Periapical biomechanics and the role of cyclic biting force in apical retrograde fluid movement

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Abstract

Kishen A. Periapical biomechanics and the role of cyclic biting force in apical retrograde fluid movement. *International Endodontic Journal*, **38**, 597–603, 2005.

Aim To investigate the stress distribution pattern in the periapical region caused by biting forces and to study the role of cyclic biting loads on periapical fluid movement.

Methodology In the first part, a digital photoelastic experiment was conducted to study stress distribution in the periapical region. In the second, 20 maxillary central incisors were selected and divided into three main groups: normal intact teeth (group 1), tooth specimens in which the root canal was enlarged and maintained wet (group 2), and tooth specimens in which the root canal was enlarged and maintained dry (group 3). The tooth specimens were placed in a polycarbonate support with a cavity filled with a sponge soaked in methylene blue solution to simulate a periapical defect with exudate. During testing, the specimens were placed in a water bath at 37 °C, and were loaded cyclically with a load of 20 N, at a rate of 72 cycles min^{-1}, to a maximum of 20 000 cycles. The specimens were then sectioned and evaluated for retrograde fluid movement using light microscopy. The data were analysed using one-way ANOVA (*post hoc* tests).

Results Digital photoelastic experiments showed that the compression of teeth produced bending stresses in the periapical region. Testing with cyclic loads demonstrated retrograde fluid movement into the apical portion of the root canal and extraradicular region in all groups. There was a significant difference amongst the apical retrograde fluid movement displayed by different groups (<0.01). Group 2, in which the root canal was enlarged and maintained wet showed maximum retrograde fluid movement, whilst group 3, in which the root canal was enlarged and maintained dry showed the least retrograde fluid movement.

Conclusions Biting forces would cause bending of the periapical bone and cyclic biting forces would contribute to retrograde fluid movement into the root canal space and extraradicular region.

Keywords: fluid movement, periapical region, stress.

Received 9 November 2004; accepted 11 April 2005

Introduction

The periapical region is considered as a dynamic interface between the tooth and the host defence system. It is the site for both inflammatory reactions in response to intraradicular infection, and healing reactions in response to root canal treatment. Microorganisms colonizing the root canal play an essential role in apical periodontitis (Nair *et al.* 1990). Clinical studies have shown that microorganisms persisted in the apical portion of the root canal in majority of teeth with post-treatment endodontic infections, and sometimes even in well-treated teeth (Nair *et al.* 1990, 1999). Regional variation in the composition of the microflora was demonstrated in the infected root canal (Fabricius *et al.* 1982). In addition, Kipioti *et al.* (1984) have suggested the possibility of cross-infection between the pulpal and periradicular region. It is claimed that the percolation of periapical exudate into an incompletely filled root canal accounts for

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approximately 60% of endodontic failures (Ingle *et al.* 1985). This claim is based on the radiographic findings of incompletely filled canals, with the assumption that incompletely filled root canal meant the presence of apical leakage. However, an understanding on how and why periapical exudate was present in the apical region of the root canal was lacking.

Occlusal loads acting on the tooth were reported to increase periapical hydrostatic pressure and this in turn affected the seal between the filling material and the root canal wall (Dobo-Nagy *et al.* 2003). A direct relationship between the magnitude of occlusal pressure and the volume of periapical leakage was also described (Esber *et al.* 1998). Although many earlier studies evaluated the effects of orthograde fluid leakage and apical seal in root-filled teeth, only a few investigations have been conducted to examine the response in the periapical region to biting forces and the role of cyclic biting forces on periapical fluid dynamics. The purpose of this *ex vivo* study was to examine the stress distribution pattern in the periapical region, and to evaluate the role of cyclic biting loads on the periapical exudate. This investigation would aid in achieving a better understanding of the biomechanical response of the periapical region to biting forces.

Materials and methods

Digital photoelasticity: stress distribution pattern at the periapical region

Digital photoelasticity combines a digital image processing system with the conventional circular polariscope. The digital image processing system consisted of a high-resolution charge coupled device (CCD) camera connected to a personal computer. The digital image processing system enabled the real-time acquisition of digital fringe patterns, and in this study the digitized fringe patterns were subjected to a digital phase-shift analysis. The digital phase-shift analysis aided in: (i) quantifying the fringe patterns with better accuracy and (ii) identifying the signs of the fringe order (Asundi & Kishen 2001). All the above features made the digital photoelastic fringe processing more appropriate for analysing complex stress patterns, as observed in dento-osseous structure. Further details of this technique and its specific advantages were presented elsewhere (Asundi & Kishen 2001).

A human mandible with teeth, obtained from a male adult cadaver, was sectioned vertically along the symphysis region. These sections were digitized using an image-processing system and the coordinates were measured from their outlines. These coordinates were utilized by a Computer Numerical Control (CNC) machine (Makino Asia, Tokyo, Japan) to fabricate two-dimensional photoelastic (sheet) models of the mandibular central incisor tooth and supporting mandibular bone. This process of machining prepared photoelastic models without any residual stresses. Photoelastic sheets (PSM-1; Measurement groups, Raleigh, NC, USA) of size 254×254 mm, thickness 3.20 mm and Young's modulus 2.5 GPa were used to prepare the models. A layer of chemically cured silicon rubber of 0.35 mm thickness was used to simulate the periodontal ligament and a specially manufactured polyester reinforced composite sheet of thickness 0.15 mm simulated the root cementum. This sheet had an elastic modulus that was similar to that of the epoxy model but with higher resilience. Dental composite (Prisma APH; Dentsply, Milford, DE, USA) with a Young's modulus of 13.6 GPa was used to fabricate the enamel portion of the model. The preparation of the models was based on the relative modulus difference between enamel, dentine, cortical bone, cementum and periodontal ligament (Kishen *et al.* 2000). Three such identical models of the tooth and the supporting bone were fabricated to test the repeatability in this study.

The experimental set up consisted of a standard circular polariscope, a CCD camera (Electrim-1000HR Electrim Corporation, Princeton, NJ, USA) and a personal computer. The CCD camera linked to the computer was used for the acquisition and analysis of the fringe patterns. A special loading device was fabricated that could hold anatomical-sized models. A load cell was placed on the superior aspect of the loading device to measure the applied load. The loading device had individual slots that could direct loads along the long axis (0°) and at 60° lingual to the long axis of the tooth. These angles were chosen to simulate the biting forces applied in different directions.

During the experiments, each model was placed separately in the loading device and different loads from 10 to 150 N (at steps of 25 N) were applied along the long axis of the tooth and 60° lingual to the long axis of the tooth. In digital photoelasticity, rotating the analyser at 0, 45, 90 and 135° with respect to the polarizer, induced the required phase steps (Asundi & Kishen 2001). These four phase-shift images were used to obtain a wrapped phase map (Rosvold 1990). Phase-unwrapping was conducted along the selected lines of interest in the wrapped image to make the fringe modulation continuous and to provide information on the absolute nature and magnitude of the stress distribution. A circular calibration disc was analysed to calibrate and to confirm the accuracy of the system. The material fringe coefficient determined by the above method was 6.825 kPa per fringe per metre in comparison with the manufacturer assigned value of 7.0 kPa per fringe per metre.

Cyclic-load testing: role of cyclic biting loads on apical retrograde fluid movement

Twenty noncarious maxillary central incisor teeth with similar dimensions (approximately 20 mm length) were selected and maintained in a phosphate-buffered saline solution (PBS 0.1 mol L^{-1}, pH 7.2). These specimens were transilluminated so that the teeth with cracks or extraction damage could be excluded from the study. The teeth were then randomly divided into the following three groups:

Group1 Normal intact teeth ($n = 10$),
Group2 Teeth in which the root canal was prepared and maintained wet ($n = 5$),
Group3 Teeth in which the root canal was prepared and maintained dry ($n = 5$).

The root surfaces of all the tooth specimens were covered with 0.35 ± 0.15 mm thickness of soft green wax to simulate the soft periodontal interface (Kronfeld 1931). Each tooth was stabilized within a polycarbonate support in such a way that the long axis of the tooth would be 120° lingual to the long axis of the tooth during cyclic loading (Fig. 1). In order to simulate a periapical defect, a spherical cavity of diameter 2 mm was drilled within the support in the apical region close to the root-tip. The cavity was packed with sponge soaked with 20 μL of methylene blue solution (0.1 mol L^{-1}). Cold-cure acrylic resin was introduced into the mould and the teeth were removed when the first signs of polymerization occurred. The acrylic resin layer after setting provided better fit between the teeth and the support. The wax spacer was later removed from the root surface, and a chemical-curing silicone rubber was reinserted to simulate soft periodontal interface. The silicon rubber layer covered the entire root surface except the apical foramen. A thin layer of cyanoacrylate adhesive was used to stick the silicon rubber layer to the root surface of the tooth.

All tooth specimens were rehydrated in PBS for a period of 24 h before testing. During testing, each specimen along with the support was placed in a rectangular chamber, filled with water at 37 °C, and

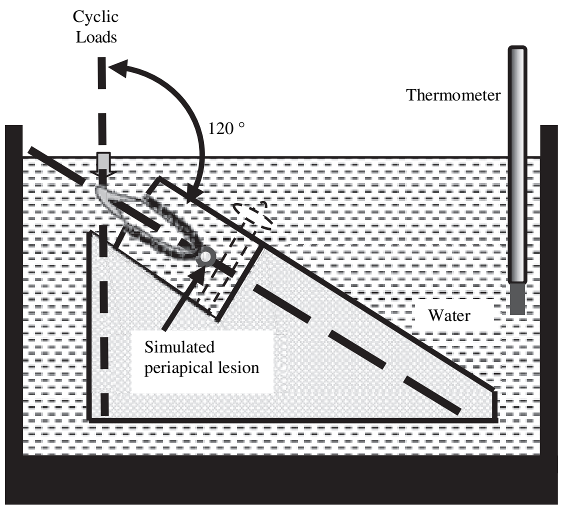

Figure 1 Schematic diagram showing the cyclic load testing arrangement.

was cyclically loaded with 20 N, at a rate of 72 cycles min^{-1} to a maximum of 20 000 load cycles (Bates *et al.* 1975). Five specimens from group 1 were subjected to a static load of 20 N for a period of 4.5 h and were used as the control. The cyclic-testing was conducted using a fatigue-loading system fabricated at the Faculty of Dentistry, National University of Singapore. The 20 N load was applied at an angle of 120°, lingual to the long axis of the tooth at a point ~10 mm coronal to the lingual cemento-enamel junction (Fig. 1). This angle was chosen to simulate the angle of contact between naturally occurring maxillary incisors (Freeman *et al.* 1998).

Results

Stress distribution pattern at the periapical region

Figure 2 shows the isochromatic fringe patterns representing the stress distribution patterns at the periapical region. It was observed in the digital photoelastic experiments that compressive loading of the tooth produced bending stress distribution in the supporting bone at the periapical region. Bending of the supporting bone resulted in compressive stress distribution on the lingual side and tensile stress distribution on the buccal side of the root apex in the periapical region. The region adjacent to the root-apex experienced zero stress or neutral stress (Fig. 3a,b). There was no evident variation in the stress distribution pattern between models loaded along the long axis of the tooth and 60° lingual

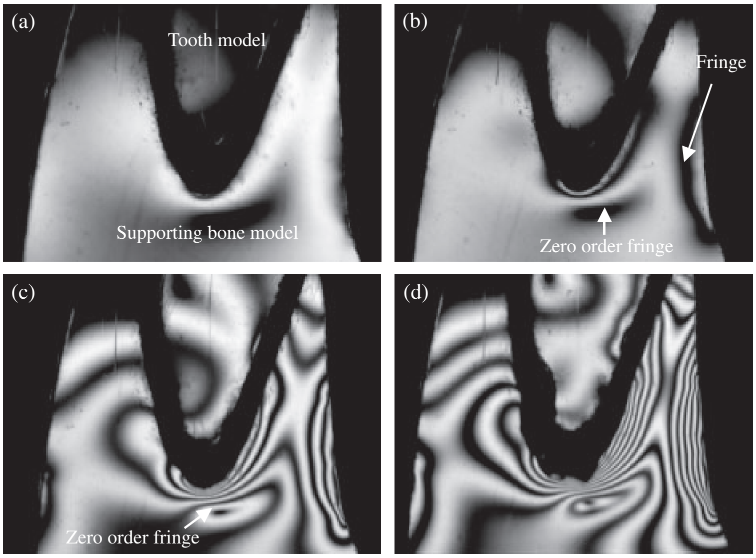

Figure 2 The isochromatic fringe patterns obtained from the tooth–bone model loaded at (a) 25 N, (b) 90 N, (c) 125 N, and (d) 200 N.

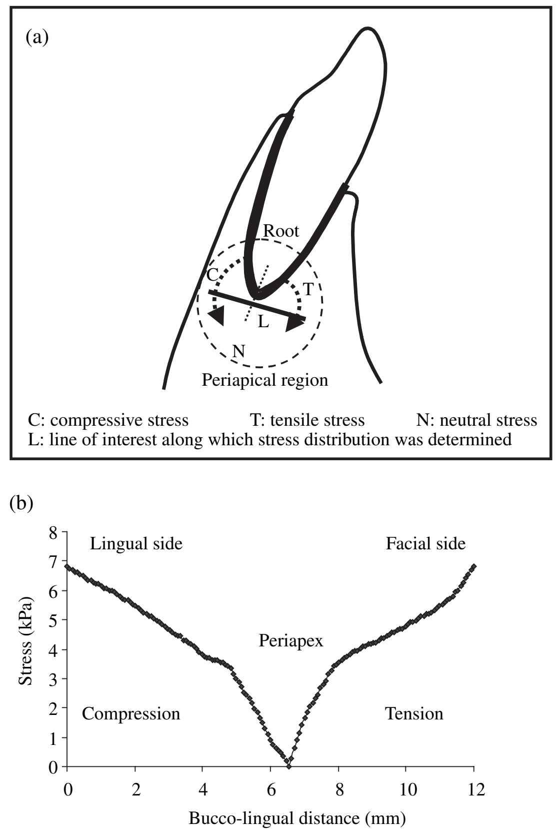

Figure 3 (a) Schematic diagram of the line of interest (L) used for the stress analysis. (b) Stress distribution pattern along the line of interest at the periapical region.

to the long axis of the tooth. The compressive and tensile stresses identified during bending were reconfirmed using a Fingernail test (Asundi & Kishen 2001). The Fingernail test suggests that if the edge of the model is pressed with a finger or the thumb nail, compression and tensile fringes react in a distinct manner, enabling them to be distinguished. If the boundary stress is compressive then the fringes are drawn towards the boundary and if the boundary stress is tensile the fringes move away from the boundary. In this study, each model was tested thrice and three similar models were tested identically to confirm the repeatability of the analysis.

Role of cyclic biting loads on apical retrograde fluid movement

This experiment showed that the cyclic loads resulted in apical retrograde fluid movement (ARFM) of the root canal for all specimens tested under all groups. In intact tooth specimens (group 1), the average retrograde fluid movement into the root canal was 3.8 mm (SD: 0.54) and in tooth specimens, in which the root canal was enlarged and kept wet (group 2), the average retrograde fluid movement into the root canal was 6.1 mm (SD: 0.29) (Fig. 4a,b). Dye was observed pumping out through the access cavity during the initial loading cycles in this group. This effect is not observed later on as the dye was diluted by the contiguous water. In tooth specimens in which the root canal was enlarged and kept dry (group 3), the retrograde fluid movement

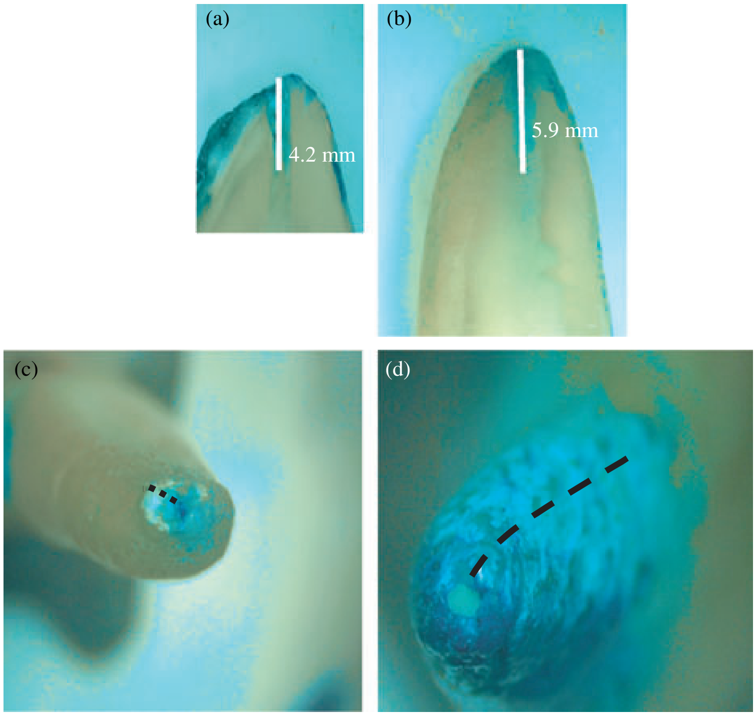

Figure 4 Light microscopic images showing retrograde fluid movement into the apical portion of the root canal in (a) group 1, (b) group 2 samples, and extraradicular fluid flushing in (c) group 2, (d) group 3 samples.

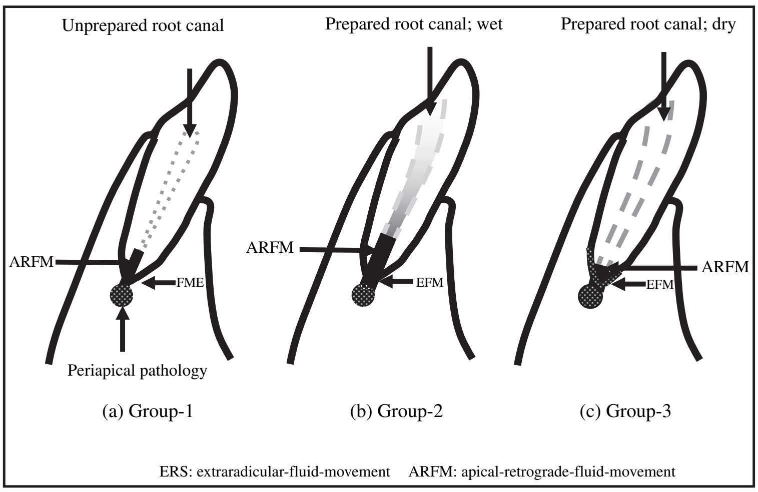

Figure 5 Schematic diagram showing the apical retrograde fluid movement (ARFM) and extraradicular fluid flushing in (a) group 1, (b) group 2, and (c) group 3 samples.

into the root canal was 2.14 mm (SD: 0.514). The control specimens (with no cyclic loads) did not show any retrograde fluid movement into the root canal. One-way ANOVA (*post hoc* tests) showed that there was a significant difference between the ARFM observed in different groups (<0.01) (Fig. 5). It was interesting to observe during the post-mortem of the tested specimens that there was a direct relationship between the retrograde fluid movement into the root canal space and the retrograde flushing of fluid on the extraradicular region (adjacent to the apical foramen). This observation was distinct on tooth specimens tested in group 2 and group 3. Group 3 specimens showed significant extraradicular fluid flushing when compared with group 2 samples (Fig. 4c,d).

Discussion

Periapical pathosis can be pre-disposed by different intervening factors such as microbiological, immunolological, fluid dynamics and biomechanical factors. Although these factors are interconnected, it is imperative to study each factor separately for a better understanding of this complex disease. Biting forces produced bending stress in structural dentine and movement of fluid within the dentinal tubules (Hirata *et al.* 1991, Asundi & Kishen 2001). Paphangkorakit & Osborn (2000) have demonstrated that occlusal forces during chewing displaced fluid from the tooth to the periapical region through the apical foramen. They showed $3.5–22.2 \times 10^3$ pL fluid displacement through the apical foramen for occlusal forces ranging from 20 to 120 N. Experiments have also shown that a load of about 10 N would conspicuously intrude a tooth into the socket due to the stretching of the periodontal fibres (Parfitt 1960, Picton 1963). These investigations highlight the role of periapical biomechanics in endodontics.

The present study reveals that cyclic biting forces result in ARFM, which causes the periapical fluid or exudate to flush the apical portion of the root canal and the extraradicular region. It was observed that retrograde fluid movement into the root canal was significant when the root canal was enlarged and wet. Noticeable retrograde fluid movement in wet canals may result from the presence of a liquid column, which facilitated movement of fluid, whereas in dry canals entrapped air (void) may have hindered fluid movement (Kontakiotis *et al.* 2001). Although retrograde fluid movement into the root canal space was less when the root canal was enlarged and maintained dry, these specimens showed obvious flushing of the extraradicular region. The lesser the entry of fluid into the root canal, the greater was the flushing of the extraradicular region. It is crucial to note that a wet environment and fluid flow will not only enhance bacterial adhesion but also facilitate their growth as biofilm structures on dentine and cementum. The biofilm mode of growth provides bacteria with the ability to survive harsh environmental conditions, and in this state the bacteria may be protected from antimicrobial agents, environmental factors and host responses. Bacterial biofilms are said to be a common cause for persistent infections (Costerton *et al.* 1999).

Earlier cultural and microscopic studies have reported the occurrence of periradicular biofilms (Siqueira & Lopes 2001). Tronstad *et al.* (1990) reported the occurrence of bacterial biofilms in the periapical region adjacent to the apical foramen of root tips removed during surgical endodontics, while Noiri *et al.* (2002) observed bacterial biofilms in the extraradicular areas in nine of 11 teeth associated with refractory periapical periodontitis. Studies have also demonstrated the occurrence of viable bacterial cells in the apical portion of the root canal in root-filled teeth with persistent periapical periodontitis (Fabricius *et al.* 1982, Kipioti *et al.* 1984). Much similarity has also been reported between the microfloras of advanced periodontitis and periapical infection (Haapasalo *et al.* 1986, Sundqvist *et al.* 1989, Kerekes & Olsen 1990). This similarity may be because of the following facts: (i) these microorganisms derive nutrition, presumably from tissue fluid (serum) which enters the root canal space via ARFM and (ii) the similarity in the existing environmental condition (anaerobic) (Molander *et al.* 1998, Sundqvist *et al.* 1998, Figdor *et al.* 2003).

Conclusions

Within the limits of this *ex vivo* investigation it could be concluded that biting forces cause bending of the periapical bone and cyclic biting forces contribute to retrograde fluid movement into the apical portion of root canal and extraradicular region. These dynamics may provide an ideal environment for any surviving bacterial species to grow and cause persistent endodontic infections.

Acknowledgement

The author wishes to thank Professor A. Asundi, School of Mechanical & Production Engineering, Nanyang Technological University, Singapore for the support with the digital photoelasticity.

This work was supported by the National University of Singapore, ARF Grant number FY 03 R-224-000-021-101 and R-224-000-020-112.

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