doi:10.1111/j.1365-2591.2007.01298.x

Apical sealing ability of Resilon/Epiphany versus gutta-percha/AH Plus: immediate and 16-months leakage

F. Paqué & G. Sirtes

Division of Endodontology, Department of Preventive Dentistry, Periodontology, and Cariology, University of Zurich Centre for Dental Medicine, Zurich, Switzerland

Abstract

Paqué F, Sirtes G. Apical sealing ability of Resilon/Epiphany versus gutta-percha/AH Plus: immediate and 16-months leakage. *International Endodontic Journal*, **40**, 722–729, 2007.

Aim To compare the long-term apical sealing ability of gutta-percha/AH Plus and Resilon/Epiphany.

Methodology The root canals of 90 single-rooted human mandibular premolars with single narrow root canals were prepared with ProFile 0.4 taper instruments to apical size 40. After each instrument, the canals were irrigated with 1% sodium hypochlorite. Subsequently, the teeth were randomly divided into four groups containing 20 teeth each. Additionally, 10 prepared premolars served as positive and 10 counterparts with intact crowns as negative controls. The root canals were filled with gutta-percha/AH Plus or Resilon/Epiphany using lateral or vertical compaction. Specimens were allowed to set for 7 days at 37 °C and 100% humidity. Subsequently, the root fillings were removed down to the apical 4 mm. Fluid movement was then assessed using a fluid transportation model and re-evaluated after 16 months of water storage. Leakage within and between groups was compared using nonparametric tests.

Results Negative controls revealed no fluid movement and positive controls displayed gross fluid movement at both times of observation. At the immediate measurement, there were no significant differences between the experimental groups (Kruskal–Wallis, $P > 0.05$). Gutta-percha/AH Plus fillings retained their seal after 16-months storage (Wilcoxon, $P > 0.05$), whilst the Resilon/Epiphany groups lost their sealing capacity (Wilcoxon, $P < 0.001$). In these groups, 29 of the 40 specimens exhibited gross leakage similar to positive controls.

Conclusion Initially, Resilon/Epiphany root fillings prevented fluid movement to the same degree as gutta-percha/AH Plus counterparts, but showed more fluid movement when tested at 16 months.

Keywords: fluid transport model, gutta-percha, leakage, Resilon, root canal filling.

Received 12 February 2007; accepted 16 April 2007

Introduction

The root filling is thought to be critical for the long-term outcome of root canal treatment (Sjögren *et al.* 1990, Buckley & Spångberg 1995). A root filling may entomb surviving bacteria, and prevent apical and coronal leakage, i.e. stop influx of periapical tissue-derived fluid from nourishing the remaining microbiota and prevent re-infection of the root canal system (Sundqvist *et al.* 1998). Animal and human outcome studies have shown that the currently used root filling materials and techniques are not optimal (Sjögren *et al.* 1997, Katebzadeh *et al.* 1999) and fail to fulfil the desired requirements (Swanson & Madison 1987, Madison & Wilcox 1988). Therefore, the development and maintenance of a seal is desirable and considered to be a major prerequisite to improve the outcome of root canal treatment. One relatively recent approach to

Correspondence: Dr Frank Paqué, Department of Preventive Dentistry, Periodontology, and Cariology, University of Zurich Center for Dental Medicine, Plattenstrasse 11, CH 8028 Zurich, Switzerland (Tel.: +4144 634 32 84; fax: +4144 634 43 08; e-mail: frank.paque@zzmk.unizh.ch).

enhance the sealing ability of root fillings has been to apply adhesive concepts to endodontics (Leonard *et al.* 1996, Mannocci & Ferrari 1998).

In 2004, a new core material, Resilon (Resilon Research LLC, Madison, CT, USA), in conjunction with an adhesive system (Epiphany, Pentron Clinical Technologies, Wallingford, CT, USA) was introduced to the market. This new thermoplastic-filled polymer core (polycaprolactone-based) has the potential to challenge gutta-percha, the 'gold standard', as a root filling core material (Shipper *et al.* 2004). Dentine adhesives can be applied as a sealer either with gutta-percha (Mannocci & Ferrari 1998) or bonded simultaneously to intraradicular dentine and to Resilon (Shipper *et al.* 2004).

Ideally, the root canal sealer should be capable of bonding simultaneously to the root canal dentine and Resilon. However, this new filling material must bond to root dentine that is less than ideal in terms of its cleanliness and surface characteristics. Beside irregular structures such as accessory root canals, resorption and repaired resorption areas, there are a lower number of dentinal tubules, irregular secondary dentine and cementum-like tissue in the apical portion of the root canal wall (Mjör *et al.* 2001). Physiological phenomena such as tubular sclerosis and dentinal fluid transudation must also be considered in this technique-sensitive treatment approach (Chersoni *et al.* 2005, Paqué *et al.* 2006).

Several leakage studies have been published comparing this newly developed filling material with gutta-percha and conventional sealers. Using a fluid transport model, some authors reported that Resilon and Epiphany were better at preventing fluid movement when compared with gutta-percha and AH Plus or AH26 (Stratton *et al.* 2006, Tunga & Bodrumlu 2006). Some reports concluded that there were no differences between the above mentioned root filling materials when using the fluid filtration model (Biggs *et al.* 2006, Onay *et al.* 2006, Shemesh *et al.* 2006). However, all these results were obtained either immediately after root filling or up to 3 months afterward. It is known from coronal application of dentine bonding systems that de-bonding can occur over time (De Munck *et al.* 2005). Furthermore, Resilon is biodegradable via enzymatic and alkaline hydrolysis (Tay *et al.* 2005a,b). Despite the suspicion that the Resilon/Epiphany root filling system may lose its sealing ability over time, no information about the experimental long-term sealing properties of this system is available.

The purpose of this *ex vivo* study was to measure and compare the long-term sealing ability of gutta-percha/AH Plus and Resilon/Epiphany along the apical 4 mm of the root canal with two different filling techniques. Fluid filtration, a sensitive, reproducible and nondestructive method, which allows repeated observation of the same specimen over time (Wu *et al.* 1993), was used to assess and compare fluid movement at two observation periods. The null hypothesis tested was that there is no difference in fluid movement between the two types of root filling materials, both immediately after placement and after 16 months.

Materials and methods

Experimental teeth and instrumentation procedures

One hundred single-rooted mandibular premolars of similar size and root shape, which had been stored in a 0.1% thymol solution at 5 °C, were selected from the department's collection of extracted teeth. Radiographs of both the bucco-oral and mesio-distal aspects were taken from the experimental teeth to verify that they contained only one canal. Teeth were cleaned from periodontal tissues with scalers, and then immersed in a 1% sodium hypochlorite (NaOCl) solution for 15 min in an ultrasonic bath. After gaining access to the root canal system with a diamond-coated bur, a step-down preparation was performed using Gates-Glidden-drills No. 4, 3 and 2 (Dentsply Maillefer, Ballaigues, Switzerland). Subsequently, a size 10 K-File was inserted into the root canal until the tip was just visible beyond the apex. Working length was determined by subtracting 1 mm from this length, and the root canals were instrumented starting with ProFile instruments (Dentsply Maillefer) size 45 .04 taper in a crown-down manner until working length was reached. Mechanical root canal preparation was finished up to ProFile size 40 .04 taper to full working length. After each instrument, apical patency was maintained with a size 10 K-file and root canals were irrigated with 1 mL of a 1% NaOCl solution using a 30-gauge irrigating needle 1 mm short of working length (Hawe Neos, Bioggio, Switzerland). After instrumentation, all root canals were rinsed with 5 mL of 1% NaOCl solution followed by 5 mL of 17% (wt/vol.) ethylenediamine tetraacetic acid (EDTA) in order to remove the smear layer. To wash out the NaOCl and EDTA solution remnants, a final flush was performed with 5 mL of 2% chlorhexidine-digluconate (CHX). This was in accordance with the manufacturer's guidelines for the Resilon/Epiphany system.

Obturation procedures

The teeth were randomly (www.random.org) divided into 4 groups of 20 teeth each. Additionally, 10 instrumented teeth and 10 unprepared teeth with intact crowns served as controls.

All filling procedures were performed using a dental microscope (ProMagis, Zeiss, Oberkochen, Germany). After the rinsing protocol was fulfilled, the root canals were dried with paper points and were filled as follows.

Group I (lateral compaction with gutta-percha)
A size 40 .04 taper gutta-percha cone (Dentsply Maillefer) was trimmed to give tugback at working length. It was lightly coated with AH Plus sealer (Dentsply Maillefer) and placed into the root canal. Lateral compaction was achieved with a finger spreader size A (Dentsply Maillefer) and accessory gutta-percha points size A (Dentsply Maillefer), that where placed initially not more than 1 mm short of working length.

Group II (vertical compaction with heated gutta-percha)
The root canals were filled using System B (SybronEndo Corporation, Orange, CA, USA) and Obtura II devices (Obtura/Spartan, Fenton, MO, USA) by fitting a size 40 .04 taper gutta-percha cone (Dentsply Maillefer) to the working length. The System B with a Buchanan fine plugger (Analytic Endodontics, Redmond, WA, USA) was set at 200 °C in the touch mode and set to full power at 10. The master cone was lightly coated with AH Plus sealer and placed into the root canal that reached working length. At the level of the cemento–enamel junction, the gutta-percha cone was seared off with the tip of the activated fine plugger. After deactivating the plugger, the cooling instrument was removed from the root canal, bringing out an increment of gutta-percha. Vertical force was then applied with a pre-fitted hand plugger (Dentsply Maillefer) to compact the gutta-percha in the coronal part of the root canal. This procedure was then repeated twice. First to a level 3–5 mm deeper to compact the gutta-percha in the middle portion of the root canal. Secondly to a level 4 mm short of the working length to compact the gutta-percha in the apical part of the root canal. The Obtura II was preset to 180 °C and used with a 23-gauge needle to back-fill the root canal with gutta-percha to 1 mm below the cemento–enamel junction, each time injecting a 3–4 mm segment and compacting the gutta-percha with pre-fitted hand pluggers.

Group III (lateral compaction with Resilon)
A size 40 .04 taper Resilon cone (Resilon Research LLC) was trimmed to give tugback at working length. A self-etching primer (Epiphany Primer, Pentron Clinical Technologies, Wallingford, CT, USA) was placed in the root canal using a microbrush (Microbrush International, Grafton, WI, USA) and paper points (Roeko, Langenau, Germany) soaked with the primer. After 30 s, excess primer was removed with paper points. The Resilon master cone was lightly coated with Epiphany sealer (Pentron) and placed into the root canal. Lateral compaction was achieved with a finger spreader size A and fine-medium nonstandardized accessory Resilon points (Resilon Research LLC) that was placed initially not more than 1 mm short of working length.

Group IV (vertical compaction with heated Resilon)
The root canals were pre-treated with self-etching primer (Epiphany Primer) in the same manner as in group III, and filled using the System B and Obtura II (Obtura/Spartan) by fitting a size 40 .04 taper Resilon cone to the working length. The System B with a Buchanan fine plugger was set at 160 °C in the touch mode and a full-set power at 10. The master cone was lightly coated with Epiphany sealer and placed into the root canal to working length. At the level of the cemento–enamel junction, the Resilon cone was seared off with the tip of the activated fine plugger. After deactivating the plugger, the cooling instrument was removed from the root canal, bringing out an increment of Resilon. Vertical force was then applied with a pre-fitted hand plugger to compact the Resilon in the coronal part of the root canal. This procedure was then repeated twice. First to a level 3–5 mm deeper to compact the Resilon in the middle portion of the root canal. Secondly to a level 4 mm short of the working length to compact the Resilon in the apical part of the root canal. The Obtura II was preset to 160 °C and used with a 23-gauge needle to back-fill the root canal with Resilon to 1 mm below the cemento–enamel junction, each time injecting a 3–4 mm segment and compacting the Resilon with pre-fitted hand pluggers.

After filling the root canals, the access cavities were sealed with glass–ionomer cement (Ketac, 3 M ESPE, Seefeld, Germany) and stored at 37 °C and 100% humidity for 7 days to allow the sealers to set. Following the 7 days, the Ketac fillings were completely removed using diamond burs (Komet, Lemgo, Germany). The coronal and middle parts of the root canal fillings were removed using Gates-Glidden-drills, leaving the apical 4 mm of root canal filling intact for the leakage test. The correct length of the remaining apical root canal filling was measured and confirmed by taking digital radiographs with a calibrated digital imaging device (Digora, Soredent, Helsinki, Finland).

Controls

A total of 20 teeth served as negative and positive controls. The negative control group consisted of 10 mandibular premolars with caries-free, intact crowns. For positive control, the root canals of 10 mandibular single-rooted premolars were prepared as mentioned above and filled with a pre-fitted gutta-percha master cone using lateral compaction without sealer.

Leakage testing

The root portion of each tooth was embedded in an acrylic resin cylinder. Using a stereo dissecting microscope (Leitz, Oberkochen, Germany), it was verified that no resin remnants were covering the root tip, i.e. the apical foramen. The embedded roots were attached to a fluid transport device, as described by Wu *et al.* (1993). Leakage along the apically remaining root canal filling was measured under a headspace pressure of 120 kPa (1.2 atm) during an 8-h period. The amount of fluid movement was recorded as microlitres over time. After the first measurement, five teeth from every experimental group were randomly chosen and immediately tested again to ensure that the applied pressure causes no damage. After that, access cavities from all teeth were sealed with glass–ionomer cement and stored for 16 months in sterile NaCl solution at 37 °C. The NaCl solution was changed every month. After 16 months, the access cavity fillings were removed, and the teeth were remounted and tested for fluid transport in the same manner as mentioned above.

Data presentation and analysis

Leakage was inhomogeneous within and between groups, i.e. data were skewed. In addition, some specimens leaked to an extent that could not be measured using the current setup, as the bubble exceeded pipette length. The measurement range was between 0.5 (detection limit) and 100 μL per 8 h of fluid movement. Numerical data are presented as medians and inter-quartile ranges. Fluid movement values obtained at each of the two time-points were compared between groups using Kruskal–Wallis ANOVA followed by Mann–Whitney *U*-test. Comparison within the same specimen between the two time-points was performed using Wilcoxon signed rank test.

Multiple comparisons were adjusted for applying Bonferroni's method. The level of significance was set at $P < 0.05$.

Results

The intact premolars used as negative controls did not allow fluid movement, whereas positive controls allowed fluid movement exceeding 100 μL per 8 h at both observation time-points.

The fluid movements measured in the experimental groups at both observation time-points are shown in Table 1. There was no difference in fluid movement between the experimental groups at immediate measurement (Kruskal–Wallis, $P > 0.05$). Moderate leakage in the range of 1.5–12.5 μL per 8 h was observed in eight, five, two and two of the 20 specimens in group I, II, III and IV, respectively.

After 16 months, 32 specimens had bubble movement that exceeded the pipette length (>100 μL per 8 h) as far like the positive controls. Three of these specimens exhibiting gross leakage were in the gutta-percha groups (I and II), 29 in the Resilon groups (III and IV). At this time, there was a significant difference at the 0.05 level between fluid movement allowed by the Resilon/Epiphany groups and the gutta-percha/AH Plus groups (Table 1). Furthermore, the roots filled with Resilon/Epiphany allowed significantly more fluid

Table 1 Leakage in μL per 8 h between different treatment groups. Medians and inter-quartile ranges (in parentheses)

Treatment	Immediate	16 months
Gutta-percha/AH Plus lateral compaction	0.0 (5.5)^{Aa}	0.0 (0.5)^{Aa}
Gutta-percha/AH Plus vertical compaction	0.0 (2.0)^{Aa}	0.5 (0.5)^{Aa}
Resilon/Epiphany lateral compaction	0.0 (0.0)^{Aa}	>100 (>100)^{Bb}
Resilon/Epiphany vertical compaction	0.0 (0.0)^{Aa}	>100 (>100)^{Bb}

Identical superscript letters indicate that there was no significant difference at the 5% level between datasets. Capital letters, comparison between treatments at respective time-points, Kruskal–Wallis followed by Mann–Whitney *U*-test. Lower script letters, comparison within treatment between two time points, Wilcoxon signed rank test.

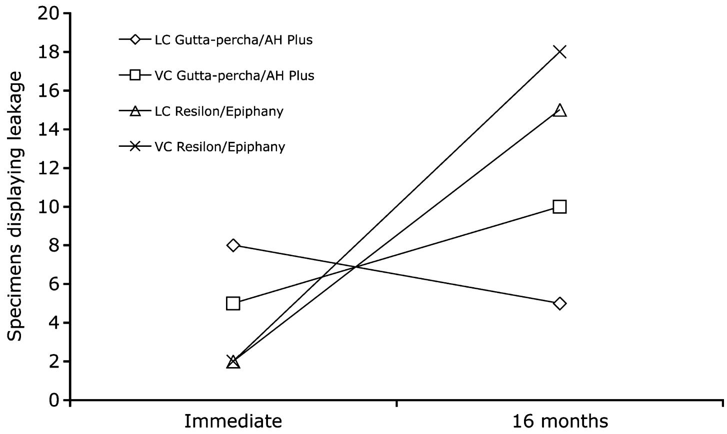

Figure 1 Change in specimens within the experimental groups displaying detectable leakage immediately after root filling placement and after 16 months of water storage at 37 °C. LC, lateral compaction; VC, vertical compaction.

movement after 16 months compared with the immediate measurement ($P < 0.001$), whilst the roots filled with gutta-percha/AH Plus maintained their seal. The number, the increase and decrease of samples allowing fluid movement within the experimental groups at both observation times are shown in Fig. 1. Some of the specimens filled with gutta-percha and AH Plus, which initially displayed leakage, had no leakage after 16 months.

The 20 randomly chosen specimens displayed the same results when testing them immediately again after the first measurement. This indicated no damage to the root fillings when applying a headspace pressure of 120 kPa (1.2 atm).

Discussion

The null hypothesis of the current study was confirmed for the short-term microleakage findings and rejected regarding the long-term microleakage results. It was concluded that a new synthetic root canal filling material (Resilon), when used with a composite sealer (Epiphany), seals the apical root canal, as well as gutta-percha and AH Plus in the short-term observation period. After 16 months, however, the Resilon/Epiphany groups leaked significantly more than the gutta-percha/AH Plus groups.

In the current study, the established fluid transport model, as proposed and described by Wu *et al.* (1993), was used. This method has been shown to be more sensitive than dye penetration for the detection of through-and-through voids along root canals and to be highly reproducible (Wu *et al.* 1993, 1994). Furthermore, the fluid filtration method is a nondestructive technique that allows repeated measurements of the same specimens over time. Recently, the glucose penetration model, as a new possibility to evaluate the sealing ability of root canal fillings, has been introduced (Xu *et al.* 2005). Shemesh *et al.* (2006) described this model as a further development of the fluid transportation concept that might be more sensitive than the measurement with an air bubble. However, re-evaluation of leakage after long-term storage of the specimens would be a problem. An increase or decrease of leakage along root canal fillings over time may reveal changes in sealing ability (Wu *et al.* 1995, 2002).

The current results for immediate measurement are in agreement with the findings of studies using similar laboratory systems (Biggs *et al.* 2006, Onay *et al.* 2006, Shemesh *et al.* 2006). In these studies, the lateral compaction technique was used for filling the root canals. However, two of the reports concluded that Resilon/Epiphany was superior to gutta-percha/AH Plus using the transport fluid method. They used a single-cone (Sagsen *et al.* 2006) or a warm vertical compaction technique (Stratton *et al.* 2006) to fill the root canals under investigation. The longest observation period, and therefore, storage of filled root specimens prior to the current communication was 3 months (Biggs *et al.* 2006). The authors found no differences looking at leakage immediate and 3 months after filling with Resilon/Epiphany or gutta-percha/AH Plus using the cold lateral compaction technique.

The current study showed a somewhat unsuspected dramatic increase in fluid movement with specimens filled with Resilon/Epiphany over time. However, the present results corroborated findings obtained with a glucose penetration model, which is described as a more sensitive method than fluid filtration (Shemesh *et al.* 2006). The reasons for the loss of seal with these materials over time cannot be found based on the current results. It may be speculated, however, that these reasons are to be found in phenomena, which are extensively documented in adhesive dentistry. As laboratory studies often lack the synergy of the more complex *in vivo* studies, the correlation between *ex vivo* data and clinical performance is not always clear (Øilo 1992). As well, it is known that clinical outcome of treatment cannot be predicted from leakage studies (Oliver & Abbott 2001). However, it is well known that polymers degrade over time through physical and chemical processes (Santerre *et al.* 2001). To simulate *in vivo* ageing, the most commonly used artificial ageing technique, namely, long-term water storage was chosen in this study (Gwinnett & Yu 1995, Fukushima *et al.* 2001). According to De Munck *et al.* (2005), after 3 months, all dentine adhesives under investigation exhibited mechanical and morphological evidence of degradation. As the bond degrades, interfacial microleakage increases which resembles the *in vivo* ageing effect. Therefore, in order to be clinically relevant, microleakage studies in conjunction with resin adhesives should report results with no less than 3 month of ageing (De Munck *et al.* 2005). In the present study, the ageing effect through storage of the specimens over 16 month possibly evokes the current limitations of dentine bonding in the root canal system. Beside the polymerization shrinkage of the Epiphany sealer and the highly unfavourable configuration factor in the root canal space (Tay *et al.* 2005c), it seems that water sorption and solubility play an important role concerning the increased microleakage in the long-term. It appears that teeth with vital pulps and root-filled counterparts do not differ significantly in their moisture content (Papa *et al.* 1994). Additionally, during root canal treatment, especially after rinsing the root canal system, it is obvious that fluid droplets are retained in the dentinal tubules and may not be completely removed through the use of paper points. Because the sealer may be exposed to tissue fluid and exudate, water sorption and solubility behaviour of the root canal sealers in the humid root canal system is of considerable importance. The currently marketed dentine adhesives, including the hydrophilic resin-based root canal sealer Epiphany, contain hydrophilic and ionic monomers, making them highly susceptible to water sorption and hydrolysis (Tay & Pashley 2003, Yiu *et al.* 2006). This water sorption plasticizes polymers and lowers their physical/mechanical properties which decrease the life expectancy of the interfaces by hydrolysis and microcrack formation (Kalachandra & Turner 1987, Beatty *et al.* 1993, Sideridou *et al.* 2003). According to Donnelly *et al.* (in press), the Epiphany sealer compared with AH Plus exhibited significantly higher apparent water sorption, 8.02% and 1.07%, respectively. High solubility of root canal sealers is undesirable because dissolution may cause the release of materials that could irritate periapical tissues (McMichen *et al.* 2003). Dissolution of sealer may also permit gap formation between root canal dentine and root filling materials that result in increased bacterial leakage over time. Versiani *et al.* (2006) measured solubility values of 3.41% for Epiphany and 0.21% for AH Plus. Donnelly *et al* (in press) also demonstrated a significantly higher solubility with the Epiphany sealer (4.02%) compared with the AH Plus sealer (0.16%), respectively.

One of the most important factors in the strength and stability of the resin/dentine bond is the incomplete resin infiltration into the demineralized dentine (hybrid layer). As a result, fluid movement occurs. This nanoleakage, or ingress of oral fluid through nanometer sized channels along collagen fibrils within the hybrid layer, is considered to be detrimental to bond integrity (Sano *et al.* 1995). Transudation of dentine fluid through dentine adhesives has been shown to occur *in vivo* in bonded vital crown dentine (Chersoni *et al.* 2005), as these adhesives behave as permeable membranes after polymerization. This may result in the entrapment of water blisters between the adhesive surface and slow-setting resin composite/cements (Chersoni *et al.* 2004). Degradation could then be enhanced additionally by enzymes released by bacteria (Santerre *et al.* 2001) and from the dentine itself (Pashley *et al.* 2004). Collagen degradation is thought to occur via host-derived matrix metalloproteinases (MMPs) that are present in dentine and released slowly over time (Pashley *et al.* 2004). Bonding is further compromized in sclerotic dentine, which is found more often in the apical area of adult teeth (Paqué *et al.* 2006), because of inconsistent dentine hybridization and occluded dentinal tubules (Tay & Pashley 2004).

One other intriguing result of the current study was the finding that some of the specimens filled with gutta-percha and AH Plus, which showed immediate moderate leakage, did not leak after 16 months. This phenomenon was most pronounced in group I (lateral compaction with gutta-percha); where six originally leaking specimens became sealed after 16 months, compared with only one in the vertical compaction/

gutta-percha group and none in the Resilon/Epiphany groups. It may be speculated that this could be explained by the continuous expansion of AH Plus in a liquid environment over time (Dag Ørstavik, personal communication). With vertical compaction, thinner layers of AH Plus are to be expected. AH Plus *per se* has a sealing capacity superior to most other sealers (De-Deus *et al.* 2006). In addition, gutta-percha by itself has a tendency to improve the root canal seal because of expansion over time (Wu *et al.* 2000).

Conclusion

Under the conditions and within the limitations of the current study, it could be shown that Resilon/Epiphany root fillings allowed significantly more fluid movement in the long-term compared with gutta-percha/AH Plus counterparts.

Acknowledgement

We gratefully acknowledge the assistance of our friend, Dr Matthias Zehnder.

References

Beatty MW, Swartz ML, Moore BK, Phillips RW, Roberts TA (1993) Effect of crosslinking agent content, monomer functionality, and repeat unit chemistry on properties of unfilled resins. *Journal of Biomedical Materials Research* **27**, 403–13.

Biggs SG, Knowles KI, Ibarrola JL, Pashley DH (2006) An *in vitro* assessment of the sealing ability of resilon/epiphany using fluid filtration. *Journal of Endodontics* **32**, 759–61.

Buckley M, Spångberg LS (1995) The prevalence and technical quality of endodontic treatment in an American subpopulation. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **79**, 92–100.

Chersoni S, Suppa P, Breschi L, *et al.* (2004) Water movement in the hybrid layer after different dentin treatments. *Dental Materials* **20**, 796–803.

Chersoni S, Acquaviva GL, Prati C, *et al.* (2005) *In vivo* fluid movement through dentin adhesives in endodontically treated teeth. *Journal of Dental Research* **84**, 223–7.

De-Deus G, Coutinho-Filho T, Reis C, Murad C, Paciornik S (2006) Polymicrobial leakage of four root canal sealers at two different thicknesses. *Journal of Endodontics* **32**, 998–1001.

De Munck J, Van Landuyt K, Peumans M, *et al.* (2005) A critical review of the durability of adhesion to tooth tissue: methods and results. *Journal of Dental Research* **84**, 118–32.

Donnelly A, Sword J, Nishitani Y, *et al.* (in press) Water sorption and solubility of methacrylate resin-based root canal sealers. *Journal of Endodontics*.

Fukushima T, Inoue Y, Miyazaki K, Itoh T (2001) Effect of primers containing N-methylolacrylamide or N-methylolmethacrylamide on dentin bond durability of a resin composite after 5 years. *Journal of Dentistry* **29**, 227–34.

Gwinnett AJ, Yu S (1995) Effect of long-term water storage on dentin bonding. *American Journal of Dentistry* **8**, 109–11.

Kalachandra S, Turner DT (1987) Water sorption of polymethacrylate networks: bis-GMA/TEGDM copolymers. *Journal of Biomedical Materials Research* **21**, 329–38.

Katebzadeh N, Hupp J, Trope M (1999) Histological periapical repair after obturation of infected root canals in dogs. *Journal of Endodontics* **25**, 364–8.

Leonard JE, Gutmann JL, Guo IY (1996) Apical and coronal seal of roots obturated with a dentine bonding agent and resin. *International Endodontic Journal* **29**, 76–83.

Madison S, Wilcox LR (1988) An evaluation of coronal microleakage in endodontically treated teeth. Part III. *In vivo* study. *Journal of Endodontics* **14**, 455–8.

Mannocci F, Ferrari M (1998) Apical seal of roots obturated with laterally condensed gutta-percha, epoxy resin cement, and dentin bonding agent. *Journal of Endodontics* **24**, 41–4.

McMichen FR, Pearson G, Rahbaran S, Gulabivala K (2003) A comparative study of selected physical properties of five root-canal sealers. *International Endodontic Journal* **36**, 629–35.

Mjör IA, Smith MR, Ferrari M, Mannocci F (2001) The structure of dentine in the apical region of human teeth. *International Endodontic Journal* **34**, 346–53.

Øilo G (1992) Biodegradation of dental composites/glass-ionomer cements. *Advances in Dental Research* **6**, 50–4.

Oliver CM, Abbott PV (2001) Correlation between clinical success and apical dye penetration. *International Endodontic Journal* **34**, 637–44.

Onay EO, Ungor M, Orucoglu H (2006) An *in vitro* evaluation of the apical sealing ability of a new resin-based root canal obturation system. *Journal of Endodontics* **32**, 976–8.

Papa J, Cain C, Messer HH (1994) Moisture content of vital vs endodontically treated teeth. *Endodontics & Dental Traumatology* **10**, 91–3.

Paqué F, Luder HU, Sener B, Zehnder M (2006) Tubular sclerosis rather than the smear layer impedes dye penetration into the dentine of endodontically instrumented root canals. *International Endodontic Journal* **39**, 18–25.

Pashley DH, Tay FR, Yiu C, *et al.* (2004) Collagen degradation by host-derived enzymes during aging. *Journal of Dental Research* **83**, 216–21.

Sagsen B, Er O, Kahraman Y, Orucoglu H (2006) Evaluation of microleakage of roots filled with different techniques with a computerized fluid filtration technique. *Journal of Endodontics* **32**, 1168–70.

Sano H, Takatsu T, Ciucchi B, Horner JA, Matthews WG, Pashley DH (1995) Nanoleakage: leakage within the hybrid layer. *Operative Dentistry* **20**, 18–25.

Santerre JP, Shajii L, Leung BW (2001) Relation of dental composite formulations to their degradation and the release of hydrolyzed polymeric-resin-derived products. *Critical Reviews in Oral Biology & Medicine* **12**, 136–51.

Shemesh H, Wu MK, Wesselink PR (2006) Leakage along apical root fillings with and without smear layer using two different leakage models: a two-month longitudinal ex vivo study. *International Endodontic Journal* **39**, 968–76.

Shipper G, Ørstavik D, Teixeira FB, Trope M (2004) An evaluation of microbial leakage in roots filled with a thermoplastic synthetic polymer-based root canal filling material (Resilon). *Journal of Endodontics* **30**, 342–7.

Sideridou I, Tserki V, Papanastasiou G (2003) Study of water sorption, solubility and modulus of elasticity of light-cured dimethacrylate-based dental resins. *Biomaterials* **24**, 655–65.

Sjögren U, Hägglund B, Sundqvist G, Wing K (1990) Factors affecting the long-term results of endodontic treatment. *Journal of Endodontics* **16**, 498–504.

Sjögren U, Figdor D, Persson S, Sundqvist G (1997) Influence of infection at the time of root filling on the outcome of endodontic treatment of teeth with apical periodontitis. *International Endodontic Journal* **30**, 297–306.

Stratton RK, Apicella MJ, Mines P (2006) A fluid filtration comparison of gutta-percha versus Resilon, a new soft resin endodontic obturation system. *Journal of Endodontics* **32**, 642–5.

Sundqvist G, Figdor D, Persson S, Sjögren U (1998) Microbiologic analysis of teeth with failed endodontic treatment and the outcome of conservative re-treatment. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiololgy, and Endodontics* **85**, 86–93.

Swanson K, Madison S (1987) An evaluation of coronal microleakage in endodontically treated teeth. Part I. Time periods. *Journal of Endodontics* **13**, 56–9.

Tay FR, Pashley DH (2003) Have dentin adhesives become too hydrophilic? *Journal of the Canadian Dental Association* **69**, 726–31.

Tay FR, Pashley DH (2004) Resin bonding to cervical sclerotic dentin: a review. *Journal of Dentistry* **32**, 173–96.

Tay FR, Pashley DH, Williams MC, *et al.* (2005a) Susceptibility of a polycaprolactone-based root canal filling material to degradation. I. Alkaline hydrolysis. *Journal of Endodontics* **31**, 593–8.

Tay FR, Pashley DH, Yiu CK, *et al.* (2005b) Susceptibility of a polycaprolactone-based root canal filling material to degradation. II. Gravimetric evaluation of enzymatic hydrolysis. *Journal of Endodontics* **31**, 737–41.

Tay FR, Loushine RJ, Lambrechts P, Weller RN, Pashley DH (2005c) Geometric factors affecting dentin bonding in root canals: a theoretical modeling approach. *Journal of Endodontics* **31**, 584–9.

Tunga U, Bodrumlu E (2006) Assessment of the sealing ability of a new root canal obturation material. *Journal of Endodontics* **32**, 876–8.

Versiani MA, Carvalho-Junior JR, Padilha MI, Lacey S, Pascon EA, Sousa-Neto MD (2006) A comparative study of physicochemical properties of AH Plus and Epiphany root canal sealants. *International Endodontic Journal* **39**, 464–71.

Wu MK, De Gee AJ, Wesselink PR, Moorer WR (1993) Fluid transport and bacterial penetration along root canal fillings. *International Endodontic Journal* **26**, 203–8.

Wu MK, De Gee AJ, Wesselink PR (1994) Fluid transport and dye penetration along root canal fillings. *International Endodontic Journal* **27**, 233–8.

Wu MK, Wesselink PR, Boersma J (1995) A 1-year follow-up study on leakage of four root canal sealers at different thicknesses. *International Endodontic Journal* **28**, 185–9.

Wu MK, Fan B, Wesselink PR (2000) Diminished leakage along root canals filled with gutta-percha without sealer over time: a laboratory study. *International Endodontic Journal* **33**, 121–5.

Wu MK, Tigos E, Wesselink PR (2002) An 18-month longitudinal study on a new silicon-based sealer, RSA RoekoSeal: a leakage study *in vitro*. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiololgy, and Endodontics* **94**, 499–502.

Xu Q, Fan MW, Fan B, Cheung GS, Hu HL (2005) A new quantitative method using glucose for analysis of endodontic leakage. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiololgy, and Endodontics* **99**, 107–11.

Yiu CK, King NM, Carrilho MR, *et al.* (2006) Effect of resin hydrophilicity and temperature on water sorption of dental adhesive resins. *Biomaterials* **27**, 1695–703.