocclusion in a premolar tooth scheduled for extraction. They found an increase in tooth mobility followed by a
gradual decrease to normal mobility, which presumably occurred as the tooth moved into a new position.

Yuodelis and Mann (1965) measured clinical tooth mobility and other periodontal and occlusal parameters of 413 teeth in 54 patients. They claim that 53% of molar teeth had non-working contacts and that mobility, bone loss and pocket depth were significantly greater in these teeth. Although frequently quoted as such, this finding does not establish cause and effect, merely an association.

O'Leary et al (1966) examined the effects of time of measurement and sleep and reported that mobility is highest in the morning and lowest in the evening. The results of this study are in agreement with the results of Muhlemann.

Ross et al (1972) examined the nature of occlusal contacts in relation to tooth mobility in periodontally healthy patients. They reported that 11% of teeth with non-vertical forces were mobile while 6% of teeth with vertical forces were mobile.

O'Leary et al (1972) compared tooth mobility in "cuspid-protected and group function" occlusions. They found that the mean mobility was higher for cuspid protected occlusions than group function occlusions.

Noble and Martin (1973) measured tooth mobility changes caused by placing inlays in supraocclusion. They found an increase in mobility until 3 days followed by a decrease with mobility returning to normal levels 2 weeks after baseline. This is in agreement with the results of Muhlemann and Herzog and again the reduction of mobility after 3 days reflects the fact that the teeth move out of a traumatic position.
It has long been argued that the overloading of teeth by occlusal interferences causes periodontal breakdown. Lindhe and Svanberg (1974) attempted to clarify this issue by studying occlusal trauma using jiggling forces on the beagle dog. Similar studies were performed by Polson (1974) and Polson et al (1976). Both groups of researchers showed that occlusal trauma in association with periodontitis increased the amount of alveolar bone loss however those of Lindhe and Svanberg showed increased loss of connective tissue attachment while those of Polson did not.

Vollmer and Rateitschak (1975) examined the effects of occlusal adjustment on the mobility of teeth in 29 subjects with gingivitis and periodontitis. Mobility values were found to decrease over a period of 30 days after occlusal adjustment.

Moozeh et al (1981) made tooth mobility measurements following two methods of eliminating non-working side interferences. They reported significant reductions of tooth mobility after both methods with greater reductions after total elimination of interferences. There were no detectable radiographic changes 2 months after occlusal adjustment.

The possibility of occlusal trauma playing a codestructive role in periodontal breakdown remains controversial but the current majority opinion asserts that the role of occlusal trauma is not significant.

4.5 Periodontal treatment

Forsberg and Hagglund (1958) measured tooth mobility after gingivectomy and flap
Clinical studies - Literature review

surgery. They reported mobility increases for up to 27 days followed by mobility decreases which had rarely reached baseline values after 90 days. Grinding teeth out of occlusion during healing produced temporary reductions in mobility.

Rateitschak (1963) examined the effect on tooth mobility of various local periodontal treatments for three years. The author reported that mobility decreased after treatment in most subjects and continued to decrease for up to three years. Some subjects demonstrated initial mobility increases followed by a decrease to less than pretreatment values.

Ferris (1966) studied the effects of scaling and root planing with subsequent improvement in periodontal condition on tooth mobility. Eighty percent of subjects showed significant reductions in tooth mobility.

Cheraskin et al (1967) measured tooth mobility before and after scaling and polishing. The study utilised a split mouth design and showed mobility reductions of up to 19 percent on the scaled side.

Burch et al (1968) measured tooth mobility before and immediately after gingivectomy procedures. Control subjects showed no change in mobility while all test subjects showed increases in mobility of an average of 20 percent. No follow up measurements are reported.

O'Leary et al (1969) produced no significant changes in tooth mobility following dietary ascorbic acid supplementation. It is unclear whether the subjects were ascorbutic at the start of this study.
Clinical studies - Literature review

Flezar et al (1980) collected clinical mobility data as part of the Michigan eight year longitudinal study of periodontal therapy. The results indicate that the periodontal pockets of clinically mobile teeth do not respond as well to periodontal treatment as do those of firm teeth exhibiting the same degree of initial disease severity.

Persson and Svensson (1980b) measured the mobility of 35 maxillary anterior teeth in 8 subjects before oral hygiene instruction and scaling procedures and at 2, 4, 8 and 12 weeks. Gradual reductions of tooth mobility were observed over the 12 week period amounting to a total decrease of 45 percent.

Persson and Svensson (1981a) measured the mobility of 25 maxillary anterior teeth in 6 subjects over a 26 week period before and after oral hygiene instruction, preoperative scaling and gingivectomy procedures. Mobility values were found to decrease for the first four weeks after gingivectomy by approximately twenty percent. No further decreases were observed during the remaining experimental period. These results are in contrast to those of Fosberg and Hagglund (1957) and Burch (1968) where increases in mobility after gingivectomy were demonstrated. It is possible that this difference is due to the low loading levels used by Persson.

Persson and Svensson (1981b) used a split mouth design to compare tooth mobility changes produced by gingivectomy and flap procedures in 28 maxillary anterior teeth of 5 subjects during a period of 68 weeks. Both procedures produced significant increases in mobility after two weeks with flap procedures causing greater increases. Mobility values then decreased to reach pretreatment values at around 16 weeks and continued to decrease until 52 weeks. Application of Muhlemanns corrective formula
Clinical studies - Literature review

to allow for physiological mobility showed the final decrease of tooth mobility to be 60 percent on the flap side and 40 percent on the gingivectomy side.

4.6 Conclusions from the review of clinical studies of tooth mobility.

1. Tooth mobility and differences in tooth mobility are a significant factor in the design of fixed bridgework.
2. There is no evidence that the splinting of teeth is beneficial to healing during periodontal treatment.
3. Tooth mobility is affected by occlusal status, however, it remains uncertain that occlusal trauma plays a codestructive role in periodontal breakdown.
4. Periodontal treatment procedures tend to cause initial increases in tooth mobility followed by reductions to below pretreatment values. These reductions may continue for several years. These changes are probably due to an initial increase in inflammation followed by gradual resolution and reorganisation.
5. Qualitative and quantitative changes in the periodontium have an effect on tooth mobility.
Chapter 5

The Periotest

5.1 The Periotest and its use

The Periotest instrument consists of a handpiece linked to a microprocessor (Figure 1). In use the handpiece is held horizontally at between 1 and 2 mm from the tooth to be tested, the axis of which should be perpendicular to the floor (Figure 2). The handpiece houses a metal slug of 8 gram mass which contains a piezoelectric accelerometer (Figure 3).
Figure 2. The Periotest in use.

On activation the slug is fired at the tooth, at a velocity of approximately 20 mm per second, by an electromagnet controlled by the dedicated microprocessor. The slug hits the tooth, is slowed down, then bounces back into the handpiece. This is repeated 16 times at a rate of 4 impacts per second. The accelerometer signals are then averaged,
Figure 3. Sectional diagram of the Periotest handpiece.
analysed and a Periotest value produced. Periotest values are on a scale of -8 to +50 with -8 representing very firm teeth and +50 exceedingly loose ones. These values are read on a digital display and a voice synthesiser produces audible readings.

The importance of standardising the site and angle of impact of the Periotest on the tooth are evaluated in detail in experiments described in a later chapter.

The manufacturers state that the duration of the accelerometer signal is used to compute the Periotest value. Details of this computation were provided at a later date.

The Periotest uses impact forces to assess resistance to tooth movement rather than the traditional measurement of tooth displacement.

5.2 Chronological review of the literature relating to the Periotest

The Periotest was conceived at the University of Tubingen in Germany. Gudat et al (1977) described a percussion instrument designed to allow for analysis of percussion sounds. This instrument provided the basis for co-operative development between academic and commercial interests.

Analysis of percussion sounds was abandoned and in 1983 Schulte et al described an instrument under development incorporating an accelerometer. A microprocessor was used to measure "braking time" from the accelerometer signals. A Periotest value was then produced on a scale of 0 to 100.
D'Hoedt et al (1985) reported on the instrument that became commercially available the following year. Details are given of the equations used by the microprocessor to convert "contact time" into Periotest value. The scale was now established from -8 to +50. Testing against various surfaces of differing resilience over a 17 month period demonstrated no long term drift in results. Periotest values were correlated with a 0 to 3 clinical mobility scale.

A wide range of factors affecting Periotest value were examined. These were presented in a superficial manner and the potential for erroneous readings was dismissed. The description of the results was frequently in disagreement with the graphical presentation of the same results. Very few of the experiments examined Periotest values above 20 but scrutiny of the graphical results suggests that the effects of factors such as crowning teeth are greater for looser teeth.

Standard Periotest values and 95% confidence limits are presented for the adult dentition. In view of the spectrum of factors affecting the tooth support system such data are largely meaningless.

Further descriptive papers followed (Schulte 1986, 1988a and 1988b) with recommendations for the use of the Periotest including the occlusal management of crown and bridge and implant cases.

Goodson and Cugini (1988) used the Periotest in a study to compare two periodontal treatment modalities. Periotest data were collected on six occasions for each of 61
teeth of 15 experimental subjects and 21 teeth of 3 control subjects. The experimental teeth exhibited an initial Periotest value of at least 20.

Periotest values correlated well with a 0 to 3 clinical index. The mean difference between two repeated Periotest measurements was 0.04 units with a standard deviation of 1.95. These differences were not examined in relation to the level on the Periotest scale.

Periotest values were found to correlate loosely with mean attachment level. Despite the initial contention it is clear from the graphical representation of this data that the majority of teeth exhibited Periotest values below 15.

The authors state that it became clear during the course of their study that the useful range of the instrument is 0 to 30. When loose teeth were tested the instrument performed in an erratic manner.

Webber (1988) reported on 2000 Periotest measurements made by a team of clinicians on "an in vitro dental phantom specifically modified to yield a diverse but temporarily constant range of values". They found differences between examiners that were small but significant. Their data also show that right handed operators obtain Periotest results which are more reproducible when testing teeth on the left side.

Webber questions the diagnostic value of an instrument which "produces a signal related to an integrated measurement of the rebound dynamics of a tooth".

67
Egloff and Hochman (1988) took Periotest measurements from 14 patients with untreated periodontal disease and 30 dental students. They reported a general increase in Periotest value with large increases in sulcus bleeding index. The authors state that it is possible that the Periotest is not capable of discriminating between gingival health and initial gingivitis.

Olive and Aparicio (1990) used the Periotest to measure the stability of osseointegrated oral implants. 204 Brånemark implants in 36 patients were evaluated longitudinally for periods varying between 4 and 20 months.

Repeated measurements showed Periotest values to be highly reproducible with a deviation of ±1 unit. Periotest values increased as the distance from the tapping point to the marginal bone level increased. In the maxilla Periotest values decreased as implant length in bone increased. This result was not reproduced in the mandible where Periotest values were generally lower.

Seven implants were found to have failed at the abutment connection stage and all exhibited Periotest values of +9 or more. Six of 8 implants that failed after prosthesis placement had initial Periotest values of +4 or more. These increased to +13 or more before the implants were removed. Twenty-two implants in 4 patients demonstrated initially high Periotest values (+3 or more). These were left unloaded for a further 4 months or longer and this produced reductions in Periotest value of at least 3 units.

Lukas and Schulte (1990) reported on an analysis of 9 characteristics of the Periotest
signal for correlation with clinical mobility. The highest agreement of approximately 90% was found when signal duration was chosen as the signal characteristic for analysis. The authors point out that this is comparing objective measurement with subjective clinical assessment.

Teerlinck et al (1991) used the Periotest to examine 60 Brånemark mandibular implants in 30 patients. Each pair of implants were joined by a Dolder bar and supported an overdenture. 240 Periotest measurements ranged between -4 and +2.

Lukas et al (1992) used high speed filming at 3000 frames per second to study the impact of the Periotest slug and subsequent tooth movement. Tooth displacements were said to have been measured relative to a grid mounted on the handpiece but no details of this are given. Three frames per millisecond is not adequate to characterise an impact which lasts from 0.25 to 2.5 milliseconds.

Schulte et al (1992) examined Periotest values in relation to percentage bone loss for 2312 teeth using orthopantomograms and 900 teeth using intraoral radiographs. Statistical analysis indicated that Periotest values were primarily related to bone loss and also to a lesser extent to inflammatory status and temporomandibular joint dysfunction.

The Periotest has been used (Giargia et al 1994) to measure tooth mobility changes during the healing of experimental periodontitis in beagle dogs. Cotton floss ligatures were placed at monthly intervals for 120 days after which debridement was performed...
and Periotest values were recorded at day 120, day 135 and day 225. A slight but statistically non significant increase in Periotest values was measured 15 days after debridement while statistically significant reductions in Periotest values were measured 105 days after debridement. No initial Periotest data is presented.

While these results appear unremarkable they confirm that the Periotest is capable of perceiving the qualitative changes in the periodontium associated with healing rather than quantitative changes alone.
Preliminary evaluation of the Periotest

At this point understanding of Periotest function and factors affecting Periotest measurements was extremely limited. For this reason a series of pilot studies was performed.

6.1 Bench testing

Pilot bench testing began with an assessment of reproducibility of Periotest measurements when used against the flexible plastic calibration cap provided by the manufacturers. The calibration cap is a friction fit onto the tip of the handpiece and is designed as a basic test of Periotest function. A Periotest value of 15 units was consistently produced every time it was tested.

Multiple series of measurements were carried out against various surfaces including blocks of metal, wood and metal plate of varying degrees of flexibility. These measurements produced Periotest values across the range that were highly reproducible with a standard deviation of less than one unit.

A similar pilot study was then performed to examine the effect of varying the material
of the surface to be impacted by the Periotest slug, using a selection of dental materials.

Materials and methods

Blocks of enamel, dentine, amalgam, composite, acrylic, plasticised acrylic resin and rubber impression material were prepared and clamped in a vice. The Periotest handpiece was also clamped at a fixed distance of 1mm from the sample to eliminate other variables. A series of 20 Periotest readings were taken from each sample.

Results and discussion

Table 1. shows the means and standard deviations of Periotest values listed against each material along with their respective elastic moduli. Periotest values were highly reproducible.

<table>
<thead>
<tr>
<th>Material</th>
<th>P.T.Mean(n=20)</th>
<th>Standard deviation</th>
<th>Modulus(gNM⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>-6</td>
<td>0</td>
<td>84.1</td>
</tr>
<tr>
<td>Amalgam</td>
<td>-5</td>
<td>0</td>
<td>21.2</td>
</tr>
<tr>
<td>Dentine</td>
<td>-5</td>
<td>0</td>
<td>18.3</td>
</tr>
<tr>
<td>Composite</td>
<td>-5</td>
<td>0</td>
<td>13.7</td>
</tr>
<tr>
<td>Acrylic</td>
<td>-5</td>
<td>0</td>
<td>2.56</td>
</tr>
<tr>
<td>Plasticised Acrylic Resin</td>
<td>-4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Rubber impression material</td>
<td>50</td>
<td>0</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 1. Mean Periotest value and elastic modulus for each material.

Figure 4. is a bar chart of Periotest value plotted for each material in order of decreasing elastic modulus.
The material of the surface made no difference to Periotest value except for rubber impression material; a specimen only tested in desperation. Enamel with an elastic modulus of 84 giga pascals was expected to give a much lower reading than say, acrylic with a modulus one thirtieth that of enamel.

**Figure 4.** Periotest values for each material in order of decreasing elastic modulus.

### 6.2 Slug Velocity

Preliminary estimation of slug velocity was established with a simple pendulum experiment. A metal ball of 2 gram mass was suspended in front of a sheet of graph paper. The Periotest slug was fired at the ball and the height reached by the ball recorded. This was repeated 5 times. This experiment produced a slug velocity of 0.17 meters per second. Details of the calculation are given in appendix 1. Slug
velocity was subsequently reported by the manufacturers to be 0.2 meters per second.

6.3 Comparison of two instruments

Two Periotest instruments were compared to establish the similarities and differences between the Periotest values produced.

Materials and methods

A series of 20 Periotest readings were taken with each of 2 Periotest instruments against various surfaces. Seven surfaces were chosen to give Periotest values across the range.

Results

Table 2. shows the mean Periotest values of each of 20 measurements for each instrument for each of the seven surfaces chosen to give Periotest values across the range.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Instrument 1 Mean Periotest value</th>
<th>Instrument 2 Mean Periotest value</th>
<th>Significant difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>-5.85</td>
<td>-7.25</td>
<td>*</td>
</tr>
<tr>
<td>2.</td>
<td>0.05</td>
<td>-0.95</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>8.95</td>
<td>6.95</td>
<td>*</td>
</tr>
<tr>
<td>4.</td>
<td>13.85</td>
<td>15.25</td>
<td>*</td>
</tr>
<tr>
<td>5.</td>
<td>27.60</td>
<td>28.40</td>
<td>*</td>
</tr>
<tr>
<td>6.</td>
<td>35.95</td>
<td>41.20</td>
<td>*</td>
</tr>
<tr>
<td>7.</td>
<td>50.00</td>
<td>50.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Mean Periotest values for the two instruments for each of seven surfaces.
The Periotest

Statistical analysis of the data was performed using SAS computer software. The table shows differences between the means which were evaluated using Bonferroni (Dunn) T tests for the variable of Periotest value for each surface. Those means marked with an asterisk are significantly different at the 0.05 alpha level. There are significant differences between the two instruments for five of the seven surfaces but these are less than 2 Periotest units except for surface number 6 where the difference between the means is greater than 5 Periotest units. Surface number 7 is probably outside the Periotest range as all 20 measurements from both instruments were 50.

Conclusions.

Care is required in the interpretation of Periotest data acquired using more than one instrument, particularly above 30 on the Periotest scale. It would therefore seem sensible to use the same instrument for longitudinal measurements for a given patient and this should be readily possible.

6.4 Electronic testing

The first recordings of the accelerometer signal were produced after addition of circuitry# to the microprocessor. They were collected using a recording oscilloscope and hard copy produced using a pen recorder. Figure 5 shows a tracing of a signal produced by a rigid structure giving a Periotest value of -2. Output voltage is plotted against time in milliseconds. The voltage spike is of 5 volts and of 0.38 milliseconds

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#This was carried out by the electronics section of the department of medical physics at University College Hospital, London and later modified by Siemens.
Figure 5. Accelerometer signal (Voltage against time with horizontal scale 1ms) from high modulus object giving a Periotest value of -2. (Scanned image)

Figure 6 shows a similarly produced signal tracing taken from a flexible metal surface with a Periotest value of 18. The voltage spike is of 3.7 volts and 0.85 milliseconds duration.

Figure 6. Periotest signal (Voltage against time with horizontal scale 1ms) from a low modulus object giving a Periotest value of +18. (Scanned image)
Preliminary experimental examination of the relationship between signal duration and Periotest value was carried out by recording Periotest signals and values from various surfaces across the Periotest range. Figure 7 shows Periotest value plotted against experimental signal duration. There appears to be a linear relationship between Periotest value and signal duration below approximately 20 Periotest units. Above this, the relationship is not linear.

![Figure 7. Periotest value plotted against measured signal duration.](image)

These results were presented to the manufacturers who then provided details of the relationship between Periotest value and signal duration. The manufacturers refer to signal duration as "contact time" in the belief that signal duration is equal to the time that the Periotest slug is in contact with its target. While this may be a reasonable approximation, it cannot be considered to be precise.

The mean signal duration from sixteen impacts is used to compute the Periotest value.
The Periotest scale is linear from -8 to +13 and parabolic from +13 to +50.

This relationship between contact time and Periotest value, designated by the manufacturers, is represented by the equation:

\[
\text{Periotest value} = \frac{\text{contact time}}{0.02} - 21.3
\]

if less than 13 and

\[
\text{Periotest value} = 10 \times \sqrt{\frac{\text{contact time} - 8.493}{0.06 \text{ ms}}} - 4.17
\]

if more than 13.

The relationship is illustrated graphically in Figure 8 which shows Periotest value plotted against signal duration and was produced from calculations using the above equations.

**Figure 8.** Periotest value plotted against calculated signal duration (ms).
Chapter 7

A Computerised recording system

7.1 The System

A new computerised signal capture system was assembled and tested. This comprised a CED 1401 analogue to digital converter and an IBM compatible microcomputer. Sigavg signal capture and analysis software allow the equipment to be used as a computerised recording oscilloscope. Data may be captured on up to 16 channels with a maximum sampling rate of 80 Kilohertz. This provides 80 data points per millisecond which was felt to be sufficient to characterise a signal which varies from a quarter to two and a quarter milliseconds in duration.

Data capture at high sampling rates may not be continuous but occurs in "frames" of specified duration. Triggering of the start of each frame may be achieved using the signal itself. The voltage threshold level to initiate triggering is adjustable but this so-called "Peri" trigger halves the maximum sampling rate.

@The hardware and software for this system were selected and assembled by Dr Alf Linney, Medical Physics, UCL.
*Cambridge Electronic design
$CAS, London.
The alternative is to use an external trigger, which requires a negative going voltage spike. The circuitry added to the Periotest allowed the signal which starts movement of the slug to be used for this purpose. The delay between this slug driving signal and the Periotest signal varies depending on the distance of the handpiece from its target. When the handpiece is held at the required 1 to 2mm from the target the delay was measured at approximately 25 ms. Frames of data of 40 ms were found to reduce the maximum possible sampling rate and use a prodigious amount of computer memory so a modifying circuit was added to the slug driving signal to reduce the required frame duration. Figure 9 shows simultaneous recordings of the slug driving signal and the Periotest signal before and after this circuitry was added to illustrate the change.

Version 1. of Sigavg was tedious and time consuming to set up however the current version (5.22) is a great improvement. Signal capturing parameters may be saved in a file and are readily loaded. Figure 10 shows the parameter window set up to capture data on 2 channels designated 0 and 1 at a rate of 35,714 Hz for a period of just under 25 ms. The trigger for data capture is external and the 25 ms frames of data will be saved in a file called Test.

The signal analysis section of the Sigavg software allows for on screen analysis of frames of data. Measurements may be made using a basemarker and cursor system and these may be noted or exported directly to log files. Log files or frames of data may also be exported for use in spreadsheet and graphics software.

Figure 11 is a screen dump from Sigavg showing an example of the Periotest
Computerised Recording System

accelerometer signal produced by a single impact with output voltage plotted against
time in milliseconds. It shows no output while the slug is moving with no force on the
accelerometer. When the slug hits the tooth the accelerometer is compressed and
produces a current. The peak output voltage represents the peak force of impact.

The output then decreases as the force decreases and the slug loses contact with the
tooth. At this point the output changes from negative to positive when the force on
the accelerometer changes from compression to tension, as the slug bounces away
from the tooth. The output falls away to zero with some oscillation.
Computerised Recording System

**Periotest signal with external Triggering pulse.**

The A/D converter requires an external trigger to maximise the sampling rate. (83 KHz when only one channel is used)

The -ve going edge of the slug driving signal (illustrated here) starts the sampling process and would require a 40 ms display.

A modifying circuit was therefore added to the slug driving signal to provide a more appropriate external trigger.

**Modified triggering pulse**

Figure 9. The modification to the trigger pulse.
Computerised Recording System

Parameters from file C:\SIGAU6\PHD.SPR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling mode</td>
<td>Save Sweeps</td>
</tr>
<tr>
<td>Points per sweep</td>
<td>892</td>
</tr>
<tr>
<td>Time per sweep (mS)</td>
<td>24.976</td>
</tr>
<tr>
<td>Automatic data filing</td>
<td>Off</td>
</tr>
<tr>
<td>Save file name</td>
<td>test.sag</td>
</tr>
<tr>
<td>CLK OUT time (mS)</td>
<td>0</td>
</tr>
<tr>
<td>Enter sampling</td>
<td>Running</td>
</tr>
<tr>
<td>Default trigger</td>
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</tr>
<tr>
<td>Display mode</td>
<td>Normal</td>
</tr>
<tr>
<td>ADC conversion is</td>
<td>Clocked</td>
</tr>
<tr>
<td>Sample rate (Hz)</td>
<td>35714.29</td>
</tr>
<tr>
<td>Number of sweeps</td>
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</tr>
<tr>
<td>Sample trigger</td>
<td>Event 4 input of 1401</td>
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<tr>
<td>Display node</td>
<td>Normal</td>
</tr>
<tr>
<td>Trigger type</td>
<td>Post</td>
</tr>
<tr>
<td>ADC chans</td>
<td>0 1</td>
</tr>
</tbody>
</table>

Figure 10. Sigavg parameter window setup to capture data on 2 channels (designated 0 & 1) at a rate of 35,714 Hz for a period of just under 25 ms.

Figure 11. Screen dump from Sigavg showing an example Periotest accelerometer signal with output voltage plotted against time (ms).
Figure 12 shows a positive spike in the accelerometer output 20 milliseconds after the primary peak. This represents the tension on the accelerometer produced when the slug is electromagnetically retracted into the handpiece under microprocessor control.

![Graph showing Periotest signal](image)

*Figure 12. Periotest signal showing slug retraction approximately 20 ms after the primary peak.*

The duration of the primary negative spike in the accelerometer output signal is said to represent the time that the slug is in contact with the tooth. (Schulte 1986) This time varies in inverse proportion to the resistance of the tooth to movement and varies from 0.25 to 2.25 milliseconds. Thus a tight tooth has a relatively high resistance to movement and produces a low contact time and a low Periotest value while a loose tooth has a low resistance to movement producing a high contact time and a high Periotest value.
7.2 Variation in slug velocity with measuring distance

The velocity of the Periotest slug prior to impact is said to be constant when the handpiece is held in the range of 1 to 2 mm from the test tooth. The slug is no longer being driven at this stage and a friction free environment is not possible. For this reason an experiment was performed to measure the velocity of the slug across its range of travel.

Materials and methods

A digital micrometer gauge measuring to 1 Micron was modified to allow reversible removal of the jaw anvil. This was then placed horizontally in a vice with the Periotest clamped in alignment with the micrometer screw spindle. The micrometer screw was then adjusted to be in contact with the Periotest slug housing, zeroed and locked.

The computerised recording system was used in "Peri" mode to record the unmodified slug driving signal and the Periotest signal. In this mode the system monitors incoming data and retains a continuously updated frame of data of specified duration ("pre-trigger"). Actual recording of data is triggered by a voltage spike on one of the channels; in this case the positive-going edge of the slug driving signal. The retained frame of data allows recording of data prior to the trigger; hence the name "Peri"
trigger. This mode is useful when no suitable external trigger is available, so the signal itself is used as an internal trigger.

Two sets of 16 pairs of signals were recorded at 0 mm from the slug housing and at 0.2 mm increments up to the maximum travel of the slug of 3 mm. Periotest values were also recorded at each stage.

The Sigavg software was then used to measure the elapsed time between the positive going edge of the slug driving signal and the start of the Periotest signal. (See Figure 13) This data was then exported into spreadsheet software where mean velocities were calculated using spreadsheet formulae.

Each of the two sets of 16 pairs of signals were measured at each of the 15 increments giving 480 measurements from approximately one million computer captured data coordinates.

Results and discussion

Figure 14 shows Periotest value plotted against measuring distance. At zero distance the Periotest value is -5. As the measuring distance increases there is a trend for the Periotest values to decrease, reaching the limit of the range of -8 at 2.6 mm. Beyond 2.6 mm the Periotest ceases to give a reading, producing 999 on the digital readout, despite the fact the Periotest accelerometer produces a signal as illustrated in Figure 13.
Figure 13. Output voltage/time graphs for the unmodified slug driving and Periotest signal at 0 and 2.8 mm from the slug housing.
In the range of 0.6 to 2 mm the value is consistently -6.

**Figure 14.** Periotest value plotted against measuring distance.

**Table 3.** Distance from the slug housing tabulated against mean time (ms), mean velocity so far and mean velocity over the previous 0.2mm.
Table 3 shows the measuring distance (mm) in column 1 listed against the mean time (ms) in column 2. This is calculated by subtracting the mean time between the two signals at zero distance from the mean delay at each measuring distance.

Column 3 gives the mean velocity (metres per second) over the total distance from the slug housing and is calculated by dividing the distance by the mean time.

Column 4 gives the mean velocity over the previous 0.2 mm and is calculated by dividing 0.2 mm by the time taken to cover that distance.

Figure 15 shows a graph of distance from the slug housing (mm) plotted against time (ms). If the velocity were constant this would be a straight line. In this case there appears to be an initial deceleration followed by a period of reasonably constant velocity from 5 to 12 ms followed by a further deceleration.

![Figure 15. Distance/Time graph for the Periotest slug.](image-url)
This is further clarified by figure 16 which shows velocity (Ms\(^{-1}\)) [The same as mm per ms] plotted against distance from the slug housing. The upper line gives mean velocity so far and the lower line gives mean velocity over the previous 0.2 mm. Both are shown because the lower line is susceptible to experimental error. The velocities are calculated over a period as short as 0.6 ms. The maximum sampling rate for two channels in "Peri trigger" mode is 34 KHz or 17 KHz per channel, giving data points at intervals of 0.058 ms. This could give rise to errors of the order of 0.1 ms.

**Figure 16.** Velocity/Distance graphs for the Periotest slug with the upper line showing mean total velocity and the lower line giving the mean velocity over the previous 0.2 mm.

The graph shows that the initial velocity of the slug as it leaves the housing is almost 0.4 Ms\(^{-1}\). Over the first Millimetre of travel the slug decelerates to approximately 0.2 Ms\(^{-1}\). The slug then continues to decelerate but at a more gradual rate. Between 1
and 2 mm from the housing the slug velocity is of the order of 0.15 Ms\(^{-1}\) and slows to approximately 0.1 Ms\(^{-1}\) at 2.6 mm.

This experiment suggests that as the measuring distance increases the slug velocity decreases leading to a decrease in Periotest value. The velocity within the 1 to 2 mm range is decreasing, albeit more slowly, and it is clearly important to position the handpiece at the correct distance from the tooth.

7.3 Handpiece movement

In the light of the results of the previous experiment an examination of the positional stability of the Periotest handpiece was performed.

Materials and methods

A non-contact displacement transducer (described in detail later) was rigidly attached to the Periotest handpiece and an aluminium transducer target was set up vertically on a laboratory bench at a comfortable working height.

Movements of the Periotest handpiece in the horizontal plane were recorded with and without a double handed finger rest, over a twenty second period. This was done with the Periotest inactive and then repeated during a series of Periotest impacts.

The real time display was not observed during recording of this data as the feedback was found to alter the results.
Results and discussion

Figure 17 shows recordings of horizontal movement of the inactive Periotest handpiece with and without a double handed finger rest. Over a twenty second period the amplitude of movement is shown to be approximately 1.8 mm when no finger rest is employed.

Using a double handed finger rest the amplitude of movement is reduced to approximately 0.3 mm.

Recordings of the movement of the handpiece during a series of impacts are shown in figures 18 and 19 and were carried out using a double handed finger rest. Figure 18 shows handpiece movement during a two second period with Periotest impacts occurring at 0.25 second intervals. The amplitude of movement is approximately 300 microns (0.3 mm) and thus does not appear to be increased by the impacts.
Figure 17. Movement of the Periotest handpiece with and without a finger rest.
Figure 18. Handpiece movement over a 2 second period with impacts occurring at 0.25 second intervals.

Figure 19 is a simultaneous recording of handpiece position (Upper trace designated 0) and Periotest signal (Lower trace designated 1) over a 25 millisecond period. When the slug hits its target the handpiece is displaced by 50 microns but this only lasts for 3 milliseconds. Thus Periotest impact does not contribute to handpiece movement.
Figure 19. Simultaneous recording of handpiece position (upper trace) and Periotest signal (lower trace) over a 25 ms period.
Modelling

Chapter 8

Modelling

Modelling will not, of course, obviate the need for experimentation on the "real" system being investigated, however it will provide information which is not readily obtained by other means. Difficulties can arise because models must be designed to fit the known facts which may prejudice the outcome of experiments.

8.1 Mechanical models.

A number of attempts were made to produce a mechanical model of the functional periodontal ligament. If this were possible, laboratory experiments to examine the effects of mechanical changes to the system would be possible. This would minimise the need for animal models as well as aiding development of the experimental apparatus.

8.1.1 Voigt element model.

The simplest mechanical model of the periodontal ligament is a spring and Newtonian damper or dashpot linked in series and is known as a Voigt element. A model was built# using a thin steel spring of variable length linked to a piston which could be

# Laboratory of the Medical physics Department, University College London.
Modelling

filled with fluids of various viscosities.

This model was clamped with the spring set vertically and the Periotest was applied at right angles to this. Ten Periotest readings were taken with the spring set at 7 different lengths between 1.5 mm and 30 mm. Single impacts from each series were recorded using a recording oscilloscope.

Figure 20 shows Periotest value plotted against spring length. As the spring is lengthened from 2 mm to 15 mm Periotest values increased from 8 to 18. When the spring length is increased from 15 mm to 30 mm the Periotest values decrease from 18 to 3.

Figure 20. Periotest value plotted against spring length.

Examination of the recordings of the individual Periotest signals (not illustrated)
Modelling showed multiple oscillations in the output from the Periotest accelerometer. When the output oscillations cross the zero output threshold the Periotest reads the signal as complete and produces an erroneously low Periotest value.

Modifications were made to the model and various liquids, including glycerine and the base of a rubber impression material, were placed into the piston but it did not prove possible to extend the useful range of the model.

8.1.2 Extracted tooth mounted in rubber.

An extracted single rooted human premolar tooth was mounted in a block of rubber impression material. This tooth was then subjected to semistatic loading with a Corex gauge at 50 gram intervals between 0 and 400 grams in a buccal and then lingual direction. The computerised non-contact displacement measuring system (Described in detail in a later chapter) was used to measure the amplitude of movement.

<table>
<thead>
<tr>
<th>Load (Gm)</th>
<th>Mean amplitude of displacement (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>63.63</td>
</tr>
<tr>
<td>150</td>
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<td>350</td>
<td>196.71</td>
</tr>
<tr>
<td>400</td>
<td>205.07</td>
</tr>
</tbody>
</table>

*Table 4. Load (grams) applied with a Corex gauge tabulated against displacement produced (microns).*

The results are given in table 4 and illustrated graphically in Figure 21 with
Modelling

displacement (microns) plotted against semistatic load (grams). The relationship between load and displacement is linear rather than being in two phases.

![Graph showing the relationship between load and displacement](image)

**Figure 21.** Displacement/load graph for a tooth mounted in rubber.

**Figure 22.** Simultaneous recording of the tooth displacement (upper trace designated 0) and Periotest signal (lower trace designated 1) from the tooth mounted in rubber.
Modelling

Figure 22 shows a simultaneous recording of the tooth displacement (upper trace designated 0) and Periotest signal (lower trace designated 1) from this model. There are 6 bounces of the Periotest slug on the tooth over a 4 millisecond period within one impact. The tooth oscillates during recovery. Reduction of the height of rubber supporting the tooth caused an increase in Periotest value.

Figure 23.a. shows the simultaneous recording of four signals designated 0 to 3. Signals 0 and 1 are the displacement and Periotest signals respectively. Signals 2 and 3 are the Periotest signal duration "clock on" and "clock off" signals. Figure 23.b. gives the same data zoomed in to show the start of the Periotest signal. The signal duration "clock on" signal (Designated 2) is triggered when the Periotest signal crosses the -80 millivolt threshold. The signal duration "clock off" signal (Designated 3) is triggered when the Periotest signal crosses the +80 millivolt threshold.

It is clear that the Hookean or spring element of this model and the Voigt element model predominate and that a greater damping element is necessary to produce a usable model of the periodontal ligament.
Figure 23a & 23b. Simultaneous recordings of 4 signals designated 0 to 3. Figure 23b shows the same data as 23a zoomed in to show the start of the Periotest signal.

<table>
<thead>
<tr>
<th>Trace 0</th>
<th>Tooth displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trace 1</td>
<td>Periotest signal</td>
</tr>
<tr>
<td>Trace 2</td>
<td>Periotest &quot;clock-on&quot; signal</td>
</tr>
<tr>
<td>Trace 3</td>
<td>Periotest &quot;clock-off&quot; signal</td>
</tr>
</tbody>
</table>
8.1.3 Extracted teeth mounted in various materials.

Extracted teeth were mounted in dental stone with a wax spacer of approximately 1 mm thickness around the roots. The wax spacer was then removed with boiling water and a steam cleaner. Various materials were then placed into the "sockets" and the teeth replaced using a jig to ensure replacement in the original position.

Figure 24 shows a recording of a Periotest signal for each of the six materials. Scotchbond, Permalastic and Humbrol are not compliant enough while Mirror impression material is too compliant.

Polybutadiene rubber and President impression material appeared promising but attempts to make models with mobilities varying across the Periotest range did not prove possible.

%Specimens prepared by Dr N Meredith, Institute of Dental Surgery.
Figure 24. Periotest signals for extracted teeth mounted in various materials.
(Specimens prepared by N. Meredith/Data collected by G. Robertson)
8.2 Cadaveric

8.2.1 Pig jaw model

A pig's head was obtained from which the mandible was dissected. The mandible was then cut in half at the midline to facilitate handling.

While obviously lacking blood pressure it was immediately clear that the periodontium of the pig's jaw would provide the most useful experimental model. Adjustment of the bone height around the teeth allowed production of teeth with mobilities varying across the Periotest range.

The pig's jaws were kept frozen in a deep freeze in sealed freezer bags between experiments and defrosted overnight prior to each experimental session.

![Graph](https://via.placeholder.com/150)

**Figure 25.** *Semistatic loading of a tooth from the pig jaw with amplitude of displacement against load.*
Modelling

The section of mandible containing the cheek teeth was secured in a vice and loaded using a corex gauge. Figure 25 shows the results of semistatic loading and plots total buccal and lingual displacement against semistatic load. The increasing displacement with increasing load is in two phases. The rate of increase of displacement with increasing load decreases above a load of 100 grams.

Figure 26. Displacement /time graph for a cheek tooth during the application and sudden removal of a 400 gram load.

Figure 26 shows the relationship between tooth displacement and time following application and sudden removal of a lingually directed load of 400 grams to a cheek tooth as measured using the non-contact transducer. The initial rapid displacement...
away from the force is followed by a more gradual displacement. The biphasic response to the removal of the load is also typical of that found in live animals and humans.

For these reasons the cheek teeth of the pig jaw model were chosen as the model upon which the majority of the in vitro experimentation was carried out.

### 8.3 Mathematical modelling

During the early stages of the experimental work computer programs were written* to compute the complex simultaneous differential equations of the impact mechanics of the Periotest. Several mathematical rheological analogues were used including a single Voigt element and the model described by Bretschi (1976). This model consists of a Maxwell element and a Voigt element in parallel.

The results of these computations provided the first suggestion of the possibility that the Periotest slug could "bounce" on the tooth within one impact. Prior to this recordings of Periotest signals exhibiting this phenomenon had been discarded as artefacts.

While this computer modelling was conceptually useful it was not pursued and its results are not presented here.

*Dr Alf Linney, University College London
Chapter 9

Pig jaw model

9.1 Post mortem changes in tooth mobility

A large section of experimental work has been carried out using the pig jaw model. It is therefore important to review the literature documenting the fundamental differences between the tooth support systems of a live animal with a functional circulatory system and a dead animal with no blood pressure.

Muhlemann (1954d) studied post mortem changes in horizontal tooth mobility curves of Rhesus monkeys. Heat and formalin caused large reductions in mobility and removed the two phase nature of the displacement/load relationship. Untreated specimens retained the characteristic double sloped mobility curves but were of greater mobility than the teeth of live animals.

Bien (1966a) compared intrusive tooth movements of rat incisors before and after exsanguination. In all experiments a biphasic intrusive cycle and biphasic restoring cycle were observed. Intrusive displacement of the teeth of dead rats was consistently greater than those of live rats. The teeth of dead rats tended to remain partially intruded and this incomplete recovery could be completed by squeezing the thorax of the animal.
Wills et al (1976) investigated the effects of exsanguination and tissue fixation on intrusive tooth mobility in macaque monkeys. The authors reported a reduction in movement compared to normal teeth. This was explained as being due to removal of blood and extracellular fluid from the periodontal ligament. The biphasic force/displacement relationship was maintained after exsanguination. Fixation in formalin caused considerable reductions in tooth displacement and this effect occurred within a few minutes of perfusing the head with formalin.

Low loads of 5, 10, 15 and 20 grams were used by Myhre et al (1979) to examine the effects of blood pressure on the axial mobility of rabbit incisors. Displacements were measured 20 seconds after the start of loading using the transmission time of ultrasonic pulses between two piezoelectric crystals. No reasons were given to explain why this loading regime was chosen over any other. While the use of an intraarterial balloon to increase blood pressure led to extrusion, the injection of noradrenalin increased blood pressure but was followed by intrusion. Papaverine caused a reduction in blood pressure and led to intrusion but none of these effects caused clear cut changes in the response to loading. In the period of 2 to 38 hours post mortem intrusion and extrusion curves in response to intermittent loading remained unchanged. Over the subsequent 20 hours the mobility gradually decreased and finally ceased altogether. No details of possible changes in the resting position of the teeth during this period are given. The authors argue that these findings support the hypothesis that the 2 phases of tooth mobility reflect properties of the collagen fibres and rule out vascular forces in resisting low axial loads.

The effects of lack of blood pressure on the response to extrusive loads of the
mandibular incisor of the rabbit have been studied by Moxham and Berkovitz (1979). Measurements were made at 1, 4 and 24 hours after death and the authors reported gradual reductions in the second phase of extrusion, and thus reductions in total displacement, with elapsed time after death. No details of changes in rest position between measurements are provided but it appears likely that each measurement began with the tooth in a more intruded position.

Ralph (1982) performed tensile tests on sections from post mortem samples of human periodontal tissues. The elastic nature of the ligament was evident but the author points out the lack of the fluid component normally present in the system. No comparison with live humans was presented.

Gathercole (1987) applied cyclic intrusive loads to cheek teeth in the dissected mandibles of pigs at loading rates of 2 and 20 Newtons per second. The author concluded that tensile support by periodontal ligament fibres is likely to be the dominant supporting mechanism for major loads while the fluid system will be dominant for minor loads. It is unclear how the author arrived at this conclusion as they provided no comparison with the in vivo situation.

It is clear from this review that post mortem changes occur in the periodontium and that these are related to lack of blood and tissue fluid pressure. The experimental evidence of the effect of lack of blood pressure on magnitude of displacement is conflicting. This probably depends on the loading history of the tooth. It is likely that preloading or priming thrusts prior to measurement will lead to a reduction of measured displacement as the tooth will not recover its position after preloading. In
the absence of preloading measured displacement is likely to be increased due to the reduction of resistance to movement.

It is possible that during the immediate post mortem period there is no blood pressure but fluid remains in the tissues and blood vessels and thus the tooth is supported by a passive hydrodynamic system.

9.2 Pig jaw model experiments

Materials and methods

A series of experiments were carried out using the cheek teeth contained in sections of pig mandible. The jawbone was secured in a vice prior to each experiment.

9.2.1 Incremental bone removal

The reproducibility of Periotest values across the Periotest range was evaluated by taking multiple readings from the molar teeth in a section of pig mandible. The buccal and lingual soft tissues were raised after which the interdental contacts were removed from one tooth. Vertical bone height was reduced circumferentially by increments of approximately 2 millimetres. Twenty readings were taken at each stage. All Periotest readings were taken using the Periotest handheld rather than clamped.

Measurements were taken from a control tooth at the start and regularly throughout each experiment to ensure that no other experimental conditions were affecting the
results. (This was done for all experiments using the pig jaw model)

The computerised signal capture system was used to record all 16 impacts for 1 of these readings at each stage. Signal analysis was then performed using the Sigavg\textsuperscript{*} software. The signal characteristic measurements taken included signal duration; signal amplitude (output voltage) and signal area. The choice of signal duration as the parameter analysed by the Periotest has not been explained by the developers or manufacturers.

Results and discussion

Table 5 shows mean of 20 Periotest values taken from one tooth tabulated against bone height and the standard deviation of Periotest values.

<table>
<thead>
<tr>
<th>Bone Height</th>
<th>Mean Periotest value (n=20)</th>
<th>Standard deviation of Periotest values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flap raised</td>
<td>5.70</td>
<td>0.833</td>
</tr>
<tr>
<td>I.D contact removed</td>
<td>6.70</td>
<td>1.159</td>
</tr>
<tr>
<td>2-3 mm bone removed</td>
<td>7.90</td>
<td>0.316</td>
</tr>
<tr>
<td>4-7 mm total bone removed</td>
<td>10.60</td>
<td>1.771</td>
</tr>
<tr>
<td>6-9 mm total bone removed</td>
<td>29.20</td>
<td>3.167</td>
</tr>
<tr>
<td>8-12 mm total bone removed</td>
<td>39.40</td>
<td>5.825</td>
</tr>
<tr>
<td>10-13 mm total bone removed</td>
<td>45.35</td>
<td>5.920</td>
</tr>
<tr>
<td>12-16 mm total bone removed</td>
<td>50.00</td>
<td>0</td>
</tr>
</tbody>
</table>

*Cambridge electronic design
Periotest value is plotted against bone removal (figure 27) as a bar chart because bone removal cannot be considered strictly linear. Raising the soft tissues and removal of interdental contact points produced small increases in Periotest value. Incremental removal of 2-3 millimetres of bone produced larger increases. At this time it was at

![Bar chart showing Periotest value against bone removal.](image)

**Figure 27. Periotest value against bone removal.**

least comforting to note the approximately linear increases in Periotest value with increasing attachment loss.

The standard deviation of Periotest values is also tabulated in table 5. Reproducibility is high in the lower part of the scale with a standard deviation of less than 1 at 6 units. Reproducibility gradually decreases further up the Periotest scale with a standard deviation of almost 6 at 45 units.
Signal analysis

Figure 28 is a screen dump from the signal review and analysis software. It shows a Periotest signal with output voltage plotted against time in milliseconds. The basemarker is set at the start of the signal and the cursor is set where the signal recrosses the zero volt threshold. The information of channel number; start time; duration; mean output voltage and signal area were output to a log file. Log files were then imported into a spreadsheet package for further analysis.

Figure 28. A screen dump from Sigavg with voltage plotted against time (ms).
Table 6. Periotest value tabulated against means of contact time (ms), signal amplitude (volts) and signal area (vsec).

Figure 29 shows Periotest value plotted against experimental contact time and is comparable to the calculated relationship.

<table>
<thead>
<tr>
<th>Periotest value</th>
<th>Mean signal duration (ms)(n=16)</th>
<th>Mean signal n=16 amplitude (volts)</th>
<th>Mean Area(vsec)(n=16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.519</td>
<td>4.198</td>
<td>-0.00111</td>
</tr>
<tr>
<td>5</td>
<td>0.590</td>
<td>4.428</td>
<td>-0.00143</td>
</tr>
<tr>
<td>7</td>
<td>0.650</td>
<td>3.440</td>
<td>-0.00109</td>
</tr>
<tr>
<td>11</td>
<td>0.810</td>
<td>2.627</td>
<td>-0.00102</td>
</tr>
<tr>
<td>17</td>
<td>0.830</td>
<td>2.430</td>
<td>-0.00107</td>
</tr>
<tr>
<td>26</td>
<td>1.192</td>
<td>1.948</td>
<td>-0.00115</td>
</tr>
<tr>
<td>27</td>
<td>1.187</td>
<td>1.852</td>
<td>-0.00111</td>
</tr>
<tr>
<td>27</td>
<td>1.251</td>
<td>1.725</td>
<td>-0.00118</td>
</tr>
<tr>
<td>35</td>
<td>1.552</td>
<td>1.038</td>
<td>-0.00089</td>
</tr>
<tr>
<td>36</td>
<td>1.836</td>
<td>1.059</td>
<td>-0.00089</td>
</tr>
<tr>
<td>36</td>
<td>1.980</td>
<td>0.924</td>
<td>-0.00086</td>
</tr>
<tr>
<td>38</td>
<td>1.679</td>
<td>1.222</td>
<td>-0.00088</td>
</tr>
<tr>
<td>44</td>
<td>1.890</td>
<td>0.490</td>
<td>-0.00081</td>
</tr>
<tr>
<td>45</td>
<td>1.900</td>
<td>1.110</td>
<td>-0.00076</td>
</tr>
<tr>
<td>50</td>
<td>2.189</td>
<td>0.727</td>
<td>-0.00078</td>
</tr>
</tbody>
</table>

Figure 29. Periotest value plotted against signal duration (ms).
Signal amplitude is presumably directly proportional to the resistance of the tooth to movement and for this reason was plotted against signal duration (Figure 30). While there is clearly a relationship between the two parameters the graph gives an indication that the resolution in the upper part of the scale would be compromised when analysing signal amplitude. At contact times of 1.5 to 2.25 milliseconds representing 35 to 50 on the current scale there is no resolution of amplitude values.

\[ \text{Area} \sim \text{signal duration (t) } \times \text{force} \]

\[ \sim \frac{t \cdot m(v-v_1)}{t} \]

\[ \sim m(v-v_1) \]

where \( v-v_1 \) = deceleration

Thus the area of a Periotest signal is proportional to change in momentum of the Periotest slug.
Figure 31 plots the areas of Periotest signals against contact time. There is no obvious relationship between the two parameters.

Figure 31. The integral (area) of the Periotest signal plotted against signal duration.
9.3 Factors affecting the Periotest signal

A series of factors affecting the Periotest signal have been identified. The slug mass and the modulus of the slug and accelerometer are constant.

The variable factors are listed below:

1. Tooth mass.
2. Enamel modulus.
3. Application point relative to the notional centre of rotation of the tooth.
4. Angle of application variable in the horizontal plane.
5. Angle of application variable in the vertical plane.
6. Tooth support constants. The spring constant is presumed to be dominant for firm teeth while the damping constant is probably dominant for loose teeth.

A series of experiments were performed to examine the effects of the variable factors on the Periotest signal.
9.3.1 Tooth mass

This experiment was performed on the pig jaw model to quantify the effect of changing tooth mass. This could occur clinically when a tooth is crowned.

Materials and methods.

Bone removal around four posterior teeth in a section of pig mandible produced teeth of mobilities varying across the Periotest range. The mandible was clamped in a vice and a series of six lead discs, of mass of up to just over nine grams, were sequentially added to each tooth using cyanoacrylate glue.

Twenty Periotest measurements were made at each level of mass addition. The computerised signal capture system was used to record a full series of Periotest signals for one Periotest measurement at each level of mass addition. The Sigavg software was then used to measure signal amplitude and signal duration for each of the sixteen signals.

Clinical cases
The clinical significance of the effects of mass addition were to some extent clarified by a laboratory survey of crown mass. The masses of thirty crowns from different clinical cases and a number of different operators were measured using a laboratory balance.

The wet weight of a small number of extracted human teeth and teeth from pig jaws were also measured.
Results and discussion.

Table 7 represents 560 Periotest measurements and lists mean values for the four teeth at the six levels of mass addition.

<table>
<thead>
<tr>
<th>Added mass (grams)</th>
<th>0</th>
<th>1.92</th>
<th>2.57</th>
<th>3.71</th>
<th>4.58</th>
<th>6.98</th>
<th>9.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth M1</td>
<td>40.00</td>
<td>49.45</td>
<td>49.40</td>
<td>50.00</td>
<td>50.00</td>
<td>21.00</td>
<td>-4.10</td>
</tr>
<tr>
<td>Tooth M2</td>
<td>26.10</td>
<td>27.40</td>
<td>28.65</td>
<td>25.90</td>
<td>15.10</td>
<td>2.50</td>
<td>30.00</td>
</tr>
<tr>
<td>Tooth M3</td>
<td>14.90</td>
<td>15.80</td>
<td>15.85</td>
<td>12.95</td>
<td>3.30</td>
<td>-2.70</td>
<td>-4.60</td>
</tr>
<tr>
<td>Tooth M4</td>
<td>4.95</td>
<td>2.50</td>
<td>3.25</td>
<td>1.30</td>
<td>-1.95</td>
<td>-1.25</td>
<td>-2.95</td>
</tr>
</tbody>
</table>

Table 7. The effects of mass addition on mean Periotest value.

Figure 32. Periotest value plotted against added mass for each of the four test teeth.

Figure 32 shows the same information in graphical form with Periotest value plotted against added mass. The firmest tooth (M4) with an initial mean Periotest value of 4.95 exhibits a gradual fall in Periotest value to -2.95 units at 9.10 grams.
The tooth with an initial mean Periotest value of 14.9 units exhibits very little change at mass addition levels of 1.92 grams and 2.57 grams followed by a dramatic fall to -4.6 units at 9.10 grams.

The tooth with an initial mean Periotest value of 26.1 units shows very little change with mass additions of up to 3.71 grams. Values then fall to 15.1 units at 4.58 grams and -2.5 units at 6.98 grams before rising again to 30 units at 9.10 grams.

The loosest tooth with an initial mean Periotest value of 40 units shows an immediate increase to 49.5 units at 1.92 grams and remains at approximately this value for addition levels of 2.57 grams, 3.71 grams and 4.48 grams. Mean Periotest values then decrease to 21 at 6.98 grams and -4.1 at 9.10 grams.

Statistical analysis of the significance of the effects of mass addition was carried out with the Bonferroni multiple comparison T-test using SAS software\(^5\). This test was used to compare Periotest means, by tooth, for the seven levels of mass addition. Differences between means were considered to be significant at the alpha level of 0.05.

\(^5\) v6.03 SAS, Medmenham, England
Pig Jaw Model

Table 8 shows the Bonferroni groupings for tooth M1. Means with the same letter are not significantly different. Thus the Periotest mean for no mass addition is significantly different from all others. The Periotest means for mass addition levels of 1.92 grams, 2.57 grams, 3.71 grams and 4.58 grams are significantly different from all other levels but not from each other. Periotest means for mass addition levels of 6.98 grams and 9.10 grams are significantly different from all other levels of mass addition and each other.
### Table 9. Bonferroni groupings for significant differences between Periotest means for tooth M2. Means with the same letter are not significantly different.

Table 9 shows the Bonferroni groupings for tooth M2. The Periotest mean for no mass addition is significantly different from all levels of mass addition except 3.71 grams. All other levels of mass addition give Periotest means significantly different from each other.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni Groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>B</td>
</tr>
<tr>
<td>2.57</td>
<td>C</td>
</tr>
<tr>
<td>3.71</td>
<td>A</td>
</tr>
<tr>
<td>4.58</td>
<td>D</td>
</tr>
<tr>
<td>6.98</td>
<td>E</td>
</tr>
<tr>
<td>9.10</td>
<td>F</td>
</tr>
</tbody>
</table>

### Table 10. Bonferroni groupings for significant differences between Periotest means for tooth M3. Means with the same letter are not significantly different.

Table 10 shows the Bonferroni groupings for tooth M3. The Periotest mean for no mass addition is significantly different from all levels of mass addition except 3.71 grams. All other levels of mass addition give Periotest means significantly different from each other.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni Groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>B</td>
</tr>
<tr>
<td>2.57</td>
<td>A</td>
</tr>
<tr>
<td>3.71</td>
<td>A</td>
</tr>
<tr>
<td>4.58</td>
<td>B</td>
</tr>
<tr>
<td>6.98</td>
<td>C</td>
</tr>
<tr>
<td>9.10</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>D</td>
</tr>
</tbody>
</table>
Table 10 gives the Bonferroni groupings for tooth M3. The Periotest mean for no mass addition is not significantly different from the Periotest means for 1.92 grams, 2.57 grams and 3.71 grams of mass addition but is significantly different from the Periotest means for 4.48 grams or more of mass addition.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni Groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>B</td>
</tr>
<tr>
<td>2.57</td>
<td>B</td>
</tr>
<tr>
<td>3.71</td>
<td>C</td>
</tr>
<tr>
<td>4.58</td>
<td>D</td>
</tr>
<tr>
<td>6.98</td>
<td>D</td>
</tr>
<tr>
<td>9.10</td>
<td>E</td>
</tr>
</tbody>
</table>

Table 11. Bonferroni groupings for significant differences between Periotest means for tooth M4. Means with the same letter are not significantly different.

Table 11 gives the Bonferroni groupings for tooth M4. The Periotest mean for no mass addition is significantly different from the Periotest means for all levels of mass addition.

Comparisons of means between teeth were considered inappropriate using this test. Non-parametric analysis of variance with Wilcoxon T-Tests were used to compare Periotest means with no mass addition against means of pooled data for all levels of mass addition, for each tooth.
Table 12 shows that the differences between Periotest value means with no mass addition are not significantly different from Periotest means after mass addition for teeth M1 and M2 but are significant for Teeth M3 and M4.

The mean mass of 30 gold crowns was approximately 1.5 grams while the heaviest was just under three grams. It is concluded that the effects of crowning may cause small but statistically significant changes in Periotest value, for teeth of the pig jaw model. These changes are more likely to be clinically significant for loose teeth than for tight teeth.

The wet weight of human and of pig teeth is of the order of 0.75 to 2 grams. The masses of the four teeth tested in the mass addition experiment varied between 0.72 and 1.36 grams and it is interesting to note that the dramatic changes in Periotest value occur as the total tooth mass approaches the 8 gram mass of the slug.
Pig Jaw Model

Signal analysis

To explain the mechanism of the effects of mass addition on Periotest values it is necessary to examine the Periotest signals collected at each stage.

Table 13 represents over 3500 cursor measurements from 900 Periotest signals and lists contact time (designated X) in milliseconds and signal amplitude (designated Y) in volts for each tooth (designated M1 to M4) at each level of mass addition.

Table 13. Mean signal duration (X)(ms) and signal amplitude (Y)(Volts) for each of four teeth (M1 to M4) for each level of mass addition. * values are means used when the periotest has averaged X1 and X2 (double bounce).

<table>
<thead>
<tr>
<th>Added mass (grams)</th>
<th>0</th>
<th>1.92</th>
<th>2.57</th>
<th>3.71</th>
<th>4.58</th>
<th>6.98</th>
<th>9.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1X</td>
<td>1.89</td>
<td>2.58</td>
<td>2.49</td>
<td>2.79</td>
<td>2.28</td>
<td>1.31</td>
<td>*0.38</td>
</tr>
<tr>
<td>M2X</td>
<td>1.11</td>
<td>1.22</td>
<td>*1.22</td>
<td>1.12</td>
<td>0.73</td>
<td>*0.39</td>
<td>1.25</td>
</tr>
<tr>
<td>M3X</td>
<td>0.80</td>
<td>0.76</td>
<td>0.78</td>
<td>0.76</td>
<td>0.49</td>
<td>0.41</td>
<td>0.34</td>
</tr>
<tr>
<td>M4X</td>
<td>0.56</td>
<td>0.49</td>
<td>0.46</td>
<td>0.43</td>
<td>0.41</td>
<td>0.40</td>
<td>0.35</td>
</tr>
<tr>
<td>M1Y</td>
<td>0.48</td>
<td>1.80</td>
<td>2.46</td>
<td>2.46</td>
<td>1.83</td>
<td>3.33</td>
<td>3.81</td>
</tr>
<tr>
<td>M2Y</td>
<td>1.53</td>
<td>3.52</td>
<td>3.12</td>
<td>2.15</td>
<td>3.40</td>
<td>3.55</td>
<td>5</td>
</tr>
<tr>
<td>M3Y</td>
<td>2.98</td>
<td>2.66</td>
<td>4.15</td>
<td>4.44</td>
<td>2.50</td>
<td>4.32</td>
<td>5</td>
</tr>
<tr>
<td>M4Y</td>
<td>4.56</td>
<td>4.91</td>
<td>4.59</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Statistical analysis of the effects of mass addition on signal duration was done using the Bonferroni multiple comparison T-test. Signal duration means were compared, by tooth, for each level of mass addition. Differences between the means were considered significant at the alpha level of 0.05.
### Table 14. Bonferroni groupings for significant differences between signal duration means for tooth M1. Means with the same letter are not significantly different.

The signal duration mean for no mass addition is significantly different from those for all levels of mass addition except 4.58 grams.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>B</td>
</tr>
<tr>
<td>2.57</td>
<td>B</td>
</tr>
<tr>
<td>3.71</td>
<td>B</td>
</tr>
<tr>
<td>4.58</td>
<td>A</td>
</tr>
<tr>
<td>6.98</td>
<td>C</td>
</tr>
<tr>
<td>9.10</td>
<td>D</td>
</tr>
</tbody>
</table>

### Table 15. Bonferroni groupings of significant differences between signal duration means for tooth M2. Means with the same letter are not significantly different.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>A</td>
</tr>
<tr>
<td>2.57</td>
<td>A</td>
</tr>
<tr>
<td>3.71</td>
<td>A</td>
</tr>
<tr>
<td>4.58</td>
<td>A</td>
</tr>
<tr>
<td>6.98</td>
<td>B</td>
</tr>
<tr>
<td>9.10</td>
<td>A</td>
</tr>
</tbody>
</table>
Table 15 shows that the signal amplitude mean for mass addition of 6.98 grams is significantly different from all other levels of mass addition.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>B</td>
</tr>
<tr>
<td>2.57</td>
<td>C</td>
</tr>
<tr>
<td>3.71</td>
<td>B</td>
</tr>
<tr>
<td>4.58</td>
<td>D</td>
</tr>
<tr>
<td>6.98</td>
<td>E</td>
</tr>
<tr>
<td>9.10</td>
<td>F</td>
</tr>
</tbody>
</table>

Table 16. Bonferroni groupings for significant differences between signal duration means for tooth M3. Means with the same letter are not significantly different.

Table 16 gives Bonferroni groupings for tooth M3 and shows that the signal duration mean at no mass addition is significantly different from those at all levels of mass addition. Other signal duration means are significantly different from each other except at 1.92 grams and 3.71 grams of mass addition.
Table 17. Bonferroni groupings for significant differences between signal duration means for tooth M4.

Table 17 shows that signal duration means at all levels of mass addition are significantly different from each other.

Figure 33 is a plot of signal duration against added mass and is comparable with the plot of Periotest value against added mass. It is, however, a radical oversimplification of the results.

Figure 33. Signal duration plotted against added mass for each of the test teeth.

Figure 34 shows individual examples of Periotest signals with accelerometer output.
voltage plotted against time for each level of mass addition. Mean Periotest value (P.T.); mean signal duration (t) in milliseconds used by the system to calculate Periotest value and mean signal amplitude are given in the frame of each graph.

All of these signals have a double peak. This occurs where the first impact fails to stop the slug and it continues to move forward to impact the tooth again. The difficulties arise when the signal crosses the zero level between two peaks, producing two possible zero points. The manufacturers have provided no details of the criteria that the system applies to analyse this type of signal however it can be deduced from the data presented here.

For the first signal with no added mass there is only one possible zero point at 1.11 milliseconds producing a Periotest value of 26 units.

The signal for mass addition of 1.92 grams has two possible zero points at 0.33 and 2.1 milliseconds. These points correspond to Periotest values of -5 and 47 respectively and yet the system produced a value of 27. This corresponds approximately to an average of the two possible contact times.

The signal for mass addition of 2.57 grams has two possible zero points but Periotest value of 29 clearly corresponds to the second zero point. This is also true for mass addition of 3.71 grams.
The effect of added mass on Periotest signals.

These traces are examples from sets of ~16 impacts.

- \( t \) = mean signal duration (ms) (of ~16)
- \( v \) = mean signal amplitude (volts) (of ~16)
- \( P.T. \) = mean periotest value (of 20)

- \( t_1 \) = end of first bounce
- \( t_2 \) = end of second bounce
The signal for addition of 4.58 grams has two possible zero points at 0.46 and 1.45 milliseconds corresponding to Periotest values of 2 and 35 respectively. The system actually produces a Periotest value of 15.

The signal for mass addition of 6.98 grams has two possible zero points but the Periotest value of -2 clearly corresponds to the first.

Finally the signal for mass addition of 9.10 grams has three peaks but only two possible zero points. The Periotest value produced corresponds to the second.

Examination of this data leads to an explanation of the behaviour of the Periotest microprocessor. The system averages contact times of each of the 16 signals then calculates Periotest value. It accepts the end of the final peak as the end of the contact time if the peak is registered. It would appear that a threshold output voltage of the order of -0.1 volts must be crossed for a peak to be registered. Presumably this has been done to eliminate erroneous readings that could be caused by signal noise. In situations when the system appears to have used an average of two possible contact times the second peak does not always register. In both examples at mass addition levels of 1.92 and 4.58 grams approximately half of the second peaks cross the -0.1 volt threshold and thus register.

Statistical analysis of signal amplitude was also done using the Bonferroni multiple comparison T-test. Means of signal amplitude were compared, by tooth, for each level of mass addition. Differences between means were considered significant at the
0.05 alpha level.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>B</td>
</tr>
<tr>
<td>2.57</td>
<td>C</td>
</tr>
<tr>
<td>3.71</td>
<td>C</td>
</tr>
<tr>
<td>4.58</td>
<td>B</td>
</tr>
<tr>
<td>6.98</td>
<td>D</td>
</tr>
<tr>
<td>9.10</td>
<td>E</td>
</tr>
</tbody>
</table>

*Table 18.* Bonferroni groupings of significant differences between signal amplitude means for tooth M1. Means with the same letter are not significantly different.

Table 18 shows that the signal amplitude mean of tooth M1 with no mass addition is significantly different from the signal amplitude means at all levels of mass addition.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>B</td>
</tr>
<tr>
<td>2.57</td>
<td>C</td>
</tr>
<tr>
<td>3.71</td>
<td>D</td>
</tr>
<tr>
<td>4.58</td>
<td>B</td>
</tr>
<tr>
<td>6.98</td>
<td>B</td>
</tr>
<tr>
<td>9.10</td>
<td>E</td>
</tr>
</tbody>
</table>

*Table 19.* Bonferroni groupings of significant differences between signal amplitude means for tooth M2. Means with the same letter are not significantly different.
Table 19 shows that the signal amplitude mean for tooth M2 with mass addition is significantly different from those at all levels of mass addition.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>B</td>
</tr>
<tr>
<td>2.57</td>
<td>C</td>
</tr>
<tr>
<td>3.71</td>
<td>D</td>
</tr>
<tr>
<td>4.58</td>
<td>B</td>
</tr>
<tr>
<td>6.98</td>
<td>C</td>
</tr>
<tr>
<td>9.10</td>
<td>E</td>
</tr>
</tbody>
</table>

*Table 20. Bonferroni groupings of significant differences between signal amplitude means for tooth M3. Means with the same letter are not significantly different.*

Table 20 shows that the mean signal amplitude for tooth M3 with no mass addition is significantly different from the mean signal amplitude at all levels of mass addition.

<table>
<thead>
<tr>
<th>Added Mass (grams)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>1.92</td>
<td>B</td>
</tr>
<tr>
<td>2.57</td>
<td>A</td>
</tr>
<tr>
<td>3.71</td>
<td>B</td>
</tr>
<tr>
<td>4.58</td>
<td>B</td>
</tr>
<tr>
<td>6.98</td>
<td>B</td>
</tr>
<tr>
<td>9.10</td>
<td>B</td>
</tr>
</tbody>
</table>

*Table 21. Bonferroni groupings for significant differences between signal amplitude means for tooth M4. Means with the same letter are not significantly different.*
Table 21 shows that the mean signal amplitude for tooth M4 with no mass addition is significantly different from the means at all levels of mass addition except 2.57 grams.

Figure 35 shows signal amplitude plotted against added mass for each of the four test teeth. It illustrates the problems that would be encountered when using signal amplitude for mobility analysis. Even low levels of mass addition cause large changes in signal amplitude. While signal amplitude is proportional to the resistance of the tooth to movement it is highly dependant on the inertial component of this resistance and is thus greatly affected by tooth mass.
9.3.2 Enamel modulus

An experiment had been planned to examine the effects of temporary crown placement on teeth of varying mobilities using the pig jaw model. On the basis of the pilot study the planned experiment was not done.

9.3.3 Application point

An experiment was carried out to examine the effects of varying the point of application of the Periotest in relation to the cusp tip.

Materials and methods

Five teeth of mobilities varying across the Periotest range from the clamped pig jaw model were used. Twenty Periotest measurements were taken from each tooth at distances of 2.5, 5, 7.5 and 10mm from the cusp tip. The normal application point is 5 mm from the cusp tip.

The cheek teeth of pigs (PM3, PM4 and M1, M2 and M3) are relatively flat sided except in the coronal 2 millimetres where they curve in sharply to the cusp tip.
Results and discussion

<table>
<thead>
<tr>
<th>Distance from the cusp tip (mm)</th>
<th>M1</th>
<th>S.D.</th>
<th>M2</th>
<th>S.D.</th>
<th>M3</th>
<th>S.D.</th>
<th>M4</th>
<th>S.D.</th>
<th>M5</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>32.9</td>
<td>1.85</td>
<td>27.3</td>
<td>1.31</td>
<td>11.4</td>
<td>0.52</td>
<td>10.7</td>
<td>0.82</td>
<td>21.9</td>
<td>1.00</td>
</tr>
<tr>
<td>5.0</td>
<td>48.5</td>
<td>4.74</td>
<td>24.1</td>
<td>1.72</td>
<td>7.8</td>
<td>1.40</td>
<td>7.3</td>
<td>0.48</td>
<td>16.1</td>
<td>0.32</td>
</tr>
<tr>
<td>7.5</td>
<td>31.5</td>
<td>1.84</td>
<td>20.8</td>
<td>1.11</td>
<td>6.0</td>
<td>0.94</td>
<td>4.1</td>
<td>0.32</td>
<td>14.4</td>
<td>0.70</td>
</tr>
<tr>
<td>10.0</td>
<td>29.6</td>
<td>2.17</td>
<td>15.6</td>
<td>0.93</td>
<td>4.8</td>
<td>0.42</td>
<td>1.2</td>
<td>1.81</td>
<td>8.0</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Table 22. The means and standard deviations of Periotest values for each tooth at each distance from the cusp tip.

Figure 36 shows the same data in graphical form with mean Periotest values plotted against distance of application from the cusp tip. The Periotest values for the four firmest teeth decrease as the application point moves apically towards the notional centre of rotation of each tooth.

Figure 36. Mean Periotest values against distance from the cusp tip for each of the five test teeth.
The situation for the loosest tooth is less clear. The values at 5mm from the cusp tip and beyond follow the same trend as for the other teeth. The value at 2.5mm from the cusp tip is difficult to interpret however, re-examination of the test tooth showed that at this point the tooth surface was highly curved.

Statistical analysis of this data was done using the Bonferroni multiple comparison T-test to evaluate the significance of the differences between the Periotest means at each application point for each tooth.

<table>
<thead>
<tr>
<th>Distance from the cusp tip (mm)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>A</td>
</tr>
<tr>
<td>5.0</td>
<td>B</td>
</tr>
<tr>
<td>7.5</td>
<td>A</td>
</tr>
<tr>
<td>10.0</td>
<td>A</td>
</tr>
</tbody>
</table>

*Table 23. Bonferroni groupings for the significance of differences between Periotest means for each application point for tooth M1. Means with the same letter are not significantly different.*

Table 23 shows that the Periotest mean for the application point 5 mm from the cusp tip is significantly different from the Periotest means of all other application points for tooth M1.

<table>
<thead>
<tr>
<th>Distance from the cusp tip (mm)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>A</td>
</tr>
<tr>
<td>5.0</td>
<td>B</td>
</tr>
<tr>
<td>7.5</td>
<td>C</td>
</tr>
<tr>
<td>10.0</td>
<td>D</td>
</tr>
</tbody>
</table>

*Table 24. Bonferroni groupings for the significance of differences between Periotest means for each application point for tooth M2. Means with the same letter are not significantly different.*
Table 24 shows that the Periotest means for each application point are all significantly different from each other for tooth M2.

<table>
<thead>
<tr>
<th>Distance from the cusp tip (mm)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>A</td>
</tr>
<tr>
<td>5.0</td>
<td>B</td>
</tr>
<tr>
<td>7.5</td>
<td>C</td>
</tr>
<tr>
<td>10.0</td>
<td>D</td>
</tr>
</tbody>
</table>

*Table 25. Bonferroni groupings for significance of differences between Periotest means for each application point for tooth M3. Means with the same letter are not significantly different.*

Table 25 shows that the Periotest means for each application point are all significantly different from each other for tooth M3.

<table>
<thead>
<tr>
<th>Distance from the cusp tip (mm)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>A</td>
</tr>
<tr>
<td>5.0</td>
<td>B</td>
</tr>
<tr>
<td>7.5</td>
<td>C</td>
</tr>
<tr>
<td>10.0</td>
<td>D</td>
</tr>
</tbody>
</table>

*Table 26. Bonferroni groupings for the significance of differences between means of Periotest values for each application point for tooth M4. Means with the same letter are not significantly different from each other.*
Table 26 shows that the Periotest means for tooth M4 for each application point are all significantly different from each other.

<table>
<thead>
<tr>
<th>Distance from the cusp tip (mm)</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>A</td>
</tr>
<tr>
<td>5.0</td>
<td>B</td>
</tr>
<tr>
<td>7.5</td>
<td>C</td>
</tr>
<tr>
<td>10.0</td>
<td>D</td>
</tr>
</tbody>
</table>

*Table 27. Bonferroni groupings for the significance of differences between Periotest means for each application point for tooth M5. Means with the same letter are not significantly different.*

Table 27 shows that the Periotest means for tooth M5 for each application point are all significantly different from each other. Thus the Periotest means for the application point 5mm from the cusp tip are significantly different from the means of all other application points for all five teeth.

Further examination of the Periotest means reveals that the effects of varying the point of application proved to be greater with increasing tooth mobility. The results of this experiment concur with those of the mass addition experiment in that teeth registering mobilities in the upper part of the Periotest range show a greater propensity to produce anomalous readings.

From a clinical standpoint it is concluded that it is important to use the correct application point and that this must be consistent if Periotest values are to be
Recordings of the Periotest signals for this experiment produced no useful additional information and are therefore not presented here.

9.3.4 Angle of application varied in the horizontal plane

An experiment was conducted to examine the effects of varying the angle of application of the Periotest handpiece in the horizontal plane.

Materials and methods

Five teeth with interdental contact points of a clamped pig jaw model were used. The correct angle of application is perpendicular to the tooth surface. Twenty Periotest measurements were taken from each tooth at the correct angle and then at 10°, 20° and 30° to this with the handpiece pointing in an increasingly distal direction. An increasingly distal angulation was chosen as this is the most liable to be necessary in a mouth where the lips and cheeks may prevent correct application. Angulations were established using a large protractor clamped at a convenient point adjacent to the test tooth.

Results and discussion.

Table 28 shows the means and standard deviations of Periotest values for each tooth at each of the four angulations.
Table 28. Means and standard deviations of Periotest values for each tooth for each of the four angulations.

Figure 37 shows the same data with mean Periotest values plotted against angle of application from the perpendicular, varied in the horizontal plane. Small changes in Periotest value were demonstrated by the four firmest teeth. The loosest tooth with an initial mean Periotest value of 48.5 showed no change at an angle of 10° but a reduction of 15 Periotest units at 20° and 17 units at 30°.

The statistical significance of the differences between the Periotest means was
evaluated using the Bonferroni multiple comparison T-test for each tooth. Periotest means were considered to be significantly different at the 0.05 alpha level.

<table>
<thead>
<tr>
<th>Horizontal angulation</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>10</td>
<td>A</td>
</tr>
<tr>
<td>20</td>
<td>B</td>
</tr>
<tr>
<td>30</td>
<td>B</td>
</tr>
</tbody>
</table>

*Table 29. Bonferroni groupings for the significance of differences between Periotest means at each angle of application for tooth M1. Means with the same letter are not significantly different.*

Table 29 shows that the Periotest mean for 0° (i.e. perpendicular to the tooth surface) is not significantly different from 10° but is significantly different from the means at 20° and 30° for tooth M1.

<table>
<thead>
<tr>
<th>Horizontal angulation</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>10</td>
<td>A</td>
</tr>
<tr>
<td>20</td>
<td>A</td>
</tr>
<tr>
<td>30</td>
<td>B</td>
</tr>
</tbody>
</table>

*Table 30. Bonferroni groupings for the significance of the differences between Periotest means for each angle of application for tooth M2. Means with the same letter are not significantly different.*

From table 30 it is clear that for tooth M2 the Periotest mean for 0° is not significantly different from that for 10° or 20° but is significantly different from that for 30°.
Table 31. Bonferroni groupings for the significance of differences between Periotest means for each angle of application for tooth M3. Means with the same letter are not significantly different.

For tooth M3 (Table 31) the mean Periotest value for 0° is not significantly different from those for 10° and 20° but is significantly different from that for 30°.

Table 32. Bonferroni groupings for the significance of differences between Periotest means for each angle of application for tooth M4. Means with the same letter are not significantly different.

The Periotest mean for 0° is significantly different from that for 10° but not 20° or 30° for tooth M4.
Table 33. Bonferroni groupings for the significance of differences between Periotest means for each angle of application for tooth M5. Means with the same letter are not significantly different.

For tooth M5 the Periotest mean for 0° is not significantly different from 10° and 20° but is significantly different from that for 30°.

Periotest values were expected to decrease as the handpiece was applied in an increasingly distal direction. The interdental contact points of pig teeth are small in comparison to those of human teeth.

The results of this experiment are in contrast to experience on human subjects. The reductions in Periotest values of teeth demonstrating mobilities of 2 or more on the Miller scale are large particularly if the test tooth is adjacent to a clinically firm tooth. For this reason errors of angulation in the horizontal plane must be avoided.

Once again recordings of the Periotest signals provided no additional useful information and are not presented.
9.3.5 Angle of application varied in the vertical plane

This experiment was carried out to examine the effect of varying the angle of application of the Periotest handpiece in the vertical plane.

Materials and methods

Five teeth of the clamped pig jaw model were used to collect Periotest data with the Periotest handpiece held at angles including and varying from the horizontal. Twenty Periotest measurements were taken for each tooth at -30° and at 10° intervals to +30°, with negative angles indicating that the Periotest handpiece is pointing coronally and positive angles indicating that it is pointing apically. The angles were established using a protractor clamped in a convenient position adjacent to the test tooth.

Results and discussion

Table 34 shows the mean Periotest values for each tooth for each of the seven angles tested.

<table>
<thead>
<tr>
<th>Vertical angulation</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>31.6</td>
<td>28.9</td>
<td>18.8</td>
<td>13.2</td>
<td>6.1</td>
</tr>
<tr>
<td>20</td>
<td>34.8</td>
<td>30.2</td>
<td>21.3</td>
<td>13.9</td>
<td>8.2</td>
</tr>
<tr>
<td>10</td>
<td>37.1</td>
<td>33.7</td>
<td>23.6</td>
<td>15.1</td>
<td>7.4</td>
</tr>
<tr>
<td>0</td>
<td>40.6</td>
<td>33.5</td>
<td>24.7</td>
<td>14.6</td>
<td>7.8</td>
</tr>
<tr>
<td>-10</td>
<td>42.3</td>
<td>35.3</td>
<td>23.2</td>
<td>16.6</td>
<td>10.3</td>
</tr>
<tr>
<td>-20</td>
<td>45.0</td>
<td>34.6</td>
<td>23.8</td>
<td>17.9</td>
<td>12.4</td>
</tr>
<tr>
<td>-30</td>
<td>46.9</td>
<td>37.7</td>
<td>24.9</td>
<td>18.9</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Table 34. Mean Periotest values for each tooth at each of the seven angles tested.
Figure 38 shows this data graphically with mean Periotest value plotted against angulation from the horizontal. Minus angles indicate that the handpiece is pointing coronally and positive angles indicate that the handpiece points apically. The line through the centre of the graph gives the correct angulation.

![Graph showing mean Periotest value plotted against angle varied in the vertical plane for each of the five test teeth.](image)

**Figure 38.** Mean Periotest value plotted against angle varied in the vertical plane for each of the five test teeth.

The trend is for Periotest values to decrease as the angle of application changes from -30° to +30°. Moving from left to right on the graph the tooth is being tested in an increasingly apical direction and thus the resistance of the tooth to movement is increasing.

Statistical analysis of these results was achieved using the Bonferroni multiple comparison t-test to test for the significance of differences between Periotest means for each angulation for each tooth.
Table 35. Bonferroni groupings for the significance of differences between Periotest means for each of the angulations for tooth M1. Angles with the same letter are not significantly different.

Table 35 shows that the mean Periotest score for 0° is only significantly different from the mean at 30° for tooth M1.

<table>
<thead>
<tr>
<th>Angulation</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>A</td>
</tr>
<tr>
<td>-20</td>
<td>A</td>
</tr>
<tr>
<td>-10</td>
<td>A, B</td>
</tr>
<tr>
<td>0</td>
<td>A, B, C</td>
</tr>
<tr>
<td>10</td>
<td>B, C, D</td>
</tr>
<tr>
<td>20</td>
<td>C, D</td>
</tr>
<tr>
<td>30</td>
<td>D</td>
</tr>
</tbody>
</table>

Table 36. Bonferroni groupings for the significance of differences between Periotest means for each angle for tooth M2. Angles with the same letter are not significantly different.

<table>
<thead>
<tr>
<th>Angulation</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>A</td>
</tr>
<tr>
<td>-20</td>
<td>A, B</td>
</tr>
<tr>
<td>-10</td>
<td>A, B</td>
</tr>
<tr>
<td>0</td>
<td>A, B, C</td>
</tr>
<tr>
<td>10</td>
<td>A, B, C</td>
</tr>
<tr>
<td>20</td>
<td>A, B, C</td>
</tr>
<tr>
<td>30</td>
<td>B, C</td>
</tr>
</tbody>
</table>
Table 36 shows that the Periotest mean for 0° is significantly different from those for 20° and 30° but no other angulation for tooth M2.

<table>
<thead>
<tr>
<th>Angulation</th>
<th>Bonferroni groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>A</td>
</tr>
<tr>
<td>-20</td>
<td>A, B</td>
</tr>
<tr>
<td>-10</td>
<td>A, B</td>
</tr>
<tr>
<td>0</td>
<td>A</td>
</tr>
<tr>
<td>10</td>
<td>A, B</td>
</tr>
<tr>
<td>20</td>
<td>B, C</td>
</tr>
<tr>
<td>30</td>
<td>C</td>
</tr>
</tbody>
</table>

Table 37. Bonferroni groupings for the significance of differences between Periotest means for each angle for tooth M3. Means with the same letter are not significantly different.

From table 37 it is clear that the Periotest mean for 0° is significantly different from those for 20° and 30° angulations for tooth M3.

<table>
<thead>
<tr>
<th>Angulation</th>
<th>Bonferroni grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>A</td>
</tr>
<tr>
<td>-20</td>
<td>A, B</td>
</tr>
<tr>
<td>-10</td>
<td>A, B, C</td>
</tr>
<tr>
<td>0</td>
<td>B, C, D</td>
</tr>
<tr>
<td>10</td>
<td>B, C, D</td>
</tr>
<tr>
<td>20</td>
<td>C, D</td>
</tr>
<tr>
<td>30</td>
<td>D</td>
</tr>
</tbody>
</table>

Table 38. Bonferroni groupings for the significance of differences between Periotest means for each angle for tooth M4. Means with the same letter are not significantly different.
For tooth M4 the Periotest mean for 0° is significantly different from the means for 30°, -20° and -30°.

<table>
<thead>
<tr>
<th>Angulation</th>
<th>Bonferroni grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>A</td>
</tr>
<tr>
<td>-20</td>
<td>A</td>
</tr>
<tr>
<td>-10</td>
<td>B</td>
</tr>
<tr>
<td>0</td>
<td>C</td>
</tr>
<tr>
<td>10</td>
<td>C</td>
</tr>
<tr>
<td>20</td>
<td>C</td>
</tr>
<tr>
<td>30</td>
<td>D</td>
</tr>
</tbody>
</table>

Table 39. Bonferroni groupings for the significance of differences between Periotest means for each angle for tooth M5. Means with the same letter are not significantly different.

For tooth M5 the Periotest mean for 0° is significantly different from those for -10°, -20° and -30°.

From a practical standpoint angulation errors of more than 15° seem unlikely unless access is severely limited but such errors cause changes which are occasionally statistically significant. The audible warning which sounds when the handpiece is held at more than 30° to the horizontal is redundant as such errors would not be made by accident.
9.4 Displacement measurement

In order to examine the behaviour of teeth when loaded with the Periotest and to compare Periotest readings with traditional tooth mobility measurements an electronic displacement measuring system was assembled.

To overcome some of the difficulties encountered when using the LVDT displacement measuring system during experiments on monkeys an LVDT was linked to the computer recording system. However, examination of the behaviour of teeth loaded horizontally is compromised if movement transducers are attached to the tooth. The effects of transducer attachment may be minimised for axial measurements by aligning the components in one axis but this is not possible when studying horizontal movement.

Equipment.

For this reason a non-contact displacement transducer \(^1\) system was added to the computer recording system. This system functions using the principle of eddy currents induced in a conductive but non-magnetic target.

\(^1\) Kaman Sciences KD 2310 Model 1µ. Supplied by Daco Scientific Ltd. Aldermaston.
The sensor is approximately 22mm in length and of threaded design with a head of 3 mm diameter. The sensor cable is linked to a signal conditioning unit and power supply. A linear output voltage of 5 volts is produced over a displacement range of approximately 1 mm. This output could then be input to the computer recording system.

Figure 39. Non contact transducer sensor.

This particular model was chosen to provide displacement measurement with a claimed resolution of 1 μm and a sensor of proportions usable intraorally. The non-magnetic target option was chosen to allow for the use of light aluminium disc targets. The frequency response is such that the output voltage rise time is 10 microseconds.
Pig Jaw Model

(0.01 Milliseconds) which is acceptable when measuring displacements over time periods of the order of 1 millisecond or more.

The system was zeroed, linearised and then calibrated before and after each experimental session. Calibration was performed using a digital micrometer%, with a resolution of 1 micron, modified to allow for reversible removal of its anvil and attachment of an aluminium target to its spindle. This equipment was then set in a rig built for the purpose (Figure 40)⁺.

Figure 40. Calibration rig made from a digital micrometer.

% Mitutoyo MDC Series 293. Japan.

⁺ Micrometer modifications and calibration rig built by Sandy Mosse, then of Medical Physics Dept. University College Hospital, London.
Pilot work with the transducer indicated the need for variable signal amplification such that different ranges of movement could be examined. A switchable amplifier incorporating the power supply was made to provide a full scale output over 5 different ranges from 10 microns to approximately 1 mm.

Figure 41. Example calibration for the 5 levels of gain with output voltage plotted against displacement.

& Amplifier designed and built by Christine Sweeting, Electronics section of Medical physics Dept. University college Hospital, London.
Nominal Gain level

<table>
<thead>
<tr>
<th>Displacement (mm)</th>
<th>0.010</th>
<th>0.100</th>
<th>0.500</th>
<th>1.000</th>
<th>2.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>0.550</td>
<td>0.137</td>
<td>0.048</td>
<td>0.035</td>
<td>0.038</td>
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<tr>
<td>1.200</td>
<td></td>
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<td></td>
<td></td>
<td>4.304</td>
</tr>
<tr>
<td>1.400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.000</td>
</tr>
</tbody>
</table>

Table 40. Example calibration with displacements tabulated against the output voltages for the five gain levels
Table 40 and figure 41 show an example calibration over the 5 different ranges with the zero point set at 0.05 mm of separation between the target and sensor. The output over each range is linear. The calibration was produced by recording transducer output at 10 micrometer positions regularly spaced across each range. On screen mathematical functions produced mean output values over a specified 10 second period which were then exported via log files and edited for use in spreadsheet software. The calibration was thus entirely electronic with no manual measurement or recording of data required.

Correlation coefficients were calculated for each range and found to be in excess of 0.99 but these statistics are an oversimplification of the accuracy of measurement. An estimate of instantaneous accuracy is produced by examining the range of a signal over a period of, say, 10 seconds. Thus signal noise, which was found to be greatest on the highest level of amplification, is taken into account. On the highest level of amplification instantaneous accuracy was found to be ±1.5 microns.

Zeroing, linearisation and calibration of the transducer were later simplified by the temporary acquisition of a more elaborate system ~ utilising the same sensor type but incorporating a digital voltmeter.

During experiments the zero point was regularly set within the range of movement, ~ Kaman model KD4200 1u SPL - Loan courtesy of Malcolm Reid, Daco Scientific, Aldermaston.
rather than at one extreme, to allow for measurement in either direction from zero. With the zero point set at the centre of the range the maximum effective range becomes approximately ±0.7 mm. This is greater than claimed by the manufacturers but still precludes the examination of teeth at the more interesting end of the Miller mobility scale.

**Figure 42. Example calibrations beyond the linear range of the transducer.**

This sensor is capable of producing output over a larger range but that output is not linear (Figure 42). Custom software was commissioned@ and produced# to allow for the use of recordings of nonlinear data. This had to be run "off line", could not be

@ G.R. and Dr Alf Linney.

# C.E.D. Cambridge.
automated and unfortunately proved unusable with the large volumes of data required. If such software were developed to a higher level and made an integral part of Sigavg the management of non-linear data would be readily possible.

For linear data 2 calibration points for each channel may be entered into the Sigavg calibration menu. On line channel calibration is then performed automatically during data collection which facilitates experimentation and analysis.

9.4.1 Comparison with traditional tooth mobility measurements.

Study of horizontal tooth movement, of the type carried out by Muhlemann, used a dial gauge to measure tooth displacements produced by a handheld dynamometer. The following experiment was designed to compare this so called "semistatic loading" with Periotest values.

Materials and Methods.

Five teeth of the pig jaw model with mobilities varying across the Periotest range were used for this study. The pig jaw was clamped such that the long axis of the test tooth was perpendicular to the floor. An aluminium foil disc of 3 mm diameter was glued to each test tooth and the transducer sensor was clamped perpendicular to the long axis of the tooth.

For each of the five teeth ten Periotest values were noted during simultaneous recording of Periotest signals and tooth displacement data. Figure 43 shows a
schematic diagram of the electronic equipment used for this purpose. The peak displacement produced was then measured electronically from these recordings.

Figure 43. Experimental equipment for simultaneous signal capture.
A handheld Corex gauge was then used to load each tooth, in semistatic fashion, with loads of 100 grams force and 200 grams force. The resultant tooth displacements were recorded and mean displacements calculated from measurements of the recordings. In order to minimise errors caused by signal noise and semistatic nature of tooth loading, tooth displacements for each load were produced by subtracting the mean displacement over a ten second period prior to loading from the mean displacement over a twenty second period after the secondary phase of movement was seen to be complete. Full recovery of each tooth was established prior to repetition of loading.

Results and discussion.

Qualitative results.

Figure 44. Simultaneous tooth displacement (designated 0) and Periotest signals (designated 1) showing 2 “bounces” of the Periotest slug on the tooth during one impact.
Figure 44 is a screen dump direct from the data Review section of Sigavg. It shows a simultaneous recording of tooth displacement (upper trace, designated 0) and the Periotest signal (lower trace, designated 1). The basemarker (dotted line) and cursor (solid line) are set at the end of the first peak and start of the second peak on the Periotest signal. This figure shows that after impact of the Periotest slug the tooth moves away from its resting position for approximately 0.2 milliseconds then begins to recover. During this recovery the velocity of the tooth and the Periotest signal voltage are decreasing. At the cursor a second peak in Periotest signal output voltage begins and the tooth velocity increases again. It is clear that the tooth has been impacted again by the Periotest slug. This phenomenon of "bounces" was first seen during experiments on anaesthetised Macaque monkeys. Following the second bounce the tooth begins to recover its position. This recovery is in two phases with the first phase lasting approximately 0.8 milliseconds. The second phase of recovery is at a slower rate and is of approximately five milliseconds duration before the tooth reaches its starting position. There is some oscillation of the tooth during recovery which continues for a further ten milliseconds (Figure 45).

The first attempts at simultaneous signal capture using an LVDT and recording oscilloscope to record tooth displacement and the Periotest signal from the teeth of anaesthetised Macaque monkeys had suggested a delay of approximately 0.25 milliseconds between the Periotest slug hitting the tooth (current produced by the Periotest accelerometer) and the tooth beginning to move.
Figure 45. The lower trace (displacement) showing oscillation of the tooth for approximately 15 ms after the impact.

Figure 46 is a screen dump of the same signals shown in figure 45 zoomed in to show the beginning of the impact. The Periotest signal is the upper trace and the displacement signal is the lower trace. The data points are not joined. There is a change in output voltage from the Periotest accelerometer before the output voltage from the tooth displacement transducer begins to change. The delay between the start of the two signals appears to be 0.06 milliseconds. This measurement cannot be considered to be accurate as the maximum sampling rate for two channel recording produces 42 data points per channel per millisecond. This is one data point for each channel every 0.024 milliseconds, recorded 0.012 milliseconds apart. The "delay" between the two signals is therefore more realistically expressed as 0.048 ± 0.012 milliseconds.
The delay of longer duration measured using the LVDT system may possibly be explained as being due to the inertia of the LVDT spindle and friction between the spindle and its housing.

**Figure 46.** The same data as figure 45 zoomed in to show the first 0.8 ms of the impact.

Practical experience with the Periotest shows that results for clinically loose teeth are highly unreliable. Figure 47 shows simultaneously recorded tooth displacement (upper signal) and Periotest signal (lower trace) from a clinically loose tooth. The displacement signal is plotted as transducer output voltage (not calibrated) against time. This recording is the first of 16 in a test series and shows why the Periotest system is unreliable for loose teeth. The tooth provides very little initial resistance to movement with the result that it is pushed across the socket by the Periotest slug which bounces on the tooth three times. The final bounce causes very little increase in displacement.
Figure 47. Simultaneous displacement and Periotest signals from a very mobile tooth. The tooth is hit 3 times and displacement continues until the periodontal ligament provides substantial resistance.
The system fails because the Periotest signal crosses the zero output threshold between bounces producing several possible zero points. The first of these is at 0.26 milliseconds which corresponds to a Periotest value of minus eight.

Figure 48 shows the same data as in figure 47 while figure 49 shows the final impact in the same series. The first bounce in the final impact is also of 0.26 milliseconds and this tooth produced a Periotest value of minus seven. The total duration of the first impact is seen to be 3.5 milliseconds and for the last impact 1.8 milliseconds, with a mean total signal duration of 2.2 milliseconds. This corresponds to a Periotest value of 49. Thus, if the system were able to recognise multiple bounces and not switch off the signal duration clock at the end of the first bounce, it could be usable for loose teeth. If this were done it would probably be necessary to extend the top of the scale from 50 to say, 70.

Figures 48 and 49. The first and last impacts in the same series. The signal duration is 3.5 ms for the first and 1.8 ms for the last.
Quantitative results.

Table 41 gives the Periotest value tabulated against the displacements produced by the Periotest, 100 grams force and 200 grams force for each of the five teeth.

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Periotest Value</th>
<th>Displacement with Periotest (mm)</th>
<th>Displacement 100g (mm)</th>
<th>Displacement 200g (mm)</th>
<th>Signal Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth 1</td>
<td>50</td>
<td>0.750</td>
<td>0.820</td>
<td>1.180</td>
<td>2.90</td>
</tr>
<tr>
<td>Tooth 2</td>
<td>45</td>
<td>0.513</td>
<td>0.570</td>
<td>0.714</td>
<td>1.96</td>
</tr>
<tr>
<td>Tooth 3</td>
<td>25</td>
<td>0.175</td>
<td>0.270</td>
<td>0.370</td>
<td>1.02</td>
</tr>
<tr>
<td>Tooth 4</td>
<td>15.5</td>
<td>0.093</td>
<td>0.158</td>
<td>0.237</td>
<td>0.73</td>
</tr>
<tr>
<td>Tooth 5</td>
<td>7.5</td>
<td>0.054</td>
<td>0.159</td>
<td>0.217</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Table 41. The Periotest values and displacements produced by 100 grams force and 200 grams force for each of the five teeth.

Figure 50. The displacements produced by the Periotest, 100 grams force and 200 grams force plotted against Periotest value.
Figure 50 shows these results graphically with the displacements plotted against Periotest value. There is clearly a relationship between Periotest value and the results of traditional semistatic loading however, the Periotest scale is not linear.

![Graph showing displacements plotted against Periotest value and signal duration](image)

Figure 51. The displacements produced by the Periotest, 100 grams force and 200 grams force plotted against signal duration.

Figure 51 shows the same displacement data plotted against contact time. There appears to be an approximately linear relationship between contact time and the displacements produced by the Periotest. Perhaps more importantly, there would also appear to be an approximately linear relationship between the displacements produced by a handheld forcemeter and contact time. The data produced by this experiment was insufficient for statistical analysis.
Conclusions.

This experiment encourages the belief that Periotest measurements may provide a reasonable basis for tooth mobility measurements for teeth exhibiting mobility of up to approximately grade 2 on the Miller scale. Modifications to the system could extend the useful range of the Periotest instrument.
Chapter 10

Animal model studies

The review of the literature has shown that the amount of tooth displacement produced by a given load is dependant on the rate of loading. Previous experimental imitation of functional loading has used loading rates of up to 100 Newtons per second.

The preliminary recordings of the Periotest accelerometer signal taken from various surfaces have suggested that the peak force applied by the Periotest varies depending on the elastic modulus of the specimen tested. High modulus specimens are subjected to a greater peak force than low modulus surfaces. The impact duration for high modulus specimens is less than for low modulus specimens. When applied to surfaces the loading rate of the Periotest can thus be considered to be dependant on the resistance to movement provided by the specimen.

The flexibility of the tooth support system may also be expressed as a modulus. This modulus is recognised as a complex composite of the spring and damping constants of the periodontium. When applied to teeth the loading rate of the Periotest varies depending on the resistance to movement provided by the specimen. Calculations of estimates of peak force and loading rate (see appendix 2) show that at Periotest value -8 peak force equals approximately 12 Newtons applied at a loading rate of over
Animal Model Studies

90,000 Newtons per second. At Periotest value +50 peak force equals 1.4 Newtons applied at a rate of 1240 Newtons per second. These calculations only provide an estimate of the order of loading rate but are useful to illustrate the differences from previous research.

10.1 Monkey studies

Materials and methods

A series of five experimental sessions were undertaken to examine the behaviour of teeth loaded using the Periotest. Macaca fascicularis monkeys were initially immobilised using intramuscular injections of 8 mg kg\(^{-1}\) ketamine (Vetelar\(^\#\)). Anaesthesia* was then induced using Pentobarbitone sodium (Nembutal\(^-\)) using a dose of 30 mg kg\(^{-1}\) body weight.

The head of the monkey was secured in the frame of a cephalostat (Picton 1984). The jaw supporting the test tooth was anchored firmly to the cross bar of the cephalostat using impression compound. In order to monitor jaw fixation stability a displacement transducer was attached to a tooth on the opposite side of the jaw to the test tooth.

Displacement measurement was accomplished by attaching the spindle of an LVDT to the test tooth using impression compound. The LVDT was linked to an amplifier, the

\(^\#\) Parke-Davis & Co. (veterinary).

*Anaesthesia was performed by Professor DCA Picton.

~ May and Baker Ltd.
signal from which was recorded using either an ultraviolet recorder or a recording oscilloscope. The LVDT was calibrated before and after each experiment using a dial gauge.

The buccal surface of the test tooth was flattened in its long axis with a diamond disk and the Periotest applied at right angles to the flat surface. To allow for remote operation and to eliminate variations in handpiece angulation a clamp was made which attached the Periotest handpiece to the base of the cephalostat via a series of locking articulated struts.

This equipment was used to record the movements of teeth produced by the Periotest. Measurements were taken from these recordings to which the relevant calibration was then applied.

Results and discussion

Figure 52 shows a representative example of the tooth movement produced by the Periotest with displacement plotted against time. It is a tracing taken from the photosensitive paper used by the ultraviolet recorder. The test tooth was clinically firm with a Miller index mobility of 0 and gave a Periotest value of -5. The upper trace was recorded at a paper speed of 5 cm per second and shows the tooth being impacted 4 times per second. The tooth is displaced approximately 10 microns by each impact then recovers almost completely. The lower trace was recorded at a
Figure 52. Ultraviolet recorder tracings of displacement/time from the tooth of an anaesthetised monkey. (Scanned image)

Paper speed of 100 cm per second and shows that the recovery of this tooth takes approximately 10 milliseconds.

The displacements produced by the Periotest when applied to teeth with mobilities across the Periotest range are tabulated against Periotest value and signal duration in Table 42, and the plots of this is illustrated in Figure 53a and b.

<table>
<thead>
<tr>
<th>Periotest Value</th>
<th>Displacement (microns)</th>
<th>Signal duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
<td>5</td>
<td>0.326</td>
</tr>
<tr>
<td>-4</td>
<td>14</td>
<td>0.346</td>
</tr>
<tr>
<td>12</td>
<td>50</td>
<td>0.666</td>
</tr>
<tr>
<td>26</td>
<td>100</td>
<td>1.056</td>
</tr>
<tr>
<td>27</td>
<td>90</td>
<td>1.093</td>
</tr>
<tr>
<td>31</td>
<td>120</td>
<td>1.252</td>
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<td>245</td>
<td>1.527</td>
</tr>
<tr>
<td>50</td>
<td>400</td>
<td>2.770</td>
</tr>
</tbody>
</table>

Table 42. Periotest value tabulated against displacement produced (microns) and signal duration (ms).
The relationship between displacement and Periotest value is not linear. A tooth with a Periotest value of 12 is displaced 50 microns while a tooth with a Periotest value of 37 is displaced almost five times as far. The Periotest scale is however not linear.

The displacement produced by the Periotest was therefore plotted against contact time (Figure 53 b). It indicates the possibility of a linear relationship between displacement produced by the Periotest and contact time.

To characterise the tooth movement produced by a Periotest impact in greater detail the tooth displacement transducer and the Periotest were attached to a recording oscilloscope.
Figure 54 shows a simultaneous recording of the accelerometer and tooth displacement signals. This was traced from the pen recorder output from the recording oscilloscope. There appears to be a short delay of approximately a quarter of a millisecond after the slug hits the tooth before the tooth begins to move. During the delay the kinetic energy of the slug is transferred to potential energy as the slug/accelerometer/tooth combination are compressed. Once the tooth starts to move the force on the accelerometer begins to decrease. The tooth moves away for approximately 1 millisecond after loosing contact with the slug, the final separation being 17 microns. Recovery is slower and is in two phases. The first phase occurs over a period of 2 milliseconds returning to within 5 microns of the starting position.
During the second phase the tooth oscillates back to its starting position over a period of about 10 milliseconds (this is off the right hand edge of the tracing).

When dropping a glass bead onto a tooth Korber and Korber (1967) found that the root did not move but the crown of the tooth bent. It is possible that the Periotest produces a similar bending of the crown and this is more likely for tight teeth than loose teeth. This possibility has not been investigated.

When the Periotest was applied to a clinically mobile tooth the accelerometer signal proved to be more complex than those produced by firm teeth. Mathematical modelling of the impact mechanics of Periotest application had suggested the possibility of multiple "impacts" of the slug within each of the 16 impact complexes. Initially the validity of the model was questioned and the first recordings were considered to be artefacts. However, loose teeth consistently produced similar signals.

Figure 55 shows a comparison of signals; the upper trace being from a clinically firm tooth giving a Periotest value of 4. The lower trace is from a clinically loose tooth with a Periotest value of 35. The accelerometer trace has two peaks because, when the slug hits the tooth, the tooth begins to move but the impact does not stop the slug moving. The slug continues to move forward to impact the tooth a second time producing the second peak on the accelerometer signal. These multiple impacts within one impact complex are referred to as "bounces". The occurrence of this phenomena is reemphasised here because these experiments preceded the direct computer data capture work presented in a previous chapter. Indeed, the first such
signals recorded were rejected as anomalous and led to extensive reexamination of the equipment!

![Accelerometer traces](image.png)

**Figure 55.** Comparison of accelerometer traces from a clinically healthy monkey tooth (upper trace) with a Periotest value of 4 and a clinically loose tooth with a Periotest value of 35.

When the slug hits a loose tooth the transfer of energy from the slug to the tooth is less than when the slug hits a tight tooth. Bounces occur when insufficient energy is transferred from the slug to the tooth such that the tooth moves away from the slug after the impact but slows down allowing the slug to impact the tooth again.

The occurrence of bounces began to explain the decreased reproducibility found in the upper reaches of the Periotest range. If the accelerometer output occasionally reaches
zero between bounces the system will only record the duration of the first bounce and not the complete signal. Thus a low and erroneous Periotest value would be produced. No details are available of the algorithm used by the microprocessor but it appears that it has no capability to analyse impacts with bounces.

In an attempt to clarify the characteristics of tooth mobility that the Periotest measures various procedures were performed that are known to cause substantial changes in axial mobility assessed with loading rates of 100 Newtons per second. Infiltrations of water or local anaesthetic containing adrenaline around the teeth of anaesthetised monkeys produced no change in Periotest value, while the changes produced by pericision (severing of the gingival attachment fibres) were not significant.

Finally, a change in Periotest value was elicited by raising a mucoperiosteal flap to allow for removal of 2 mm of buccal bone (i.e. The tension side). This caused an increase in Periotest value from 14 to 26.

These results suggest that the Periotest measures factors related to the elastic components of the viscoelastic tooth support mechanism. Injections containing water or adrenaline affect the viscous components and, for this reason, have no effect on Periotest values. It is assumed that the high speed of action of the Periotest allows no time for fluid movement. Hookean movement is almost instantaneous while viscous movement is time dependant.
Animal Model Studies

Comments on monkey studies

These experiments were useful in improving understanding of the Periotest system and provided descriptive data. However the equipment demonstrated shortcomings. These are listed below:

1. The recording oscilloscope is only capable of recording the accelerometer signal of one impact of the series.
2. Measurements of the pen recorder output from the oscilloscope must be made manually using a calliper or ruler.
3. Use of the ultraviolet recorder to record tooth displacement proved ungainly due to the high paper speeds required to give detailed traces of signals.
4. The ultraviolet recorder functions by "exposing" photosensitive paper with a small point of light. The high paper speeds required produced very faint traces which are difficult to read.
5. Photosensitive paper degrades in light and must be kept in the dark when not in use. Analysis and measurements must therefore be carried out before degradation occurs. As an alternative to this, photocopies may be made from which measurements may be taken. Attention to detail is essential when setting up the photocopier for this as only one attempt is possible. Tracing paper copies are another alternative.
6. Measurements of these ultraviolet recorder traces also required the use of a calliper or ruler.
7. Measurement of Periotest value before and after attachment of the LVDT to the tooth showed that the LVDT "splints" the tooth. When a tooth is loaded horizontally it moves horizontally but also rotates. If the vertical component of
this rotation is greater than the tolerance of fit of the spindle of the LVDT friction becomes significant.

The reduction in Periotest value after LVDT attachment was greatest for the looser teeth. Several arrangements for flexible attachment of the LVDT to the tooth were tried but none proved satisfactory.

10.2 Minipig studies.

A series of experimental sessions was undertaken in an attempt to continue examination of the behaviour of teeth under various loading regimes. The computerised displacement measuring and signal capture system was used but the technical problems proved great.

Managing anaesthesia of the minipig is more complex than for Macaque monkeys. Intubation is required, which is difficult due to the small size of the trachea. Once anaesthetised, maintenance of an even depth of anaesthesia was also difficult. Initially high levels of anaesthetic agent are required due to the high proportion of body fat. This dosage must be reduced once the body fat is saturated.

Breathing movements regularly disturbed the apparatus despite utilising a custom made clutch to hold the displacement transducer.
The 70 Kilogram bulk of the animal made adjusting the jaw position, such that the test tooth was perpendicular to the floor, tiresome. Such adjustments often caused disturbance of the anaesthetic equilibrium.

Minipig experiments were abandoned after much hard work but with the production of no useful data.
Chapter 11

Pilot studies on human subjects

A series of informal pilot studies was carried out on human volunteers. The data from these studies is not formally presented as it represents a preliminary clinical evaluation done at a time when little of Periotest function was understood and were thus not designed for full statistical analysis.

Periotest values were compared to the Miller clinical mobility index with favourable results. Table 43 shows the approximate ranges of Periotest values corresponding to points on the Miller scale.

<table>
<thead>
<tr>
<th>Miller scale</th>
<th>Periotest range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-8 - +5</td>
</tr>
<tr>
<td>1</td>
<td>+6 - +20</td>
</tr>
<tr>
<td>2</td>
<td>+19 - +35</td>
</tr>
<tr>
<td>3</td>
<td>+36 - +50</td>
</tr>
</tbody>
</table>

*Table 43. The Miller tooth mobility scale with the corresponding Periotest ranges.*

This is, however, comparing the unknown with the inaccurate.

Periotest values were highly reproducible at the lower end of the scale. In the range
of -8 to +5 a series of 10 measurements produced a maximum difference from the mean of ±2 units and a standard deviation of less than 1 unit.

In the range of +6 to +30 repeated measurements produced a maximum difference from the mean of 5 units and a standard deviation of approximately 3 units.

In the range of +31 to +50 units reproducibility continues to decrease with a maximum difference from the mean of ±9 units and a standard deviation of 6 units.

Approaching the top of the scale reproducibility improves because readings over 50 are not possible. The incidence of obviously erroneous readings also increases in this upper range as does the incidence of no reading being produced. If the microprocessor cannot analyse enough signals a reading of 999 is displayed.

Examination of the time interval between testing showed that firm teeth recovered their position and could be tested again within one minute. Loose teeth proved to have a wide range of resting positions, the Periotest value produced being dependant on the initial tooth position relative to the lingual socket wall. Digital preloading of the test tooth in a lingual direction decreased the reading and increased reproducibility.

Moving the point of application in an apical direction closer to the notional centre of rotation of the tooth caused a decrease in Periotest value.

Varying the angle of application of the instrument in a more apical direction caused a decrease in reading. The audible warning that sounds when the handpiece is held at more than 30° to the horizontal is redundant as such an error would not be made by
accident.

Varying the angulation of instrument application in the horizontal plane caused a decrease in Periotest value for teeth with interdental contact points.

Subjects describe the sensation of Periotest application as unusual rather than uncomfortable. Discomfort was elicited when attempts were made to test teeth in an axial direction. This was attempted in order to abrogate the effects of tight interdental contact points and because previous research has concentrated on axial studies (Picton 1990). Reproducible estimation of the direction of the long axes of teeth proved critical and impossible to achieve so axial testing was abandoned. The few teeth tested suggested that axial Periotest values are much lower than the corresponding horizontal values and that the range of values is considerably narrower.
Chapter 12

Conclusions and Discussion

The conclusions from these experiments may be summarised as follows:

1. Comparison of two instruments across the Periotest range showed significant differences between the two and thus comparison of data produced by different instruments should be avoided or made with care.

2. The percussion rod slows down as it travels away from the handpiece.

3. It is possible to control the position of the handpiece so that this deceleration is not a factor in measurement.

4. The teeth of cadaveric pig jaws proved the most useful models for testing the Periotest despite the obvious differences with the live animal system.

For teeth in pig jaw models:

5. The reproducibility of Periotest values decreases as Periotest values increase.

6. Measurements of Periotest signal amplitude show that computation of this signal characteristic to produce a "moveability" value would give poor resolution for tight teeth.

7. Increasing tooth mass affected signals and Periotest values obtained. These
Conclusions and Discussion

changes were statistically significant. The results also show that significant changes in signal amplitude were produced at the first level of mass addition for all teeth. Thus signal amplitude is highly dependant on tooth mass and explains why this signal characteristic was not chosen by the instrument developers.

8. Periotest values decreased significantly as the application point was moved in an apical direction.

9. Significant changes in Periotest value were produced by changing the angle of application in the horizontal and vertical plane by more than 10° from normal for some of the test teeth.

10. When testing very loose teeth Periotest signals are complex and the system gives highly unpredictable results. This is explained by the method of analysis used by the microprocessor and could be modified to allow the instrument to function over a wider range.

11. The human studies reported in Appendix 3 have indicated the place of the Periotest in the clinical setting.

In the light of these conclusions it is important to consider whether this work has achieved the overall aims of the study. (listed on page 22)

The mode of action of the instrument has become clear and the factors affecting Periotest values have been measured and to some extent explained by analysis of the signals.
Conclusions and Discussion

The behaviour of teeth when loaded at the very high but variable rates produced by the Periotest has been described for the first time. This is perhaps a small increment in the understanding of tooth support physiology.

There is no doubt that the future of tooth support physiology research lies with computer based systems for recording and measuring tooth movement. The system used for this study was initially very cumbersome and tedious to use but improved as software updates arrived. The system was never capable of recording a full series of Periotest impacts (taking a minimum of 4 seconds) at a high enough sampling rate to characterise tooth displacement (and recovery) and Periotest signals and thus relied on "frames" of data with delays between each frame.

The non-contact transducer fulfils the aim of measuring displacement while having no effect on that which is being measured and for this reason must represent the way forward. However, in order to fulfil the constraints of sensor size and instrument resolution, measurement range is compromised. The model of transducer used for this study has micron resolution but an effective maximum range of 1.4 centimetres and while this is sufficient for teeth within the physiological range of movement, it was disappointing not to be able to examine extremely loose teeth.

There is no doubt that the continuing rapid improvements in computer hardware and software and microelectronics in general will assist in the evolution of computer based recording and measuring systems.
Conclusions and Discussion

The Periotest instrument could be adapted to function across a wider range by changing the algorithm used to measure signal duration to take account of multiple bounces of the percussion rod within one impact.

Finally, what does the Periotest actually measure? The answer to this question is not clear cut. The developers of the system arrived at measurement of signal duration, computed to give "Periotest values", by experimental examination of many signal parameters rather than by theoretical means. The Periotest scale, designated by the manufacturers, is arbitrary.

In general terms the signal duration is related to the resistance of the tooth to movement. At the lower end of the scale the time taken for the Periotest signal to reach its peak is equal to the time taken for the percussion rod to give up its energy. At this instant the tooth and percussion rod are in contact and stationary. The potential energy of the percussion rod has been lost in the periodotium or stored as potential energy in the periodontium, percussion rod and tooth. Thus the time taken for the Periotest signal to reach its peak is proportional to rate of energy transference. In physical terms the rate of energy transference is Power. Thus signal duration could be said to be inversely proportional to the power of the periodontium.

The situation of looser teeth is not simple. The tooth moves away from the percussion rod without absorbing all of its energy and the rod continues to move forward to hit the tooth again. When this happens simple energy calculations are inappropriate.
A more detailed explanation would have been forthcoming if Periotest accelerometer output could have been calibrated against known loads. Attempts to procure one for calibration were not successful.

Knowledge of slug velocity after impact would also have been useful. Attempts to measure this by firing the Periotest at the non-contact transducer merely succeeded in breaking the transducer sensor!

The teeth in pig jaws proved to be the most useful models and were used for the vast majority of the work presented here. There is however, no doubt that there are clear differences from those of live animals because of the lack of blood pressure. The use of these model systems is defended on the grounds that the computerised measuring and recording system was under development and the procedures performed were highly repetitive. Once a fully functional system is developed work must concentrate on the teeth of live human subjects.
Chapter 13

The value of the Periotest as a tool & The Future.

13.1 The significance of tooth mobility levels and the value of the Periotest as a tool.

The fundamental aims of dentistry are the detection of systemic disease originating in the mouth and the preservation of dentitions. The secondary aim is the restoration of damaged or missing teeth to produce a dentition that is comfortable, functional and as stable as possible.

Poor quality or ill advised dentistry and undiagnosed or untreated dental disease may lead to increased mobility of teeth. It is common for teeth to be removed when mobility levels reach the point of being uncomfortable or where they alarm the patient or dentist.

Interpretation of the significance of mobility level is not straightforward because of the many factors affecting the status of the tooth support system. Thus mobility values or Periotest values cannot stand alone as the measure of the periodontal status of a tooth. They do, however, provide additional information to add to radiographic and clinical findings to give a more complete assessment.
The Periotest as a Tool

The factors affecting tooth mobility include attachment level, periapical and periodontal inflammatory status and occlusal status (all of which may be under a measure of control of the clinician) and root morphology, the quality of the periodontium and biting/chewing force (over which we have no control). Thus it is unlikely that specific therapeutic measures could be based on mobility levels alone.

In comparison with the clinical scale of tooth mobility assessment the Periotest provides an improvement with increased resolution and reproducibility. The instrument is quick and easy to use in the clinical setting but is not usable for very loose teeth. It is possible to measure changes in mobility which is not a realistic possibility using the clinical scale and changes in Periotest value give information which is more useful than Periotest value alone. Decreases of Periotest value during the healing phase after trauma or periodontal therapy give confirmation that all is well while increases in Periotest value after the fitting of a crown will draw attention to a possible occlusal problem.

The uses of the current Periotest system:-

a) Monitoring mobility levels before and after periodontal therapy including initial therapy and regenerative surgery and during periodontal maintenance.

b) Monitoring the healing after trauma.

c) Monitoring the changes of mobility after occlusal adjustment by selective grinding or occlusal changes following crown cementation.

d) Monitoring the osseointegration of implants.
13.2 The future of the Periotest

The Periotest is very little used in Britain but is mandatory for clinical practice in Germany. The instrument has not gained wide acceptance in this country because of the lack of properly performed studies and the poor reproducibility of measurements of clinically very loose teeth.

The following recommendations for changes to the Periotest are based on the results of the experiments presented in this thesis:-

The microprocessor should be programmed to recognise and measure the full length of each accelerometer signal rather than measuring the duration until the signal first crosses the +80 millivolt output threshold. If this change were made the reproducibility of Periotest values in the upper part of the scale would be improved. The scale could then be extended upwards from +50 to allow measurements of teeth of Miller scale mobility 3. This would greatly increase the usefulness of the instrument.

Having established an understanding of the function of the Periotest system future experiments could use it as a clinical research tool. For example:-

a) To assess improvements to the tooth support system produced by periodontal treatment procedures such as guided tissue regeneration and grafting techniques.

b) To examine the effects of bridgework and its design on the tooth support
c) Implantology research. When considering linking implants to natural teeth it may be possible to choose a resilient attachment of a specific resilience, the choice of which would be based on the Periotest value of the natural tooth.

13.3 The future of tooth support physiology research

In order to increase the precision of the system for load application, load measurement and displacement measurement future instrumentation will require total computer software control. Such a system would allow for a variable loading rate and provide simultaneous load and displacement recordings. The displacement recordings would be both axial and horizontal or conceivably in three dimensions.

Previous research has concentrated on clinically firm teeth. A more complete understanding would be provided by examining factors affecting the tooth support systems of teeth across the entire mobility range.

On a purely theoretical level data produced by a computer controlled system could be used to perfect the rheological analogue model of the tooth support system. Currently there is no single model which behaves in agreement with experimental data across a wide range of loading rates.
14.1 Presentations

This research has been presented as work in progress on the following occasions:


2. 1988 (March) The British Society of Dental Research, Belfast, Ireland.


14.2 Related Publications:


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16.1 Calculation of slug velocity.

For simplicity total transfer of momentum and a friction free environment were assumed. Estimation of slug velocity used the following equation:

\[ \frac{1}{2} M_1 V^2 = M_2 gh \]

\[ V = \sqrt{\frac{2M_2 gh}{M_1}} \]

where \( M_1 \) = slug mass

\( M_2 \) = ball mass

\( h \) = height reached by ball

The derivations of these equations of kinetic and potential energy are to be found in an Advanced level physics textbook (Duncan 1982).
Appendix 2.

16.2 Calculation of peak force and loading rate.

An estimate of peak force of a Periotest impact can be calculated using the equation:

\[ \text{Force} = \text{mass} \times \text{acceleration} \] (from Newton's second law of motion)

Assuming that the slug stops moving at the output peak; taken as half the signal duration:

\[ F = m(\text{change in velocity}) \times 2 \]
\[ \text{time} \]

The rate of loading, if impact forces can be expressed as such, is given by:-

\[ \text{Loading rate} = \frac{\text{Peak force}}{\text{time}} \]

Table 43 shows Periotest value tabulated against corresponding signal duration (milliseconds), peak force (Newtons) and loading rate (Newtons per second). Signal durations were calculated using the formulae provided by the manufacturers and peak force and loading rate were calculated using the equations above. The calculations were performed by applying these formulae in a spreadsheet.
### Appendix 2

<table>
<thead>
<tr>
<th>Periotest value</th>
<th>Signal duration (ms)</th>
<th>Peak force (Newtons) [to 2 decimal places]</th>
<th>Loading rate (Newtons per second)</th>
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Table 44. Periotest values tabulated against the corresponding calculated values of: signal duration (ms); peak force (Newton) and loading rate (Newton/sec).

Figure 56 shows peak force plotted against Periotest value. The peak force ranges from 12 Newtons at a Periotest value of -8 to 1.4 Newtons at a Periotest value of 50.
Figure 56. Peak force (Newtons) plotted against Periotest value.

Figure 57 shows loading rate plotted against Periotest value.

Figure 57. Loading rate (Newtons second⁻¹) plotted against Periotest value.
Appendix 2

The loading rate ranges from over 90,000 Newtons per second at a Periotest value of -8 to just over 1200 Newtons per second at Periotest value 50.

Thus when a tight tooth is hit by the Periotest slug the peak force is relatively high and the loading rate is astronomical while for a loose tooth the peak force is very low and the loading rate is relatively low. The loading rate for a loose tooth is however approximately ten times that seen during chewing.
Appendix 3.

16.3 Human clinical studies.

A series of studies was done on human subjects to demonstrate the place of the Periotest instrument in the clinical setting. Data was gathered to demonstrate changes in Periotest value produced by various treatment procedures. These data are presented in an appendix because they are for illustrative purposes and not suitable for statistical analysis. The data presented are single measurements not means of multiple measurements. In this setting it is not possible to standardise clinical parameters or time intervals between measurements. For example, plaque scores and inflammatory status vary between and within patients, over time and not in an entirely predictable manner. Patient numbers vary for each study and the data is largely presented graphically.

16.3.1 Occlusal adjustment by selective grinding

Occlusal adjustment by selective grinding may be performed on an individual tooth when the clinical judgement is made that the mobility is inconsistent with its periodontal and inflammatory status. Selective grinding is also a useful aid in reducing the load on a seriously weakened tooth.
Appendix 3

The adjustment procedure involved removal of excursive interferences and maintenance of intercuspal contact. Intercuspal contacts were only adjusted when a tooth was in fremitus. In this situation intercuspal contact points are reduced so that contact is maintained but the tooth is no longer intruded on closure.

Nine teeth were measured but only five are included as these were measured at approximately weekly intervals.

A tooth on the other side of the dental arch was measured at the same time as a control.

Results and discussion.

The results for the five teeth are shown in figure 58 in which Periotest values are plotted against time (days). The general trend is for Periotest values to decrease and some patients reported concomitant improvements in comfort.

The reduction then increase of values for tooth 4 suggests that the occlusal contact was lost during adjustment and that the tooth or its opponent erupted back into contact.
Figure 58. Periotest value plotted against time after occlusal adjustment (days) for each of five teeth.

Tooth number 3 showed no change while tooth number 5 gave a Periotest value reduction of 13 units from 26 to 13. Ideally this study should have been continued for a longer period as not all teeth had reached a stable Periotest level.

The control teeth showed no changes in Periotest value.

16.3.2 Provisional bridgework

Periotest values were measured for the abutment teeth of full coverage three unit fixed bridges before and after tooth preparation and prior to fitting permanent bridgework. Provisional bridgework was constructed at the chairside and cemented temporarily
Appendix 3

after tooth preparation. The occlusion was adjusted so as to hold shim-stock (13 microns thick) in intercuspal contact for each of the three teeth and excursive interferences were removed. These restorations were removed prior to subsequent measurements.

A tooth on the other side of the dental arch was measured at the same time to act as a control.

Results and discussion.

The results are given in figure 59 with Periotest value plotted against time (days) for each pair of abutment teeth (Labelled A and B) for each of the five bridges (numbered 1 to 5).

The time interval that the provisional bridgework was in place varied from 7 to 27 days. No tooth showed gross changes in Periotest value immediately after preparation. All abutment teeth showed a tendency for an increase in Periotest value. This is hardly surprising and is assumed to be due to a functional adaptation to increased loading.

Bridge number 3 is the most interesting as there is the largest differential in initial mobility (13 units) and was observed for the longest time. All other abutments are within Miller scale 0 mobility. Tooth A of this bridge (initial Periotest value 11) was a lower second premolar with healthy periodontal status but a relatively short root. This tooth gave an initial decrease of Periotest value from 11 before preparation to 8 at seven days and 9 at thirteen days but increased again to 12 at twenty days and 13 at
twenty-seven days. The other tooth of this bridge (Tooth B) with an initial Periotest value of -2 increased to 4 at seven days, 3 at thirteen days and 5 at twenty and twenty-seven days. This increase of 7 units was the greatest demonstrated by any abutment but was loaded for almost four weeks as opposed to two weeks. Despite this these findings support the concept that linking a clinically firm tooth to a looser tooth will lead to increases in mobility of the tighter tooth.

The control teeth showed no changes in Periotest value.

It would be interesting to examine situations with larger differences in mobility but it is unusual to make bridges using abutment teeth with Miller scale mobilities of 1 or more.
Figure 59. Periotest value plotted against time for each pair of abutments (A & B) for bridges 1-5.
16.3.3 Initial periodontal therapy

Initial periodontal therapy was carried out and Periotest values noted for one tooth of each of nine patients. This therapy consisted of plaque control instruction including tooth brushing and interdental cleaning usually with interdental brushes. Home care advice was given at the initial visit and reinforced at each subsequent appointment. This was followed by gross supragingival scaling and then quadrant deep scaling under local analgesia.

As with the other studies the timing was at the patients convenience rather than following a strict protocol. Nevertheless the aim was a series of five visits at weekly intervals followed by a six week "healing period" at which point a reevaluation was done. Before the initial therapy and at reevaluation pocket probing depths were measured at six points on each tooth.

No teeth were included which had received occlusal adjustment by selective grinding or antibiotic therapy.

The use of control teeth was not possible as initial periodontal therapy affects all teeth in a mouth. The instrument was therefore checked against the calibration cap and other surfaces.

Results and discussion

Figure 60 shows Periotest values plotted against time for a tooth from patient 1. As with all teeth included here this tooth was deep scaled one week after gross scaling.
and Periotest measurements were taken on the three subsequent weeks when the other quadrants were deep scaled and then six weeks after the final quadrant of scaling.

Figure 60. An example of Periotest value plotted against time (weeks) during initial periodontal therapy. Oral hygiene instruction was performed at time 0 and deep scaling after one week. (Tooth 1)

An initial slight decrease after home care instruction and gross scaling was followed by an increase of 8 units to 22 at one week after deep scaling. In the following weeks Periotest values reduced from 22 to 17 then to 11 at three weeks after deep scaling. Six weeks later at nine weeks after deep scaling the Periotest value had further decreased to 7. Thus this tooth gave a reduction of 9 Periotest units from its initial value and 15 units from the maximum recorded. An initial increase followed by a
Appendix 3

gradual decrease is consistent with the work of Perrson (1981).

In this example the patients plaque control changed rapidly from poor to excellent. Initially profuse immediate bleeding on probing, pain on probing and pus exudate with a probing pocket depth at a maximum of 8 millimetres was reduced to a 4 millimetre probing depth with none of the aforementioned signs of inflammation.

This tooth is the lower left second molar on the example six point probing chart illustrated in figure 61. The two sets of readings were taken ten weeks apart. It is assumed that the reductions in probing pocket depth are produced by a combination of factors. These include the differences in the position of the probe tip between inflamed and non-inflamed tissues and these differences may be substantial if "pocket closure" occurs. Reductions in pocket depth are also caused by a decrease in soft tissue swelling and other causes of recession. The measurements from the other patients are not included here because attachment level measurements would be necessary to be meaningful.
Figure 61. Six point probing charts from patient 1 taken at time 0 and 10 weeks later, before and after initial periodontal therapy. The Periotest data from the lower second premolar is shown in figure 60.
Data from the other eight patients is shown in figure 62. These examples were chosen in an attempt to provide teeth with an initial Periotest value across the Periotest range.

A variety of patterns of change in Periotest value are demonstrated. Five of the nine teeth showed reductions from their initial Periotest value and one tooth demonstrated no change. Tooth 2 showed an increase from 8 to 12. Tooth 7 developed a periodontal abscess and its Periotest value increased from 17 to 28. This tooth was deep scaled again at the reevaluation visit. Tooth 9 was initially of Miller scale mobility 3 and Periotest value 42. Under normal circumstances this tooth would have been extracted during initial therapy but was extracted at the reevaluation visit when its Periotest value was 49.

The instrument gave consistent readings when checked against the calibration cap and other surfaces.

In conclusion it appears that the Periotest is capable of measuring the functional effects of the changes in the supporting tissues of teeth associated with the resolution of inflammation.
Figure 62. Periotest values plotted against time (weeks) for each of 8 teeth (2 to 9) during initial periodontal therapy.
16.4 Illustrative Human Data

The following experiment was performed to provide illustrative data for comparison with that produced from the teeth of the pig jaw model and of Macaque monkeys.

The test tooth was an upper second premolar of a very patient and tolerant human subject and demonstrated a Periotest value of 5.

A hard acrylic bite plane was made on a cast of the maxillary teeth to house the non contact transducer sensor. The sensor was mounted perpendicular to the long axis of the test tooth and the position of the sensor relative to the palatal surface could be adjusted via the sensor screw mounts.

A custom transducer target was made from aluminium foil for the test tooth so as to present a flat surface parallel to the long axis of the tooth. The non contact transducer was calibrated against this target. The target and bite plane were then cemented into place on the maxillary teeth of the subject and the sensor position was adjusted to allow a suitable range of tooth movement.

Recordings were then made of the tooth movements produced by the Periotest. Figure 63 is an example of such a movement with displacement plotted against time. In this example the tooth is displaced by 23 microns taking 0.225 milliseconds to
reach peak displacement. The tooth returns to its rest position after 0.615 milliseconds and oscillates for a further 5 milliseconds.

**Figure 63. The displacement of a human tooth by the Periotest.**

Comparison with data from the teeth of macaque monkeys shows that a tooth of Periotest value -4 was displaced 14 microns while a tooth with a Periotest value of 12 was displaced 50 microns. Linear extrapolation between these two points would suggest that a tooth with a Periotest value of 5 would be displaced approximately 34 microns.

Comparison with data from the pig jaw model shows that a tooth of mean Periotest value 7.5 was displaced 54 microns while a tooth of mean Periotest value 15.5 was displaced 93 microns. Linear extrapolation from this data would suggest an approximate displacement of just over 40 microns for a tooth of Periotest value 5.
(These extrapolations are approximate but allow for simple comparison of the data).

This human data would appear in no substantive way different from that from the pig jaw model except that the teeth of the pig jaw model are probably displaced further after impact by the Periotest slug. This is not surprising and is considered to be due to the lack of blood and fluid pressure, and thus lack of damping effect, in the periodontia of the pig jaw model.
Acknowledgements

I wish to thank the following people who have given of their time and expertise to help me during this project:

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