Effect of obturation technique on sealer cement thickness and dentinal tubule penetration

M. V. Weis, P. Parashos & H. H. Messer
School of Dental Science, University of Melbourne, Melbourne, Victoria, Australia

Abstract

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Aim To compare the average sealer cement film thickness and the extent and pattern of sealer penetration into dentinal tubules in association with four obturation techniques in curved root canals.

Methodology Mesial canals of 44 extracted mandibular molars were randomly divided among the SimpliFill, continuous wave, Thermafil and 0.04 matched taper (master cones) lateral compaction obturation groups (22 canals per group). AH26 sealer cement was coloured blue-black using Sudan Black B dye. Roots were sectioned 1, 3 and 5 mm from the working length. Specimens were photographed under 25× magnification, mounted as 35 mm slides and projected. Average sealer cement thickness (measured at 10 points around the canal wall), depth of dentinal tubule penetration and frequency of voids were determined at the 1, 3 and 5 mm levels. Data were analysed statistically for effect of obturation technique and level of section on sealer thickness and on the depth and distribution of tubule penetration.

Results Thermafil demonstrated superior GP adaptation at all levels with a mean overall sealer cement thickness of 2.2 μm, followed by lateral compaction (11.1 μm), continuous wave (12.2 μm) and SimpliFill (47.6 μm). SimpliFill also demonstrated the highest frequency of voids ($P < 0.05$). Sealer cement penetrated dentinal tubules as far as the outer one-third of dentine, with greater penetration observed buccally or lingually ($P < 0.001$). Penetration was not significantly affected by obturation technique, but on average was deeper and more frequent at the 3 and 5 mm levels than at the 1 mm level ($P < 0.001$).

Conclusions Sealer thickness was strongly dependent on obturation technique. Assuming that minimal sealer thickness and fewer voids are good measures of long-term sealing ability, Thermafil resulted in the best outcome. Consistent, extensive sealer penetration into dentinal tubules was seen and was unrelated to the obturation technique.

Keywords: sealer cements, sealer thickness, tubule penetration, obturation.

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Introduction

It is currently accepted that the major goal of root canal filling is to prevent any interchange between the oral cavity, the root canal system and the periradicular tissues, providing a barrier to canal infection and reinfection (Gutmann & Witherspoon 2002). Not all teeth with positive bacterial cultures fail, nor do all teeth with negative cultures succeed (Sjögren *et al.* 1997). Thus 'entombing' residual microorganisms and irritants by sealing them within the root canal system may have a major influence on clinical outcome. Farzaneh *et al.* (2003) assessed the impact of the root filling technique on the treatment outcome by direct clinical comparison. They showed statistically significantly better results with the vertical compaction technique (95%) than with the lateral compaction technique (80%). Studies such as these imply that a closer approximation between

Correspondence: Professor Harold H Messer, School of Dental Science, University of Melbourne, 711 Elizabeth Street, Melbourne, Victoria 3000, Australia (Tel.: +61 3 9341 0414; fax: +61 3 9341 0339; e-mail: hhm@unimelb.edu.au).

gutta-percha and the canal wall would limit or restrict the passage of microorganisms and their by-products responsible for periapical disease (Kersten & Moorer 1989).

Leakage of fluids through an obturated root canal occurs between the sealer and dentine, the sealer and gutta-percha, or through voids within the sealer (Sen *et al.* 1996). Although sealers enhance sealing ability by filling in any residual spaces (Hata *et al.* 1992), and bonding to dentine (Najar *et al.* 2003), the optimal outcome in obturation is to maximise the volume of the core material and minimise the amount of sealer between the inert core and the canal wall (Peters 1986, Wu *et al.* 1995).

Although smear layer removal remains controversial, its poorly adherent and permeable nature may in a short period of time degrade, permitting gap formation between the root filling and canal wall (Sen *et al.* 1995). Irrigants that can remove this layer have been found to increase both the adaptation and sealability of warm and cold compaction techniques (Gutmann 1993, Economides *et al.* 1999) whilst allowing penetration of sealers into dentinal tubules (White *et al.* 1987, Pallares *et al.* 1995, Sen *et al.* 1996, Kouvas *et al.* 1998). The phenomenon of smear layer removal and sealer penetration into dentinal tubules may also serve an important role by preventing re-infection from the oral cavity and incarcerating and depriving residual microorganisms of a nutrient source (Assouline *et al.* 2001).

The obturation technique as well as the physical and chemical properties of the sealer cement, will determine to a large degree the resultant sealer film thickness (Eguchi *et al.* 1985, Peters 1986). Obturation techniques are largely dependent on the preparation technique employed to clean and shape the root canal system, and superior leakage results have been found with canal preparation using rotary nickel–titanium instruments (von Fraunhofer *et al.* 2000). This has given rise to various ‘instrumentation–obturation systems’ that can be matched and adapted more closely to a uniformly and centrically prepared root canal (Bal *et al.* 2001).

The evaluation and comparison of current obturation techniques is therefore important in determining their relative efficacy in achieving an optimal seal. Most current evaluation methods are based on dye and bacterial leakage studies. These linear and quantitative studies are based on the supposition that the depth and degree of tracer penetration will reflect the extent of the gap between the root filling and canal wall. However, they have been shown to be variable and poorly reproducible due to a lack of standardisation of experimental technique (Wu & Wesselink 1993). Moreover, short-term leakage studies may evaluate only differences of the specific sealer tested at varying thicknesses, at different times (Wu *et al.* 1995, Kontakiotis *et al.* 1997).

The aims of this study were to compare systematically the average sealer cement film thickness and the extent, pattern and degree of sealer penetration into dentinal tubules in association with four contemporary instrumentation/obturation techniques (Thermafil; 0.04 matched taper Lateral Compaction; Continuous Wave; and SimpliFill) at different levels in narrow curved root canals prepared by rotary Ni–Ti instrumentation. The null hypothesis for this study is that sealer cement thickness and tubule penetration of sealers are not affected by obturation technique.

Materials and methods

Sample selection

Extracted intact human mandibular molars with closed apices were stored in 10% buffered formalin. Only teeth with separate mesial canals and distinct major foramina were selected. A size 10 H-file (Dentsply Maillefer, Ballaigues, Switzerland) was introduced into each of the mesial canals until it appeared at the apical foramen and the working length was established by subtracting 0.5 mm from this measurement. Forty-four suitable teeth were then randomly distributed among four obturation groups so that there were 22 canals per group. (This was the maximum number that could be obtained for the study, with 20–25 canals per group considered desirable for statistical analysis). Mesiobuccal and mesiolingual canals were alternated among techniques, attempting to control for both tooth and canal variability. During all procedures throughout the study, the teeth were kept moist, using sterile gauze soaked in saline, and stored in saline.

For all techniques, each canal was irrigated with 1% sodium hypochlorite (NaOCl) solution throughout canal preparation. Apical patency was maintained with a size 10 file. Prior to obturation, the teeth were irrigated with 5 mL NaOCl, followed by 10 mL 15% liquid ethylenediaminetetracetic acid (EDTA, Colgate Oral Care Company, Waverly, Australia), and then again with a final rinse of 5 mL NaOCl, to remove the smear layer. The final irrigating solutions were left in each root canal for approximately 3 min.

AH26 (De Trey, Dentsply, Konstanz, Germany) sealer cement was mixed according to the manufacturer's instructions of a powder : liquid ratio of 2 : 1 at room temperature. To differentiate sealer cement from the surrounding dentine, AH26 was coloured by the addition of a small amount of Sudan Black B (Poly Scientific R&D, Bay Shore, NY, USA), which was added until completely dissolved within the sealer cement. The mix was standardised using a colour reference guide. Canals were dried with paper points and sealer cement was introduced into all prepared canals with a size 25 Lentulo Spiral (Dentsply Maillefer) in a slow-speed handpiece until the sealer could be seen exiting the root apex. At the completion of obturation, all excess filling materials were removed from the pulp chamber using a cotton wool pledget soaked in 95% ethanol. The access cavities were filled with Cavit G (ESPE, Seefeld, Germany), and then stored at 100% humidity for 14 days allowing the AH26 to set completely.

Instrumentation/obturation techniques

All canal preparation techniques were conducted according to manufacturers' instructions, resulting in different sizes of both apical preparation and canal taper. In view of the differing tapers of instruments used, it is impossible to standardise apical size and taper across all groups. To simulate clinical conditions, the manufacturers' recommendations for canal preparation, linked to a specific method of obturation, were followed.

Group 1: ProFiles® and matched taper master cone with lateral compaction

Canals were prepared using rotary Ni–Ti ProFile® files of 0.04 mm taper (Dentsply Maillefer) in a crown-down technique, until working length was achieved with a master apical rotary file (MAR) size of 30. The canals were then obturated using matched 0.04 taper master GP cones by first achieving 'tugback' at working length. After coating the canal walls, the master cone was also lightly coated with a standardised mix of AH26 and seated to working length in a slow plunging motion. The remainder of the canal space was then obturated using lateral compaction with nonstandardised, XXF (Dentsply, Abbotsford, Victoria, Australia) accessory cones with a medium-fine finger spreader (Kerr, Romulus, MI, USA) ensuring that all accessory cones were placed to the spreader depth.

Group 2: Greater Taper (GT)™ and continuous wave of compaction

Rotary Ni–Ti Greater Taper (GT)™ files (Dentsply Tulsa Dental, Tulsa, OK, USA) of 0.12, 0.10, 0.08, 0.06 taper were used in a crown-down technique until working length was achieved with MAR size of 20/0.08. These canals were then obturated using the continuous wave technique (Buchanan 1998) involving the compaction of matched 0.08 taper Autofit GP cones (Analytic Technology, Glendora, CA, USA), warmed by a matched electrically heated plugger (size FM). The pluggers are specifically designed for use with the electric heat carrier 'System-B' (Analytic Technology, Redmond, VA, USA) set at 200 °C on full power to provide simultaneous heating and compaction of gutta-percha within the root canal system. The pluggers were pre-fitted so that the 'downpack' procedure did not extend closer than 4 mm from the working length (Buchanan 1998). After seating the Autofit GP cone, the excess was seared at orifice level using the activated plugger and compacted. The plugger was then reactivated and inserted into the gutta-percha with gentle apical movement to a point 5–7 mm short of the working length. The activating spring of the plugger was released, allowing it to cool while keeping light pressure against the gutta-percha for some 10 s. To remove the plugger, the spring was briefly activated and simultaneously removed from the canal, leaving an apical mass of gutta-percha. The remainder of the root canal system was back-filled using an injectable gutta-percha system (Obtura II, Obtura Corporation, Fenton, MO, USA), by inserting a single bolus of thermoplasticised gutta-percha and vertical compaction by means of a hand plugger. The part of the canal filled using the Obtura was coronal to the sites of subsequent sectioning and evaluation of sealer thickness.

Group 3: ProFile® and Thermafil® core-carrier

ProFile files of 0.04 mm taper were used in a crown-down technique until working length was achieved with a MAR size of 30. After complete instrumentation, a size 25 or 30 Thermafil obturator was selected, based on the 'best-fitting' verifier, and heated in the Therma-Prep Plus Oven® (Tulsa Dental Products) for the recommended time. The canal was dried and sealer cement placed using the size 25 Lentulo spiral as indicated above. The preheated Thermafil obturator was then inserted firmly and slowly to working length without any twisting or rotation. Both the excess GP and carrier were severed at orifice level using the

System-B electrical device at a power setting of 10 at 400 °C. No coronal compaction was performed.

Group 4: LightSpeed®/SimpliFill®

Canals were pre-flared coronally using rotary Ni–Ti ProFile® files of 0.04 mm taper in a crown-down technique until a size 45 file reached 6 mm short of working length. Canals were then instrumented to length with sequentially larger LightSpeed instruments according to the LightSpeed instructional Guide (http://www.lightspeedusa.com) and standardised to MAR size 50. With the next largest LS instrument (size: 52.5) the canal was then enlarged 4 mm from the working length. At completion of instrumentation, a matched size 50 SimpliFill® GP Plug (LightSpeed Technology, San Antonio, TX, USA) was selected for obturation. Each GP plug was trial fitted to achieve a 'snugness' at 1–3 mm from working length. Canals were then dried and AH26 sealer cement placed as described above, also coating the GP plug lightly. The carrier was slowly advanced into the canal until working length was reached, often requiring a firm push and finally released by turning it in a counter-clockwise direction. No back filling procedure was performed as it was beyond the range of sectioning. The manufacturer also recommends filling the remainder of the canal with sealer and a single cone without compaction.

Specimen preparation

After storage for 14 days at 100% humidity the teeth were sectioned perpendicular to the root canal at 1, 3 and 5 mm from the anatomical root apex using a 0.3 mm thick diamond rotary blade (Struers, Rødovre, Copenhagen, Denmark) at low speed with constant water cooling. The root segments were mounted on glass slides with the appropriate surface facing upwards (at the 1, 3 and 5 mm levels from the apex). Sections were smoothed using a new scalpel blade for each tooth, with a light shaving motion to remove any torn or smeared GP and dentinal chips. This ensured that the sealer layer could be detected around the entire root canal filling perimeter.

Evaluation

Part A: Measurement of sealer thickness

The sections were viewed under an Olympus BH-2 standard light microscope (Olympus Optical, Tokyo, Japan) at 25× magnification and illuminated with reflected light using a dual-head quartz halogen light with fibre-optic cables. An Olympus single-lens reflex (SLR) camera using 64-Tungsten emulsion film (Eastman Kodak Company, Rochester, NY, USA) was attached to the triocular eyepiece and sections were photographed and mounted as 35 mm slides. The slides were then projected resulting in a final magnification of approximately 880× the original specimen size.

Sealer thickness was measured by superimposing a transparent grid system based on a morphometrical method as described by Andreasen (1987) for root resorption, and previously modified for canal cleanliness assessment (Tan & Messer 2002). The grid system consists of 10 equally spaced radii projecting from the centre of the canal cavity and intersecting with the sealer-canal wall interface (Fig. 1). The sealer film, which appeared blue-black in colour, was measured at each of the 10 intercepts using a millimetre ruler. If a void was detected, its presence was noted and the intercept excluded from the average. A separate analysis of the total number of voids was performed with these calculations.

To standardise the orientation of the 10 radiating lines between canals and between teeth from the left and right hand sides of the mouth, intercept 1 was always aimed towards the isthmus and intercept 2 mesially (away from the furcation) (Fig. 1).

Part B: Depth of sealer penetration

Those sections demonstrating sealer penetration into dentinal tubules, as determined by the staining procedure using Sudan Black B, were re-photographed at a lower magnification (10×) so that the images showed the whole root cross-section out to the cementodentinal junction (CDJ). Sealer penetration depth and density were scored using a four-quadrant pie chart superimposed over each of the projected images (Fig. 2a). The centre of the pie chart was placed in the approximate centre of the root canal filling. The chart was orientated such that the isthmus bisected quadrant 1 and quadrant 2 was directed toward the mesial root surface.

Penetration or absence of sealer into tubules was scored for each quadrant. Because of the different dimensions of each cross-section between teeth and at different levels, scoring was standardised using the following scoring system rather than absolute values (Fig. 2b).

A - Absent. No sealer penetration into tubules evident.

I - Inner one-third. Depth of penetration extended into the inner third of the distance to the CDJ.

M - Middle one-third. Depth of penetration extended into the middle third of the distance to the CDJ.

Figure 1 Cross-section of the SimpliFill sectional method 5 mm from working length. Superimposed with the grid system, it can be used to measure sealer thickness at 10 points of intersection with the canal wall. Intercept 1 is always oriented towards the isthmus (original magnification: 25×).

O - Outer one-third. Depth of penetration extended into the outer third of the distance to the CDJ.

Statistical analysis

The model set up to analyse sealer thickness and sealer penetration involved random and fixed effects. The random effects reflect the multiple levels of variation in the experimental design. The structure started with teeth on the highest level, canals were nested under each tooth, the 1, 3 and 5 mm levels of cross-sections were nested within each canal, and finally, four quadrants were nested within each level of cross-section. The obturation techniques were assigned at the canal level. It follows that the levels of cross-sections and quadrants nested within that canal will inherit the same treatment.

The analysis was conducted using the software package GenStat (VSN International, Hemel Hempstead, UK), and the fixed effects were tested using the Wald tests for fixed effects to determine the level of statistical significance of difference among obturation techniques, levels and quadrants for depth of sealer penetration. Depth of sealer penetration was numerically coded as 1 (absent), 2 (inner-third), 3 (middle-third) and 4 (outer-third) in ascending order of depth to allow statistical analysis on a pseudo-ordinal scale. A separate analysis was conducted to compare the frequency of voids resulting from the four-obturation techniques discarding the level effect. All statistical analyses were performed at the 0.05 level of significance.

Results

One cross-section at the 5 mm level in the SimpliFill group and one specimen at the 1 mm level in the lateral compaction group fractured during the sectioning and preparation phases of the study and were excluded. Examples of the adaptation of the root filling techniques are demonstrated in Fig. 3.

Sealer thickness

In general, all cross-sections at all levels demonstrated a visible and circumferentially continuous sealer layer that could be measured at the 1–2 μm range depending on the quality of the projected slides. On average, the SimpliFill technique resulted in the largest sealer thicknesses (Fig. 4), and Thermafil the smallest at all levels, with mean overall sealer thicknesses of 47.6 and 2.2 μm, respectively. The results from the Wald tests for fixed effects showed that the sealer thickness varied statistically significantly among different techniques ($P < 0.001$) and among different levels ($P = 0.002$). Moreover, the interaction effect of techniques and levels was also found to be statistically significant ($P < 0.001$). All pairwise comparisons between obturation techniques were highly significant ($P < 0.01$) except for the mean difference between continuous wave (12.2 μm) and lateral condensation (11.1 μm) that were not statistically different from each other. SimpliFill also demonstrated a significantly smaller mean sealer thickness at the 5 mm level compared with the 3 and 1 mm

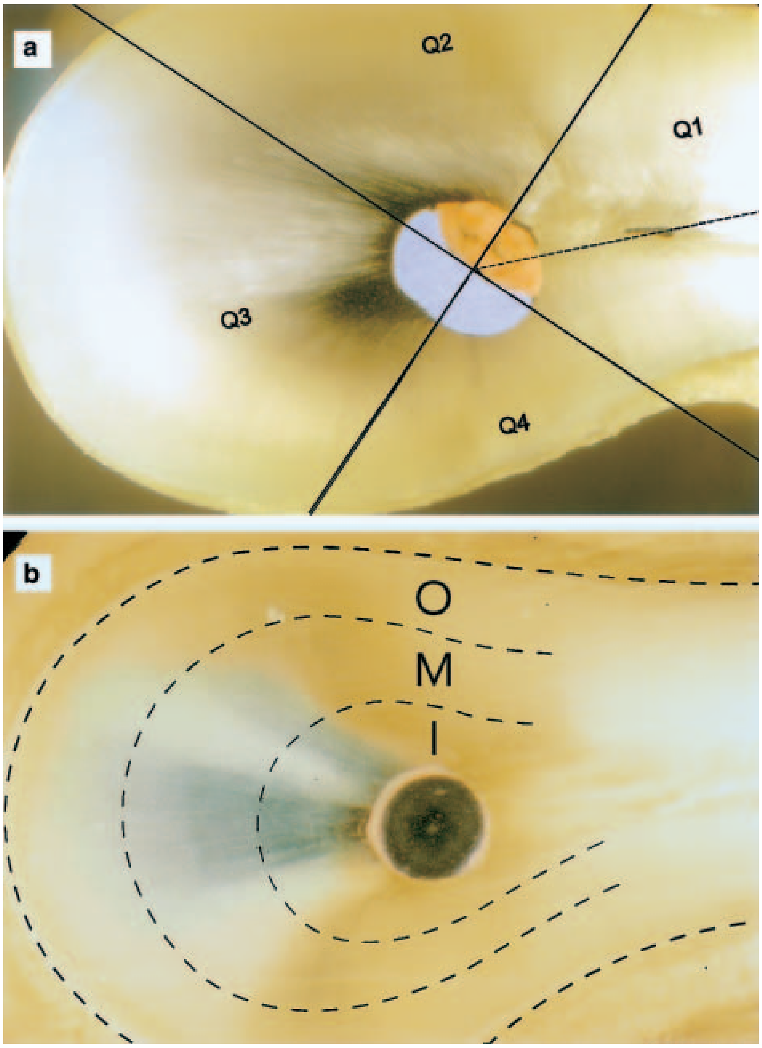

Figure 2 (a) Cross-section of the 0.04 matched taper lateral compaction technique method 5 mm from working length. The four-quadrant pie chart was superimposed to assess systematically the pattern and degree of sealer penetration into dentinal tubules. In this example, sealer can be seen to penetrate into quadrants 2 and 3 (original magnification: 10×). (b) Cross-section of the Thermafil technique 5 mm from the working length. Depth of sealer penetration was evaluated based on the presence of sealer into but not exceeding the I, inner one-third; M, middle one-third or O, outer one-third of distance to the cemento-dentinal junction. In this example, sealer can be seen to penetrate into the outer one-third (original magnification: 10×).

levels ($P < 0.001$), while this was not the case for the other techniques.

Depth of sealer penetration

Overall, the results suggested that different obturation techniques produced similar depths of sealer penetration on average ($P > 0.05$). In approximately 10% of samples, sealer was able to penetrate dentinal tubules as far as the outer one-third of the distance to the CDJ. The greatest average frequency and depth of sealer penetration was observed at quadrant 3, 5 mm level, where penetration was detected in approximately 80% of samples (Fig. 5). The smallest average penetration was observed at quadrant 4, 1 mm level, where penetration was demonstrated in approximately 25% of samples, rarely extending past the inner-third (Fig. 5).

Comparing sealer penetration depth according to level, an increasing frequency and depth of penetration were found in an apical to coronal direction. Greatest penetration was found at the 5 mm level followed by the 3 mm level, which was in turn greater than at the 1 mm level. The differences between scores at different levels were all highly significant ($P < 0.001$).

Similarly, comparisons between quadrants showed that the greatest depth of sealer penetration was scored for quadrant 3 (away from the isthmus) and the least penetration observed at quadrant 1 (towards the isthmus). All pairwise comparisons between quadrants also showed highly significant differences ($P < 0.01$). The interaction effect of level and quadrant was also found to be statistically significant ($P < 0.001$); ignoring one of them would be inadequate to explain the variation in the degrees of sealer penetration.

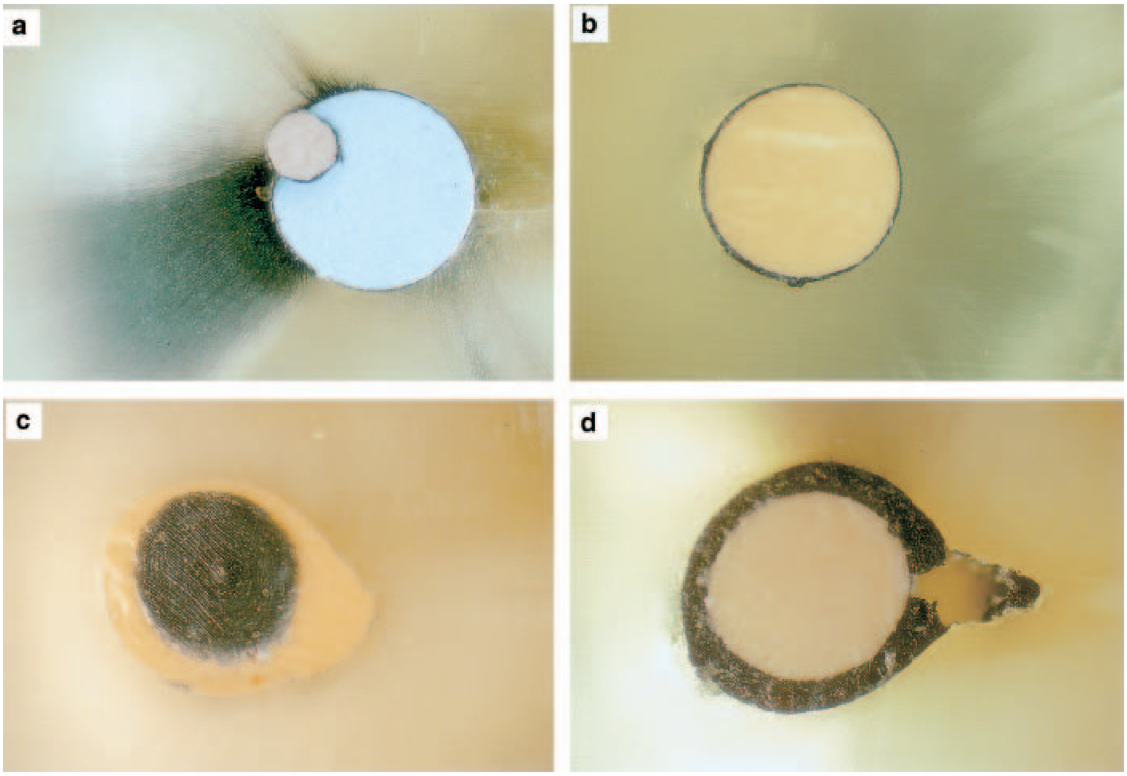

Figure 3 Cross-sections of each of the four-obturation techniques 3 mm from working length (a) 0.04 matched-taper lateral compaction technique. The blue coloured master cone (size: 30/0.04) can be seen occupying most of the canal space. Note also the apparent compression of dentine by the spreader adjacent to the accessory cone and the variation in the degree and depth of sealer penetration around the canal wall. (b) Continuous wave of compaction technique showing a very thin but continuous layer of sealer cement and the absence of dentinal tubule sealer penetration. (c) Thermafil technique demonstrating a well adapted root-filling and complete encasement of the central core-carrier. (d) SimpliFill sectional method showing a thick and continuous sealer layer. Note also the presence of a moderately sized void adjacent to the fin (original magnification: 25×).

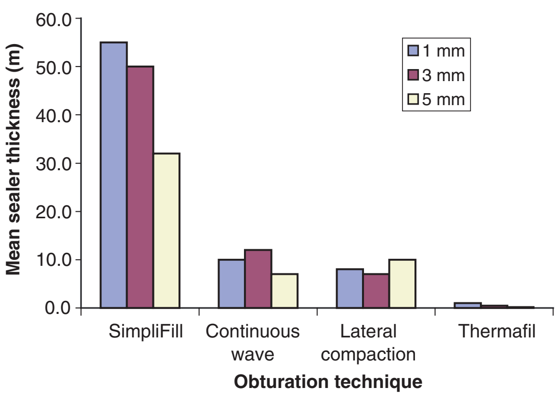

Figure 4 Mean sealer thickness at the gutta-percha core and canal wall interface at the 1, 3 and 5 mm levels for each of the four obturation techniques.

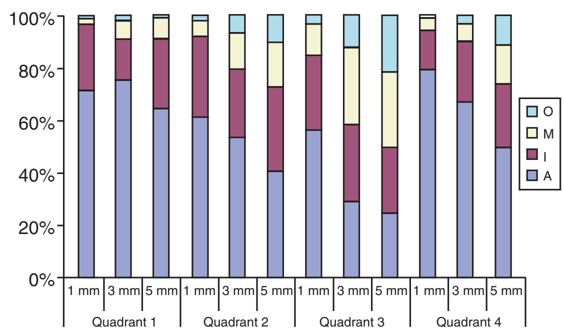

Figure 5 Depth of sealer penetration for all techniques into dentinal tubules in different quadrants at the 1,3 and 5 mm levels from working length. A, absent; I, inner one-third; M, middle one-third; O, outer one-third.

Table 1 Numbers of voids at each of the measuring locations

	Obturation technique			
Level	SimpliFill* (%)	Continuous wave (%)	Lateral compaction (%)	Thermafil (%)
1 mm	29 (13)	5 (2.3)	6 (2.9)	0
3 mm	22 (10)	8 (3.6)	7 (3.2)	0
5 mm	28 (13)	3 (0.9)	6 (2.7)	1 (0.4)
Total	79 (12.2)	16 (2.4)	19 (2.9)	1 (0.2)

*Percentages relate to the number of measuring locations for each group, which was 220 except for SimpliFill (5 mm) and lateral compaction (1 mm) which had 210.

Voids

The total number of voids and their frequencies (percentage of measuring locations) are given in Table 1. SimpliFill recorded the greatest number of voids (79 in total) at all levels, accounting for approximately 12% of all measuring locations. Conversely, for the continuous wave and lateral condensation techniques, voids accounted for only 2 and 3% of all measuring locations, respectively. Thermafil demonstrated the presence of only a single void and was thus deleted from statistical analysis. All the pairwise comparisons showed that the only significant difference was between the continuous wave and SimpliFill techniques ($P < 0.05$).

Discussion

Sudan black B, a histological stain for lipid, is an excellent stain for implanted polymeric biomaterials such as glycol methacrylate and epoxy resins (Hoeksma *et al.* 1988). Preliminary investigations confirmed that this hydrophobic dye was completely soluble in AH26 and did not affect the handling or setting characteristics of the sealer. The dye provided sufficient contrast between AH26 sealer, dentine and gutta-percha, enabling direct, light microscopic evaluation of sealer cement thickness and penetration into dentinal tubules (Figs 1 and 2). The grid system used to evaluate sealer cement thickness and the number and extent of voids in this study has been used previously to assess both root resorption (Andreasen 1987) and canal cleanliness (Tan & Messer 2002) to a high level of precision. This quantitative method is an alternative to methods for assessing the relative ratios of gutta-percha and sealer over the entire cross-sectional surface (Eguchi *et al.* 1985, Silver *et al.* 1999, Gençoglu *et al.* 2002, Wu *et al.* 2002).

Previous investigations assessing sealer distribution after obturation have shown only limited canal wall coverage, with scores ranging between 40 and 60%, dependent on compaction technique and apical level (Hall *et al.* 1996, Wu *et al.* 2000). The results of the current study are in direct contrast to these, but agree with Pallares *et al.* (1995) and Silver *et al.* (1999) demonstrating a circumferentially continuous sealer layer at all levels, for all groups (Fig. 3). This may be attributed to the greater contrast imparted by the Sudan Black stain and high magnification. Thermafil, however, occasionally demonstrated breaks in sealer layer continuity, suggesting that thermosoftened gutta-percha had penetrated and flowed into patent dentinal tubules rather than a lack of canal wall sealer coverage (Gutmann 1993, Gençoglu *et al.* 1993, Pallares *et al.* 1995).

Thermafil, a core-carrier technique, demonstrated superior predictability in achieving a homogenous, well-adapted root filling with a minimum film thickness (approximately 2 μm) in narrow curved canals. These results are consistent with other investigations assessing canal wall adaptation (Gençoglu *et al.* 1993, Gutmann *et al.* 1993) or gutta-percha to sealer ratios (Gençoglu *et al.* 2002). No stripping of gutta-percha from the carrier was noted in any section, contrary to the findings of Gutmann *et al.* (1993), using a low magnification clearing technique. The LightSpeed/SimpliFill technique consistently resulted in the greatest sealer film thickness (approximately 50 μm) and the highest frequency and extent of voids at all levels (Figs 1 and 3d). Two reasons have been postulated to account for these results. First, the wedging effect of the 'press fit' design (Wildey & Senia 2002) could inadvertently entrap air apically. Secondly, the LightSpeed instrumentation technique itself may be a factor. Hall *et al.* (1996) speculated that the parallel-walled apical preparation might prevent sealer delivery to all parts of the canal. The manufacturers acknowledge a greater reliance on the sealer cement for obturation, rather than gutta-percha adaptation (LightSpeed Technology Inc. 2003).

The matched 0.04 taper lateral condensation and Greater Taper/continuous wave techniques resulted in similar mean sealer thicknesses (approximately 11–12 μm) and total number of voids at all levels. For 0.04 matched taper lateral condensation, lack of spreader penetration and accessory cones did not affect sealer cement thickness, especially at the 1 mm level. This is in contrast to conventional lateral condensation using 0.02 tapered master cones, where spreader penetration to within 1 mm of the working length has been clearly shown to improve the apical seal (Allison *et al.* 1979). Our results are consistent with those of Bal *et al.* (2001), indicating that spreader penetration to within 1 mm may be made redundant by the better matching of master cones to more uniformly prepared canals with the same taper (Fig. 3a). Overall, using greater taper master cones would seem a more predictable and efficient technique.

The thermoplastic continuous wave technique resulted only in sealer thickness comparable to the lateral condensation technique. Adequate depth of heat application (Venturi *et al.* 2002) and a sufficient amount of gutta-percha in the apical region are essential in any vertical compaction procedure (Wu *et al.* 2002). Venturi *et al.* (2002), measuring temperature changes of apical gutta-percha with the System-B heat source, showed that optimal changes of 4 °C for warm vertical compaction were never achieved, even when the plugger penetrated to within 2–4 mm from the apex. This is deeper than that recommended by Buchanan (1998) of 5–7 mm from the working length. Thus, the continuous wave technique may be ineffective in heat-softening apical gutta-percha, so that the seal achieved is related to the close fit between canal taper and gutta-percha point taper. Using matched 0.08 taper Autofit cones may be essential for good apical adaptation to the canal wall (Fig. 3b).

The colouring of AH26 sealer cement blue-black and the division of the pulpal cavity into four quadrants in this study enabled the systematic evaluation of sealer penetration (Fig. 2). This study corroborated the ability of plastic filling materials to penetrate dentinal tubules in the absence of the smear layer (White *et al.* 1987, Gutmann 1993, Gençoglu *et al.* 1993, Pallares *et al.* 1995, Sen *et al.* 1996, Kouvas *et al.* 1998). Regional differences in the predictability and depth of sealer penetration into dentinal tubules were observed both in an apico-coronal (Gutmann 1993) and mesio-distal orientation. Least penetration occurred apically, and greater penetration occurred buccally or lingually, in the area of greatest canal wall curvature (Figs 2 and 3a). Surprisingly, in this experimental model the differences were found to be unrelated to the obturation technique, inferring that sealer penetration is primarily a function of dentinal tubule permeability and the chemical and physical characteristics of the sealer used (Sen *et al.* 1996, Kouvas *et al.* 1998). Nonresin-based sealers demonstrated a granular appearance within the tubules, indicating that sealer penetration depth might be attributable to its particle size, flow and surface tension properties following the removal of the smear layer (Kouvas *et al.* 1998). Sealers, such as epoxy resins, which exhibit structural integrity, homogeneity and tightness of seal within the tubule (White *et al.* 1987) may be more important than the depth of tubular penetration in relation to leakage or incarceration of residual microorganisms. Although regional variations in dentinal tubule permeability may limit penetration to specific dento-anatomical sites, variations in microbial invasion patterns have also been demonstrated in an apico-coronal direction (Love 1996). A corollary to these findings is that where tubules are patent, sealer cements with sufficient flow, wetting and bonding potential should be able to penetrate, seal and entomb the few remaining microorganisms that remain viable after the instrumentation and medicament phase of therapy (Sjögren *et al.* 1997).

Conclusions

Assuming that minimal sealer thickness and fewer voids are good measures of long-term sealing ability, Thermafil resulted in the best outcome. SimpliFill resulted in large sealer thicknesses and a high frequency of voids. Matched taper 'instrumentation–obturation' systems provided excellent gutta-percha adaptation for both cold (lateral condensation) and warm (continuous wave) techniques that were not statistically significantly different from each other. Regional variations in sealer cement penetration both in an apico-coronal and mesio-distal orientation may have significant implications for disinfection, bonding and 'entombment' techniques. The frequency and depth of sealer penetration were unrelated to the obturation technique employed.

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