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Evaluation of canal filling after using two warm vertical gutta-percha compaction techniques *in vivo*: a preliminary study

M. Venturi

Department of Dental Sciences, Alma Mater Studiorum, University of Bologna, Bologna, Italy

Abstract

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Aim To evaluate the quality of root canal filling when comparing two warm gutta-percha filling techniques *in vivo*.

Methodology Human teeth were randomly divided into two equal groups, with 30 canals each. The root canals were shaped by hand and ProFile 0.04 rotary instruments to size 20–40 at the end-point and then filled with gutta-percha cones and AH-Plus. In group A, a traditional warm vertical compaction technique was performed using the Touch'n Heat, and back-filling with the Obtura II. In group B, a modified warm vertical compaction technique was used: small amounts of gutta-percha were removed, and the remaining most apical 3 mm were compacted with a 1 mm movement; then thermomechanical back-filling was performed. The teeth were extracted, stored in dye, cleared, and the distance between the apex and apical limit of the filling, linear dye penetration, and voids were measured from the buccal, lingual, mesial and distal perspective.The homogeneity of variance and means was verified using Levene's test and *t*-test. ANOVA and Dunnett *post hoc* test were used to establish the significance and to analyse the effects through multiple comparisons.

Results Compared with the specimens of group A, the specimens of group B exhibited less mean linear dye penetration ($P < 0.05$), smaller void length ($P \leq 0.05$) and maximal width ($P \leq 0.05$) when examined in all four views, and a more precise filling when viewed from the buccal aspect ($P < 0.05$).

Conclusions The modified warm vertical compaction technique with apical back-filling produced a more effective and precise three-dimensional filling.

Keywords: clearing, endodontic treatment, filling technique, gutta-percha.

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Introduction

After proper cleansing and shaping of the root canal system, a filling is required to prevent re-infection (Seltzer *et al.* 1967, Nguyen 1987, Ingle & Bakland 1994). Gutta-percha and endodontic sealers are currently the most common materials used to fill root canals (Nguyen 1987, Canalda-Sahli *et al.* 1992).

Vertical condensation of warm gutta-percha as described by Schilder (1967) has been demonstrated to provide effective canal filling (Schilder 1967, Dulac *et al.* 1999). It has been stated that the ideal application of this technique is obtained after softening the apical gutta-percha at 2–4 °C above body temperature (Goodman *et al.* 1981), and by compacting to a minimum distance of 7 mm from the apex (Marlin & Schilder 1973). However, it has also been demonstrated that an inconsistent temperature rise occurs in the apical gutta-percha when using flame heated carriers in a wide canal (Marlin & Schilder 1973).

Electric heaters, such as the Touch'n Heat (Analytic Technology, Redmond, WA, USA) and the System B Heat Source (Analytic Technology) have been developed to allow an easier approach to vertical condensation. However, it has been demonstrated that there is almost no temperature rise within the apical

Correspondence: Dr Mauro Venturi, Viale Oriani, 52, 40137 Bologna, Italy (Tel./fax: +39 051 19984083; e-mail: info@endodonziamauroventuri.it).

gutta-percha when using these devices in narrow canals (Venturi *et al.* 2002). These data seem to suggest that apical gutta-percha is often compacted at body temperature (Venturi *et al.* 2002, Jung *et al.* 2003).

With the Schilder technique, back-filling was effected with pieces of warmed gutta-percha (Schilder 1967), but it has been observed that the Obtura II (Obtura Corp., Fenton, MO, USA) can provide a more rapid and effective solution (Bowman & Baumgartner 2002, Jacobson *et al.* 2002, Jarrett *et al.* 2004).

The aim of this study was to compare *in vivo* the quality of canal filling using two different filling techniques:

1. A traditional warm vertical compaction technique (Schilder 1967), with sequential removal of thermoplasticized gutta-percha and vertical condensation of the remaining gutta-percha, followed by back-filling using Obtura II (Obtura Corp.).

2. A modified vertical compaction technique (Venturi & Breschi 2004), with gutta-percha removal with a Gates-Glidden bur (Dentsply Maillefer) and a single compaction movement to adapt the apical 3 mm of gutta-percha at body temperature to the canal walls, followed by a thermomechanical back-filling.

Materials and methods

The present study was conducted with the understanding and written consent of each subject, in full accordance with current ethical principles, and in accordance with local laws and regulations. The informed consent of all human subjects who participated in the experimental investigation was obtained after the nature of the procedure and possible discomforts and risks had been fully explained. Adequate measures were taken to minimize pain or discomfort.

Pairs of similar teeth, scheduled for extraction due to periodontal disease, caries or orthodontic reasons, were selected. A standardized periapical radiograph was taken for each tooth in buccolingual projection to allow proper selection. The teeth had no roots with resorption, fractures or open apices. They had canals that could be representative of clinical situations showing medium to high treatment difficulty. Each tooth of each pair was randomly assigned to one of two groups, A and B, taking care that the same numbers of the same types of teeth, with an equal number of canals similar in length, size, and curvature were included in each group. A total of 13 teeth were discarded after filling and extraction, because no matching pair could be found. The completed groups included 30 canals and 18 teeth (Table 1). The four canines were affected by severe periodontal disease and were extracted from elderly patients. All the roots revealed narrow canals without sharp curves.

Table 1 Teeth and root canals included in Group A and Group B

	Group A		Group B	
	Teeth (n)	Root canals (n)	Teeth (n)	Root canals (n)
Maxillary lateral incisors	2	2	2	2
Maxillary canines	2	2	2	2
Maxillary first premolars	4	8	4	8
Maxillary second premolars	2	2	2	2
Maxillary first molars	2	6	2	6
Maxillary second molars	1	3	1	3
Maxillary third molars	1	3	1	3
Mandibular lateral incisors	2	2	2	2
Mandibular canines	2	2	2	2
Total	18	30	18	30

All teeth were treated by the same operator under ×4.3 magnification (Zeiss telescopes; Carl Zeiss GmbH, Zeiss Group, Jena, Germany). After administration of local anaesthesia and isolation under rubber dam, conventional endodontic access was achieved using a tapered diamond bur (Number 845.314.012; Komet Brasseler, Lemgo, Germany) mounted on a contra-angle hand piece (Kavo Intramatic 25C; Kavo GmbH & Co., Biberach, Germany).

Working length was established with the Apex Finder (Endo Analyzer 8001; Analytic Technology, Redmond, WA, USA). The canals were first instrumented to working length with sizes 08–15 Hedström files (Micro-Mega, Besançon, France). Then a modified double flared technique (Saunders & Saunders 1992) was performed using K-files (Dentsply Maillefer, Ballaigues, Switzerland) sizes 15–40. Finally, ProFile 0.04 taper rotary NiTi instruments, size 15–40 (Dentsply Maillefer) were used at 300 rpm with an Endo Micro-NITI contrangle handpiece (Anthogyr, Sallanches, France) to obtain the final shaping of the apical third of the root canals. A size 20–40 K-file was used to refine the preparation at working length. All root canals were shaped to obtain a continuous, tapered funnel, without an apical stop. Apical patency was maintained with a size 10 K-file. Size 1–3 Gates-Glidden burs (Dentsply Maillefer) were also used in middle and coronal thirds of the root canals. The canals were irrigated with 5% sodium hypochlorite between changes of instruments; instruments were lubricated with RC-Prep (Hawe Neos Dental, Bioggio, Switzerland).

The apices of the prepared canals had diameters of 0.20–0.40 mm. Following preparation, the specimens were rinsed with water, dried with absorbent paper points and measured again with the Apex Finder (Endo Analyzer 8001; Analytic Technology).

Tapered 0.04 GT gutta-percha cones (Dentsply Tulsa Dental, Johnson City, TN, USA) were measured 1 mm shorter than the working length in anticipation of the apical movement of the gutta-percha during condensation. The gutta-percha cones were coated with AH-Plus cement (Dentsply DeTrey GmbH, Konstanz, Germany) and then placed into the root canals, prior to warm vertical compaction:

1. Group A: Root canals were obturated using a traditional warm vertical compaction technique (Schilder 1967). The heat source for this group was Touch'n Heat device (model 5004; Analytic Technology) at a power setting of 7. Sequential removal of thermoplasticized gutta-percha and vertical condensation of the remaining gutta-percha were completed when a number 9 (0.9 mm diameter tip) vertical plugger (Hu-Friedy Manufacturing Co., Chicago, IL, USA) was 5–7 mm from the working length. The canals were back-filled using the Obtura II unit (Obtura Corp.), with a 25 gauge needle (external diameter 0.5 mm) according to the manufacturer's instructions.

2. Group B: a modified warm vertical compaction technique with apical back-filling was used according to Venturi & Breschi (2004). After insertion of the gutta-percha cone, small amounts (1–2 mm) of heated gutta-percha were removed using Touch'n Heat, and the gutta-percha was adapted with standard pluggers, applying delicate pressure. To reduce the distance to the apex to 4 mm, gutta-percha was removed with a Gates-Glidden bur (Dentsply Maillefer), size 1, without water-spray on a contra-angle hand piece (Kavo Intramatic 25C, Kavo GmbH & Co., Biberach, Germany). Then a single compaction movement was performed at body temperature, pushing a size 30 finger plugger 1 mm apically to move the gutta-percha and adapt it to the canal walls. A size MF nonstandardized gutta-percha cone (Mynol; Block Drug Corporation, Jersey City, NJ, USA) was subsequently placed in the root canal and cut with the Touch'n Heat device at the orifice. Thermomechanical compaction at 8000–10 000 rpm for at least 5–10 s (McSpadden 1980) with size 25 stainless-steel Gutta-Condensors (Dentsply Maillefer) against the apical gutta-percha plug was performed: the Gutta-Condensors were pushed to within 5 mm of the apex to preserve the most apical 2 mm of the gutta-percha plug. Back-filling was achieved by thermomechanical and manual compaction until the canal was filled. The cavity access was sealed with Ketac Silver (3M ESPE Dental Products, St Paul, MN, USA).

After filling, each specimen was radiographed in mesiodistal and buccolingual projection. During the week following the treatment, each patient kept notes of the presence and degree of pain (mild, moderate, and severe) and of consumption of analgesics. After 1 week, the teeth were extracted and immersed in saline solution for 24 h, then dried, covered with two layers of nail varnish except for the apical 3 mm, and immersed in an aqueous solution of 2% Methylene Blue for 48 h (Barthel *et al.* 1999).

The nail varnish was removed with acetone, the specimens were rinsed under tap water, cleared (Venturi *et al.* 2003), and stored in methyl salicylate. A stereomicroscope (Zeiss Stemi 2000C; Carl Zeiss GmbH) equipped with a calibrated grid was used to evaluate each specimen with a micrometer, recording: apex diameter; distance between apex and apical limit of the filling from the buccal aspect; number of lateral canals in each third of the canal; linear dye penetration; and voids in the filling when viewed in a buccal, lingual, mesial, and distal view. The voids were measured on the surface of the filling, and between the contour of the filling and the contour of the canal wall, thus considering two of the three dimensions in each view: for example, in the distal view the empty spaces were measured on the distal surface, and along the buccal and lingual contours of the filling. The length of the voids corresponded to the sum: (a) of the spaces in which the filling had not adhered to the canal walls; (b) of the voids observed on the surface of the filling. The width of the voids corresponded to the width of the widest single empty space. Working length and apical diameter after instrumentation were also recorded. Compaction depth was reported as residual apical compacted gutta-percha.

Statistical analysis

Levene's test was used to verify whether the distributions had equal variances (homogeneity of variance). Some statistical tests, such as analysis of variance, assume the variances are equal across groups. The Levene test was used to verify this assumption. The *t*-test was used to estimate the homogeneity of the means.

The analysis of variance (ANOVA) was used to establish whether any of the factors had a significant effect. The Dunnett *post hoc* test was used to analyse the effects through multiple comparisons. *P*-value was set at 0.05.

Results

Following the completion of root canal treatment none of the patients required analgesics. Two patients complained of mild pain on biting that disappeared the day after; one maxillary premolar in group A, and one maxillary first molar in group B caused the pain.

Homogeneity of the groups was confirmed. Analysis of the data (Table 2) revealed no statistical difference between the groups for canal length and number of lateral canals. A statistical difference ($P \leq 0.05$) was found only for the mean diameter (but not variances) of the canal end-point.

Filling precision was evaluated by the distance between the apex and apical limit of the filling in the buccal view. Table 2 shows that filling in group B was more precise ($P \leq 0.05$). Compaction depth was calculated by analysing mean values of compacted apical gutta-percha. The recorded compaction depth was greater in group B ($P \leq 0.05$), as shown in Table 2.

As reported in Table 3:

- dye penetration was lower ($P \leq 0.05$) in group B than in group A in all views; on the mesial surface dye penetrated more deeply ($P \leq 0.05$) than on the lingual surface;
- group B demonstrated smaller voids ($P \leq 0.05$) in all four views;
- group B had voids with smaller maximal width ($P \leq 0.05$) in all four views.

The images obtained after tooth clearing (Figs 1 and 2) revealed the different morphological features representative for each group of specimens, and can be compared with the radiographs obtained before and after extraction of the teeth.

Discussion

Homogeneity between the groups was confirmed for canal length and number of lateral canals. The statistical difference found for the mean values of apical diameters was not likely to affect the results.

Due to the size of dye molecules (Kersten & Moorer 1989), dye penetration tests have been used to measure the quality of sealing, although it is questionable whether and how they really estimate the possible penetration of microorganisms or antigens (Barthel *et al.* 1999). Vacuum techniques or centrifugation (Oliver & Abbott 1991, Boussetta *et al.* 2003) have been considered as useful by some (Goldman *et al.* 1989, Spangberg *et al.* 1989), or not useful by others (Dickson & Peters 1993, Karagoz-Kucukay *et al.* 1993). Previous studies (Matloff *et al.* 1982, Kersten & Moorer 1989, Tamse *et al.* 1998) reported more penetration with Methylene Blue than with Black India Ink, but Methylene Blue may be decoloured by some dental filling materials (Wu *et al.* 1998) and may be dissolved during the clearing procedure (Ravanshad & Torabnejad 1992). In the present study, the major concern was to evaluate the presence of voids within the filling using

Table 2 Canal length, apical diameters, number of lateral canals, compaction depth and filling precision in Group A and Group B

	Group	Mean (mm)	SD (mm)	Canal third	Mean (n)	SD (n)
Canal length	A	20.06	1.97			
	B	20.22	1.95			
Apical diameters	A	0.29	0.07			
	B	0.25	0.06			
Number of lateral canals	A			Apical	1.30	1.66
				Middle	0.53	0.86
				Coronal	0.57	0.97
	B			Apical	1.43	1.33
				Middle	0.67	1.15
				Coronal	0.57	1.36
Compaction depth	A	5.02	0.73			
	B	2.96	0.11			
Filling precision[a]	A	−0.31[b]	0.53			
	B	0.09	0.33			

[a]Filling precision was evaluated by the distance between the apex and apical limit of the filling in buccal vision.
[b]Negative values correspond to filling shorter than working length.

Table 3 Dye penetration, voids length and voids maximal width in buccal, lingual, mesial, and distal view in Group A and Group B

Group	MES Mean (mm)	MES SD (mm)	BUC Mean (mm)	BUC SD (mm)	DIST Mean (mm)	DIST SD (mm)	LING Mean (mm)	LING SD (mm)
Dye penetration								
A	3.483	1.703	3.070	1.555	2.954	1.216	2.403	0.997
B	0.043	0.086	0.127	0.151	0.043	0.101	0.067	1.147
Total	1.763	2.107	1.598	1.845	1.498	1.699	1.235	1.374
Void length								
A	2.903	1.329	1.037	1.275	2.827	1.527	1.157	1.526
B	0.141	0.369	0.083	0.146	0.140	0.196	0.227	0.389
Total	1.522	1.696	0.560	1.020	1.483	1.732	0.692	1.200
Void maximal width								
A	0.2440	0.7151	0.0787	0.1528	0.3240	0.7374	0.0633	0.1755
B	0.0150	0.0351	0.0277	0.0623	0.0287	0.0578	0.0380	0.0675
Total	0.1295	0.5151	0.0532	0.1185	0.1763	0.5395	0.0507	0.1324

a stereomicroscopic observation of the cleared teeth; the dye penetration test, performed by immersion only, was used as subsidiary evaluation. A period of 48 h of dye exposure was chosen because that interval has often been used (Barthel *et al.* 1999); longer exposure may result in increased dye penetration (Zmener 1987, Kersten & Moorer 1989). The weak demineralizing solution employed (Venturi *et al.* 2003) was believed to minimize the risk of Methylene Blue dissolution. Greater apical dye penetration was observed in group A, but in many specimens it was difficult to detect clearly the limit of Methylene Blue penetration, as in previous results reported by Scott *et al.* (1992).

Visible voids within the fillings have been used as evidence of poor three-dimensional filling (Venturi & Breschi 2004). Obviously, there was no visible penetration of dye other than in the lack of a seal in the 3 apical mm, whilst the evaluation of voids pertained to the whole canal.

The Schilder technique produced greater voids (Fig. 2o–r) compared with the modified warm vertical compaction technique with apical back-filling. Some of the voids, found between the surface of the apical filling and the canal wall, might be due to less effective apical compaction of the gutta-percha cones. Other voids, observed within the mass of the filling, might be explained by inadequate back-filling.

It has been reported that, with the warm vertical condensation technique, gutta-percha has to be compacted to within 4–7 mm of the working length (Marlin & Schilder 1973, Schilder *et al.* 1974a,b, Goodman *et al.* 1981, Figdor *et al.* 1983, Weller & Koch 1995), and that apical gutta-percha has to be heated to a temperature of 40–42 °C (Goodman *et al.* 1981). Such a minimal temperature increase is impossible to achieve or control under clinical conditions. Moreover, Venturi *et al.* (2002) recorded negligible apical temperature increases, when a heated plugger was placed to within 2.86–3.26 mm of the apex, and Villegas *et al.* (2005) observed that a mean temperature rise of 4 °C at 2 mm from working length was insufficient to make the filling conform to the details of the canal wall.

When gutta-percha is compacted at around body temperature, to avoid poor quality filling placement of the plugger close to the canal end-point is more desirable (Allison *et al.* 1981, Bowman & Baumgartner 2002, Jung *et al.* 2003, Venturi & Breschi 2004), but it may leave empty apical spaces within the filling (Jurcak *et al.* 1992, Venturi & Breschi 2004) which are difficult to refill. Size 25 Gutta-Condensors (Dentsply Maillefer) may effectively soften apical gutta-percha in narrow spaces. On the contrary, the smallest size 25 gauge needle of the Obtura II (Obtura Corp.) cannot reach the apical third in narrow, 0.04 tapered root canals. This might explain why there were fewer voids detected in group B, although the mean compaction depth was greater than in group A.

Deitch *et al.* (2002) obtained a significant improvement of gutta-percha density using a two-phase ultrasonic compaction after a lateral condensation, thus suggesting a two step procedure, with cold apical compaction followed by a warm back-filling. In the present study, in group B the canals were filled by compacting the apical 3 mm of a gutta-percha cone at body temperature with a single 1 mm movement toward the apex. The apical plug may have prevented extrusion (Lugassy & Yee 1982), whilst permitting the moving Gutta-Condensors (Dentsply Maillefer) to soften

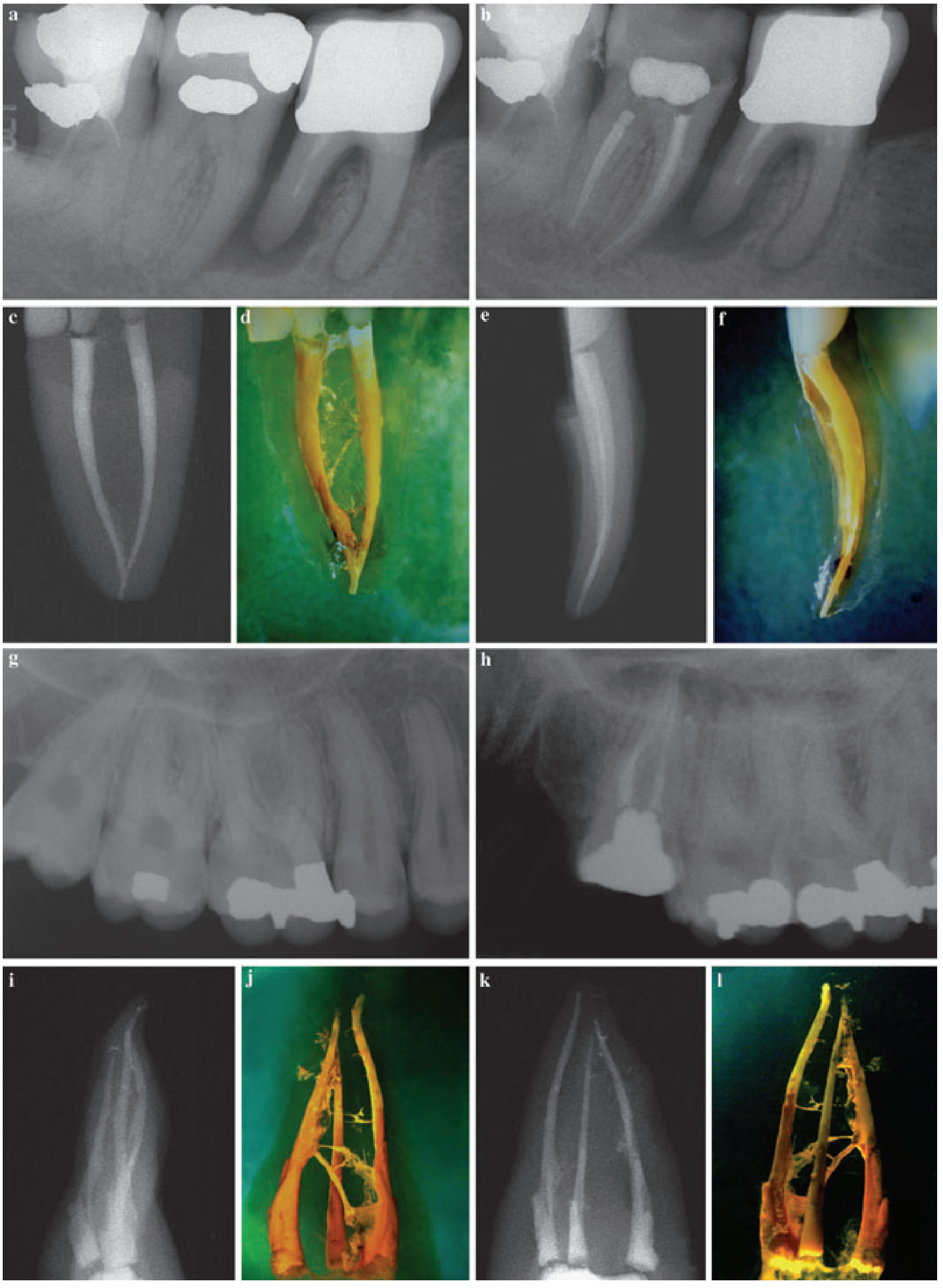

Figure 1 Image of the mesial root of a second mandibular molar (a-f) and a third maxillary molar (g-1) obturated using 'vertical compaction with apical back filling'. In both specimens the apical plug acted as a stop and allowed to perform thermomechanical compaction without risk of extrusion. Both the back-filled gutta percha and the coronal part of the apical gutta-percha were softened and fused together, minimizing the possibility of creating voids, and many accessory canals were filled (a-f). It can be observed that the radiographic images were quite unreliable in reflecting the morphological characteristics determined using the clearing technique.

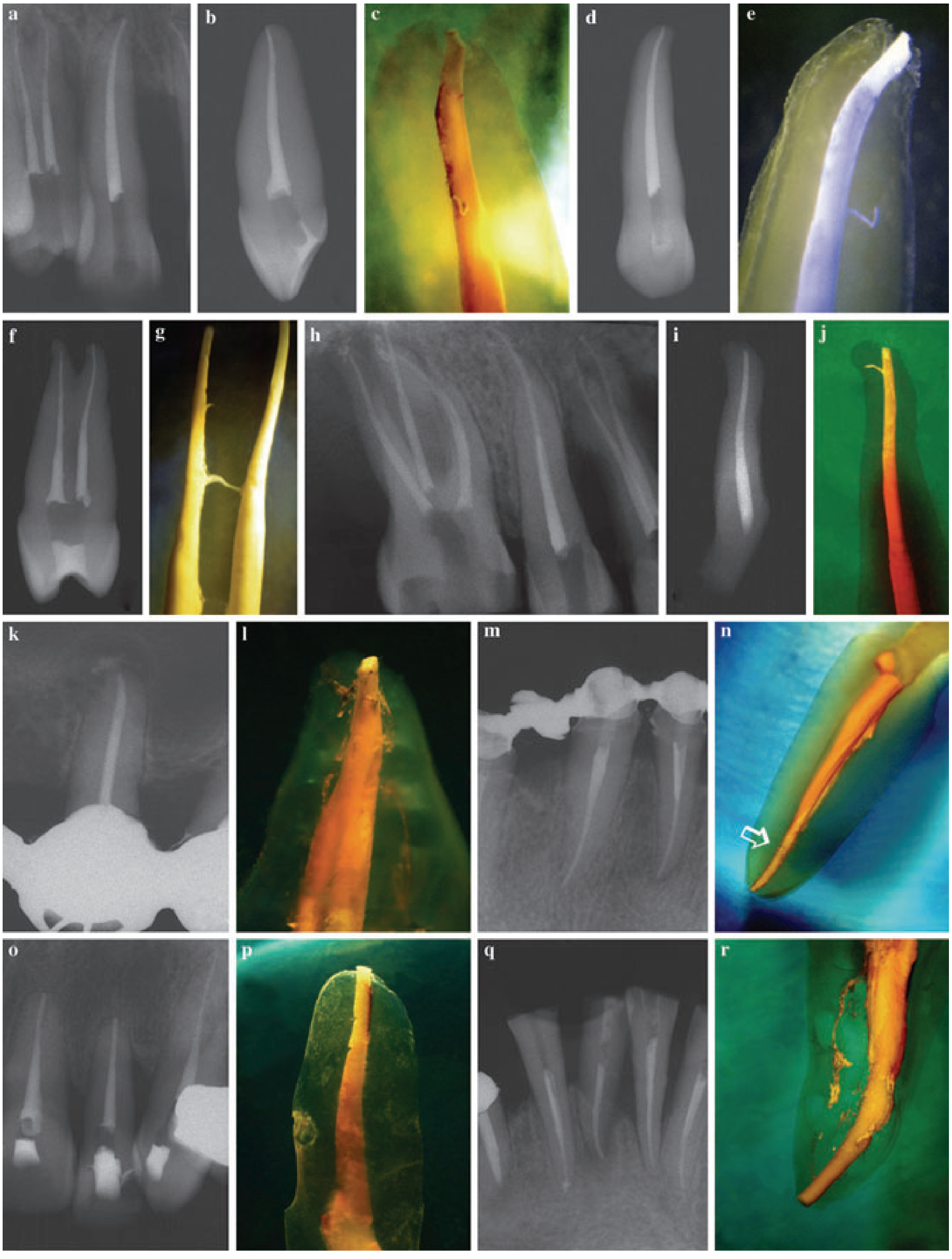

Figure 2 Images of a maxillary canine, of a first maxillary premolar (a-h) and the disto-buccal root of the adjacent first maxillary molar (i-j) obturated using 'vertical compaction with apical back-filling'; accessory canals filled with gutta percha and AH plus can be observed. A second maxillary premolar (k-l) showing partial filling of apical lateral canals with AH Plus. A mandibular lateral incisor (m-n) that was filled with the same technique and reveals a void between the apical plug and the backfilled gutta-percha (arrow). A maxillary lateral incisor (o-p) and a mandibular central incisor (q-r) that were obturated using the Schilder technique.

both the back-filled gutta-percha and the coronal part of the apical gutta-percha, blending them together (Figs 1a–f and 2a–n). The homogeneous appearance of the filling materials, observed in most specimens, might also have been produced by the solvent action of AH-Plus on gutta-percha (Tagger *et al.* 2003).

To estimate the capability of the two techniques for maintaining the working length, the distance between the apex and the apical limit of the filling was examined in a buccal view. A greater accuracy was found in group B. It may be hypothesized that the light pressure applied in down-packing the apical plug in group B left it relatively unaltered in shape and allowed better control of the final movement and setting of the gutta-percha (Figs 1a–f and 2a–n). In group A, the compaction performed at a greater distance from the apex, with several cycles of heating and compression, provided less predictable results.

Temperature increases of 10 °C above body temperature for >1 min may be sufficient to cause periradicular bone tissue injury (Eriksson & Albrektsson 1983). During thermomechanical compaction, temperature increases up to 35 °C have been recorded on the root surface by Fors *et al.* (1985), up to 97 °C by McCullagh *et al.* (1997), and up to 23.8 °C by Lipski (2005). Such temperature increases could be minimized *in vivo* by heat transfer to the periradicular circulating blood (Saunders 1990) and to the fluids within dentine tubules (Weller & Koch 1995), by the insulating properties of the endodontic cements (Barkhordar *et al.* 1990) and by dentine thickness (Fors *et al.* 1985).

Conclusions

The present study demonstrated *ex vivo* that less mean linear dye penetration, smaller length of voids and reduced width of voids, as well as a more precise filling in a buccal view, were achieved in 0.04 tapered root canals with apex diameters of 0.20–0.40 mm, using a modified warm vertical compaction technique with apical back-filling, compared with the traditional vertical condensation of warm gutta-percha technique followed by back-filling with the Obtura II (Obtura Corp.).

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References

Allison DA, Michelich RJ, Walton RE (1981) The influence of the master cone adaptation on the quality of the apical seal. *Journal of Endodontics* **7**, 61–5.

Barkhordar RA, Goodis HE, Watanabe L, Koumdijan J (1990) Evaluation of temperature rise on the outer surface of teeth during root canal obturation techniques. *Quintessence International* **21**, 585–8.

Barthel CR, Moshonov J, Shuping G, Òrstavik D (1999) Bacterial leakage versus dye leakage in obturated root canals. *International Endodontic Journal* **32**, 370–5.

Boussetta F, Bal S, Romeas A, Boivin G, Magloire H, Farge P (2003) In vitro evaluation of apical microleakage following canal filling with a coated carrier system compared with lateral and thermomechanical gutta-percha condensation techniques. *International Endodontic Journal* **36**, 367–71.

Bowman CJ, Baumgartner JC (2002) Gutta-percha obturation of lateral grooves and depressions. *Journal of Endodontics* **28**, 220–3.

Canalda-Sahli C, Brau-Aguade E, Sentis-Vilalta J, Aguade-Bruix S (1992) The apical seal of root canal sealing cements using a radionuclide detection technique. *International Endodontic Journal* **25**, 250–6.

Deitch AK, Liewehr FR, West LA, Patton WR (2002) A comparison of fill density obtained by supplementing cold lateral condensation with ultrasonic condensation. *Journal of Endodontics* **28**, 665–7.

Dickson SS, Peters DD (1993) Leakage evaluation with and without vacuum of two gutta-percha filling techniques. *Journal of Endodontics* **19**, 398–403.

Dulac KA, Nielsen CJ, Tomazic TJ, Ferrillo PJ, Hatton JF (1999) Comparison of the obturation of lateral canals by six techniques. *Journal of Endodontics* **25**, 376–80.

Eriksson AR, Albrektsson T (1983) Temperature threshold levels for heat induced bone tissue injury: a vital-microscopic study in the rabbit. *Journal of Prosthetic Dentistry* **50**, 101–7.

Figdor D, Beech DR, Waterson J (1983) Factors affecting heat generation in the McSpadden compaction technique [abstract 62]. *Journal of Dental Research* **132**, 664.

Fors U, Jonasson E, Berquist A, Berg JO (1985) Measurements of the root surface temperature during thermomechanical root canal filling in vitro. *International Endodontic Journal* **18**, 199–202.

Goldman M, Simmonds S, Rush R (1989) The usefulness of dye-penetration studies reexamined. *Oral Surgery Oral Medicine and Oral Pathology* **67**, 327–32.

Goodman A, Schilder H, Aldrich W (1981) The thermomechanical properties of gutta-percha, part IV: a thermal profile of the warm gutta-percha packing procedure. *Oral Surgery Oral Medicine and Oral Pathology* **51**, 544–51.

Ingle JI, Bakland LK (1994) *Endodontics*, 4th edn. Baltimore, USA: William & Wilkins, pp. 1–46.

Jacobson HLJ, Xia T, Baumgartner JC, Marshall JG, Beeler WJ (2002) Microbial leakage evaluation of the continuous wave of condensation. *Journal of Endodontics* **28**, 269–71.

Jarrett IS, Marx D, Covey D, Karmazin M, Lavin M, Gound T (2004) Percentage of canals filled in apical cross sections – an in vitro study of seven obturation techniques. *International Endodontic Journal* **37**, 392–8.

Jung IY, Lee SB, Kim ES, Lee CY, Lee SJ (2003) Effect of different temperatures and penetration depths of a System B plugger in the filling of artificially created oval canals. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontics* **96**, 453–7.

Jurcak JJ, Weller N, Kulid JC, Donley DL (1992) In vitro intracanal temperature produced during warm lateral condensation of gutta-percha. *Journal of Endodontics* **18**, 1–3.

Karagoz-Kucukay I, Kucukay S, Bayirli G (1993) Factors affecting apical leakage assessment. *Journal of Endodontics* **19**, 362–5.

Kersten HW, Moorer WR (1989) Particles and molecules in endodontic leakage. *International Endodontic Journal* **22**, 118–24.

Lipski M (2005) Root surface temperature rises in vitro during root canal obturation using hybrid and microseal techniques. *Journal of Endodontics* **31**, 297–300.

Lugassy AA, Yee F (1982) Root canal obturation with gutta-percha: a scanning electron microscope comparison of vertical compaction and automated thermatic condensation. *Journal of Endodontics* **8**, 120–5.

Marlin J, Schilder H (1973) Physical properties of gutta-percha when subjected to heat and vertical condensation. *Oral Surgery Oral Medicine and Oral Pathology* **36**, 872–9.

Matloff IR, Jensen JR, Singer L, Tabibi A (1982) A comparison of methods used in root canal sealability studies. *Oral Surgery, Oral Medicine, Oral Pathology* **53**, 203–8.

McCullagh JJ, Biagioni PA, Lamey PJ, Hussey DL (1997) Thermographic assessment of root canal obturation using thermomechanical compaction. *International Endodontic Journal* **30**, 191–5.

McSpadden J (1980) *Self-Study Course for the Thermatic Condensation of Gutta-Percha*. Toledo, OH, USA: Ransom and Randolph.

Nguyen NT (1987) Obturation of the root canal system. In: Cohen S, Burns RC, eds. *Pathways of the Pulp*, 4th edn. St Louis, MO, USA: Mosby, pp. 183–94.

Oliver CM, Abbott PV (1991) Entrapped air and its effects on dye penetration of voids. *Endodontic Dental Traumatology* **7**, 135–8.

Ravanshad S, Torabnejad M (1992) Coronal dye penetration of the apical filling materials after post space preparation. *Oral Surgery Oral Medicine and Oral Pathology* **74**, 644–7.

Saunders EM (1990) In vivo findings associated with heat generation during thermomechanical compaction of gutta-percha. 1 Temperature levels at the external surface of the root. *International Endodontic Journal* **23**, 263–7.

Saunders WP, Saunders EM (1992) Effect of noncutting tipped instruments on the quality of root canal preparation using a modified double-flared technique. *Journal of Endodontics* **1**, 32–6.

Schilder H (1967) Filling the root canal in three dimensions. *Dental Clinics of North America* **11**, 723–44.

Schilder H, Goodman A, Aldrich WA (1974a) The termo-mechanical properties of gutta-percha. Part I. The compressibility of gutta-percha. *Oral Surgery Oral Medicine and Oral Pathology* **37**, 946–53.

Schilder H, Goodman A, Aldrich WA (1974b) The termo-mechanical properties of gutta-percha. Part III. Determination of phase transitions temperature for gutta-percha. *Oral Surgery Oral Medicine and Oral Pathology* **38**, 109–14.

Scott AC, Vire DE, Swanson R (1992) An evaluation of the Thermafil endodontic obturation technique. *Journal of Endodontics* **18**, 340–3.

Seltzer S, Bender IB, Smith J, Freedman I, Nazimov H (1967) Endodontic failures-an analysis based on clinical, roentgenographic, and histologic findings. I. *Oral Surgery Oral Medicine and Oral Pathology* **23**, 500–16.

Spangberg LSW, Acierno TG, Cha BY (1989) Influence of entrapped air on the accuracy of leakage studies using dye penetration methods. *Journal of Endodontics* **15**, 548–51.

Tagger M, Greenberg B, Sela G (2003) Interaction between sealers and gutta-percha cones. *Journal of Endodontics* **29**, 835–7.

Tamse A, Katz A, Kablan F (1998) Comparison of apical leakage shown by four different dyes with two evaluating methods. *International Endodontic Journal* **31**, 333–7.

Venturi M, Breschi L (2004) Evaluation of apical filling after warm vertical gutta-percha compaction using different procedures. *Journal of Endodontics* **30**, 436–40.

Venturi M, Pasquantonio G, Falconi M, Breschi L (2002) Temperature change within gutta-percha induced by the System-B Heat Source. *International Endodontic Journal* **35**, 740–6.

Venturi M, Prati C, Capelli G, Falconi M, Breschi L (2003) A preliminary analysis of the morphology of lateral canals after root canal filling using a tooth-clearing technique. *International Endodontic Journal* **36**, 54–63.

Villegas JC, Yoshioka T, Kobayashi Ch, Suda H (2005) Intracanal temperature rise evaluation during the usage of the System B: replication of intracanal anatomy. *International Endodontic Journal* **38**, 218–22.

Weller RN, Koch KA (1995) In vitro radicular temperature produced by injectable-thermoplasticized gutta-percha. *International Endodontic Journal* **28**, 86–90.

Wu MK, Kontakiotis EG, Wesselink PR (1998) Decoloration of 1% methylene blue solution in contact with dental filling materials. *Journal of Dentistry* **26**, 585–9.

Zmener O (1987) Evaluation of the apical seal obtained with two calcium hydroxide based endodontic sealers. *International Endodontic Journal* **20**, 87–90.

