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Accuracy of two root canal length measurement devices integrated into rotary endodontic motors when removing gutta-percha from root-filled teeth

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Abstract

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Aim To evaluate *ex vivo* the accuracy of the integrated electronic root canal length measurement devices within TCM Endo V® and Tri Auto ZX® motors whilst removing gutta-percha and sealer from filled root canals.

Methodology Forty freshly extracted maxillary and mandibular incisor teeth with mature apices were selected. Following access cavity preparation, the length of the root canals were measured visually 0.5 mm short of the major foramen (TL). The canals were prepared using the HERO 642 system and then filled with gutta-percha and AH26 sealer using a lateral compaction technique. After 7 days the coronal temporary filling was removed and the roots mounted in an alginate experimental model. The roots were then randomly divided in two groups. The access cavities were filled with chloroform to soften the gutta-percha and allow its penetration using the Tri Auto ZX® and the TCM Endo V® devices in groups 1 and 2, respectively. The 'automatic apical reverse function' (ARL) of both devices was set to start at the 0.5 setting and the rotary instrument inserted inside the root canal until a beeping sound was heard and the rotation of the file stopped automatically. Once the auto reverse function had been initiated, the foot pedal of the motor was inactivated and the rubber stop placed against the reference point. The distance between the file tip and rubber stop was measured using a digital calliper to 0.01 mm accuracy (ARL). Then, a size 20, 0.02 taper instrument was attached to each device and inserted into the root canals without rotary motion until the integrated ERCLMDs positioned the instrument tips at the 0.5 setting as suggested by the devices. This length was again measured using a digital calliper (EL). The Mann–Whitney *U*-test was used to investigate statistical differences between the true canal length and those indicated by the two devices when used in 'automatic ARL and when inserted passively (EL).

Results In the presence of gutta-percha, sealer and chloroform, the auto-reverse function for the Tri Auto ZX® and TCM Endo V®, set to start at 0.5 level, was initiated beyond the foramen in 60% and 95% of the samples, respectively during active (rotary) penetration of the instruments. There was a statistically significant difference between the devices for the mean discrepancies between the length at which the auto reverse function was initiated and the true length ($P < 0.001$). Electronic detection of the apical terminus when the instruments were introduced passively (not rotating) was beyond the foramen in 20% and 37% of cases in the Tri Auto ZX® group and the TCM Endo V® group, respectively. There was a statistically significant difference between the devices for the mean discrepancies between the electronically determined (passive) length and true length ($P < 0.01$).

Conclusion The auto reverse function of the Tri Auto ZX® and TCM Endo V® devices, set to start at 0.5 level, were initiated beyond the foramen in the majority of root-filled teeth during active (rotating) penetration

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of root filling material. Thus, this automatic function must be used with caution when removing gutta-percha root fillings. There were significant differences between the accuracy of measurements in active (rotating) and passive (not-rotating) modes; both devices were more accurate when used in passive mode. However, the Tri AutoZX® was significantly more accurate in a greater proportion of cases.

Keywords: automated root canal preparation, electronic apex locator, electronic root canal length measurement devices, retreatment, TCM Endo V®, Tri Auto ZX®.

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Introduction

The main objective of root canal treatment is to eliminate sources of inflammation and/or infection from within the root canal system (Chugal *et al.* 2003). This involves the debridement of the root canal system that must be filled completely in an attempt to prevent reinfection (Sjögren *et al.* 1990). It is generally accepted that all the steps of root canal treatment should be limited to within the root (Ricucci 1998). To achieve this goal, the canal terminus should be detected precisely (Ricucci & Langeland 1998). Theoretically, the canal terminus is considered to be the cemento dentinal junction (Burch & Hulen 1972). However, this 'landmark' is a histological site and cannot be detected precisely clinically, and as a result it is not an ideal position to use as the canal terminus. Unfortunately, the apical constriction is also an inconsistent landmark; for example, Dummer *et al.* (1984) reported that the topography of the apical constriction was not consistent and had a variety of morphological variations. Thus, in clinical situations, the minor apical foramen is a more consistent anatomical feature (Katz *et al.* 1991) and is a more reliable landmark to use as the canal terminus. It is generally accepted that the minor apical foramen and apical constriction is on average located 0.5–1.0 mm short of the radiographic apex (Kuttler 1955, 1958, Katz *et al.* 1991, Morfis *et al.* 1994).

Poor quality root canal treatment may result in post-treatment disease that most often can be corrected via a nonsurgical technique (Wu *et al.* 2006). The goal of a nonsurgical approach is identical to primary treatment, i.e. the elimination of antigenic sources through the elimination of infection (Hepworth & Friedman 1997, Paik *et al.* 2004). Therefore, in an attempt to eliminate the antigenic source from within the root canal system precise detection of the minor foramen (as the root canal terminus) is crucial to reduce the probability of insufficient removal of root filling material or of damaging the periapical tissues by instrumentation beyond the tooth. Not unexpectedly, the detection of the minor apical foramen by electronic methods has gained popularity in nonsurgical treatment of post-treatment disease (Nekoofar *et al.* 2002).

Recently, a variety of electronic root canal length measurement devices (ERCLMD) have been integrated into engine-driven rotary systems (Campbell *et al.* 1998). The manufacturers claim that more rapid and easier root canal preparation and more effective working length determination can be achieved with their use (http://www.stefident.com/TCM_Endo_V.html, http://www.jmoritausa.com/tri_auto_zx.asp). The TCM Endo V® (Nouvag, Goldach, Switzerland) is one of the combined devices that is equipped with a motor that gives an adjustable speed and torque levels that is integrated with a ERCLMD (Topuz *et al.* 2007). The Tri Auto ZX® (J Morita Co., Kyoto, Japan) is another type of combined device where the Root ZX®, an impedance ratio-based ERCLMD, has been installed in the Tri Auto ZX® handpiece (Zmener *et al.* 1999). Topuz *et al.* (2007) compared the accuracy of the electronic root-end terminus detection functions of the TCM Endo V® and Root ZX® and reported that at the tolerance limit ±0.50 mm, the TCM Endo V® was as reliable as the Root ZX®. Engine-driven rotary instruments are also used to remove gutta-percha and sealer in nonsurgical root canal treatment (de Carvalho Maciel & Zaccaro Scelza 2006, Saad *et al.* 2007). However, there are few studies that evaluate the accuracy of integrated ERCLMDs during the nonsurgical removal of gutta-percha and sealer from filled root canals (Grimberg *et al.* 2002, Carneiro *et al.* 2006).

The aim of this *ex vivo* study was to evaluate the accuracy of the integrated ERCLMDs of the TCM Endo V® and Tri Auto ZX® motors when removing gutta-percha and sealer from filled root canals.

Materials and methods

Forty freshly extracted maxillary and mandibular incisor teeth with mature apices and patent single and straight root canals were selected. The teeth were stored in saline solution to prevent dehydration following extraction. After radiographic evaluation and visual examination with a dental operating microscope at 8× magnification (Möller-Wedel Dento 300, Wedel, Germany) the teeth were cleaned with scalers. Then, the teeth were decoronated at the CEJ to provide direct access to the canal and to provide a flat, horizontal surface as a reference point.

Assessing working length

To estimate the true working length (TL) a size 10 stainless steel K-file (VDW Antaeos, Munich, Germany) was passively introduced into the root canal until the tip of the file was seen level with the root surface at the major foramen. This length was measured by adjusting the rubber stop in contact with the flat, horizontal surface of the tooth. The distance between the file tip and the rubber stop was measured using a digital calliper to an accuracy of 0.01 mm; the measurements were repeated thrice for each tooth and the mean value of three measurements was computed. Then, 0.5 mm was subtracted from this measurement and the resulting value considered as the true working length (TL).

Preparation of root canals

Root canals were prepared using the Hero 642® NiTi rotary sysytem (Micro-Mega, Besançon, France) in combination with a 16 : 1 reduction handpiece powered by a torque and speed-controlled electric motor (Tecnika; ATR, Pistoia, Italy). The electric motor was set at a constant speed of 400 rpm. The instruments were used in the following sequence: size 20, 0.06 taper was used to two-thirds of the working length (TL), size 20, 0.04 taper to 2 mm short of the TL, and size 20, 0.02 taper to the TL. This sequence was followed by using size 25, 0.04 taper to 2 mm short of the TL, and size 25, 0.02 taper at TL. Size 30, 0.02 taper was then used as the master apical instrument that was used to the TL.

The root canals were irrigated with 2.5% sodium hypochlorite whilst the instruments were being used and at each change of instrument. Then, the root canals were dried with paper points and filled using lateral compaction of gutta-percha cones and AH 26 sealer (Dentsply De Trey, Konstanz, Germany). Access cavities were sealed with Cavit (ESPE, Seefeld, Germany) and the roots were stored in 100% humidity for 7 days.

Penetration of root fillings

After 7 days, the temporary filling was removed with a round bur and the roots were mounted in alginate (Cavex Holland BV, Haarlem, Netherlands) within a cylindrical plastic container of 4.5 cm height and 4.5 cm diameter. Each root was placed through a central hole that had been previously made in the top of the container and fixed with acrylic resin to avoid movement during instrumentation. A second smaller hole was made in the top of the container to hold the electrode (lip-clip) and allow it to contact the alginate. The samples were embedded into the alginate before it had set. The *ex vivo* model was adopted and modified from Aurelio *et al.* (1983) and Kaufman *et al.* (2002).

The access cavities were then filled with chloroform to soften the gutta-percha and the material in the cervical and middle thirds was removed using sizes 2 and 1 Gates-Glidden burs.

The roots were then randomly divided in two groups: group 1, 20 roots prepared using Tri Auto ZX® (J Morita Co.) and group 2, 20 roots prepared using TCM Endo V® (Nouvag).

The 'automatic apical reverse function (ARL)' of both of the devices was set to start at the 0.5 setting. To compare the accuracy of the integrated ERCLMDs, the length of the instrument at which the auto reverse function was initiated (ARL) during active (rotary) penetration was measured. Then, a second electronic measurement of canal length (EL) was obtained when the instrument was re-inserted into the canal passively (without rotation). Mean discrepancies between each electronic measurement and true length (TR) were compared.

The Tri Auto ZX® was used according to the manufacturer's recommendations. The handpiece was adjusted to the high torque level and a size 20, 0.02 taper HERO 642 instrument inserted into the root canal and the Tri Auto ZX® device operated. The rotating instrument was advanced down the canal to penetrate the softened gutta-percha and sealer without exerting excessive force. When a beeping sound was heard the integrated root canal length measurement device of the Tri Auto ZX® determined that the instrument tip was at the 0.5 level. At this length and just before the instrument began to rotate in the opposite direction, the instrument was stopped by the operator. Then, the rubber stop on the instrument was adjusted to the flat coronal surface. The rubber stop was fixed to the instrument with Aeliteflo® (Bisco Inc., Schaumburg, IL, USA), a flowable light curing resin. The instrument was removed and the distance between the rubber stop and the file tip was measured using the digital calliper to 0.01 mm accuracy; this length was referred to as ARL1. Then, another size 20, 0.02 taper instrument was attached to the device and inserted into the canal passively without rotary motion until the integrated Tri Auto ZX® device determined the tip was again at the 0.5 mm level. The rubber stop of the instrument was fixed with Aeliteflo® and the length measured using a digital calliper; this length was referred to as EL1.

The same procedure was repeated for the TCM Endo V®. According to the manufacturer's recommendations, the device was adjusted to a speed of 250 rpm and a high torque level. One specimen in this group was excluded because of a crack on the root surface following use of the Gates-Glidden burs. The lengths measured with the TCM Endo V® were referred to as ARL2 and EL2.

All measurements were performed by an experienced operator who was blind with respect to the true length measurements.

Because of the non-normal distribution within the groups, the Mann–Whitney *U*-test was used to investigate statistical differences between EL1 and EL2 and differences between ARL1 and ARL2.

Results

The results are summarised in Figs 1–4.

Figure 1 shows the differences between the length of the instrument at which the auto reverse function of Tri Auto ZX® (ARL1) was initiated and true length (TL). In 60% of samples, the auto reverse function was initiated when the file tip was beyond the foramen. In the ARL1 group, 80% of measurements were within ±0.50 mm of true length whilst all measurements were within ±1.00 mm of true length.

Figure 2 shows the results of the electronic length measurement whilst the instrument was not rotating. In the Tri Auto ZX® group (EL1), 80% of electronic measurements were short of the foramen and 90% were within ±0.50 mm of the true length (TL1). In all cases, the Tri Auto ZX® device was accurate within ±1.00 mm of true length.

The difference between the true length (TL2) and the length at which the auto reverse function was initiated in the TCM Endo V® (ARL2) is shown in Fig. 3. The ARL2 group had the widest range of length distributions; 37% of measurements were within ±0.50 mm of true length, 31.5% were between ±0.51 and 1.00 mm and a further 31.5% were between ±1.01 and 3.50 mm of true length (TL2).

Figure 4 illustrates the results of the TCM Endo V® group measurements whilst the instrument was not rotating (EL2). Overall 63% and 37% of electronic measurements were short of or beyond the foramen, respectively. In the EL2 group, 74% of measurements were within ±0.50 mm of true length, a further 21%

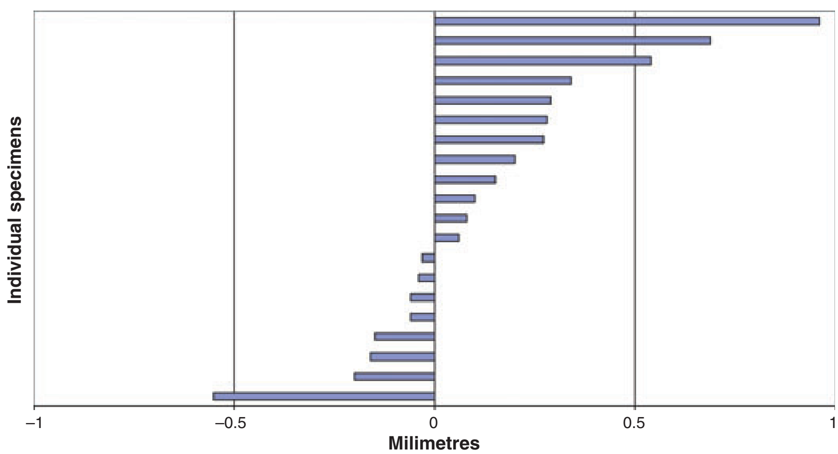

Figure 1 Differences (mm) between the true length (TL1) and the length measured when using the auto reverse function (ARL1) as determined by the Tri Auto ZX®.

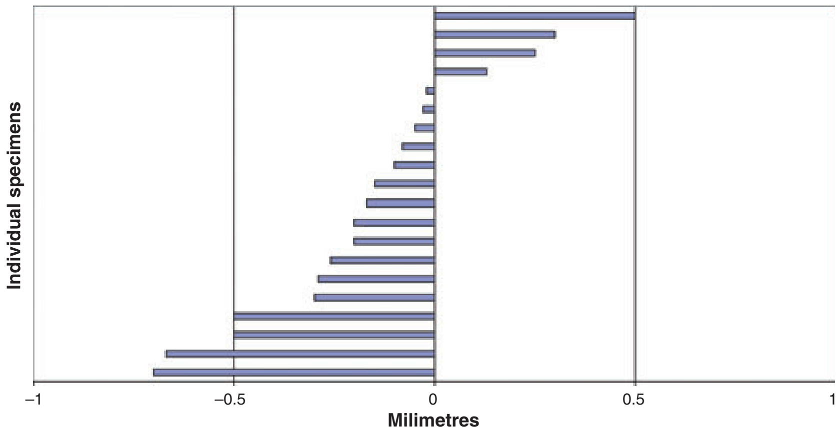

Figure 2 Differences (mm) between the true length (TL1) and the length measured when instrument was inserted passively (EL1) as determined by the Tri Auto ZX®.

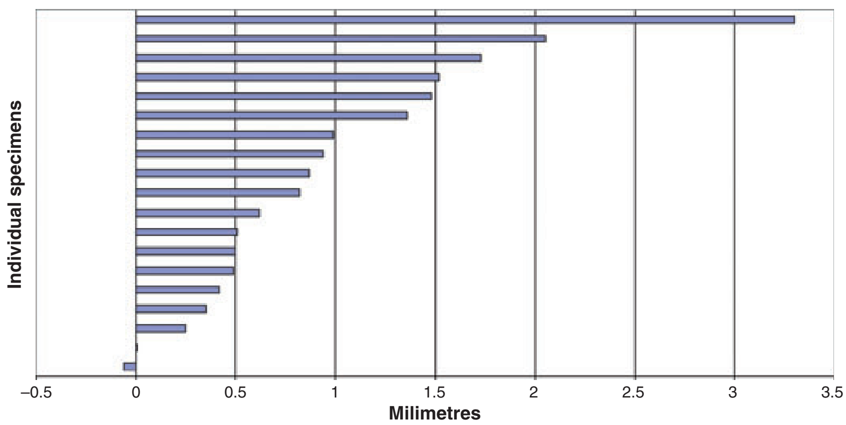

Figure 3 Differences (mm) between the true length (TL2) and the length measured when using the autoreverse function (ARL2) as determined by the TCM Endo V®.

were between ±0.51 and 1.00 mm and a further 5% were between ±1.01 and 1.50 mm.

Differences between EL1 and EL2 measurements and those between ARL1 and ARL2 were investigated using the Mann–Whitney *U*-test. There was a significant difference between EL2 and EL1 ($P < 0.01$). There was also a significant difference between ARL1 and ARL2 ($P < 0.001$).

Discussion

The devices used in this study have more than one function. Both the Tri Auto ZX® and TCM Endo V® can be used as an electronic root canal length measurement device (ERCLMD) without rotary motion and/or as an endodontic motor with 'Auto Reverse Function'. This triggers reversal of the instrument rotation when its tip reaches the perceived apical terminus, the point of the canal that the ratio of the calculated impedance of two different frequencies that is applied by the integrated ERCLMD tends toward the minimum value. The reverse mechanism can be adjusted and preset by the operator short of the canal terminus in the hope that when the integrated ERCLMD detects the tip at the adjusted level (e.g. 0.5 mm), clockwise rotary motion stops and a counter clockwise motion begins, thus preventing further penetration. The instrument display (LED) also indicates this function. Reversal of rotation can also be triggered when too great a pressure is applied to the handpiece. There is also an 'Auto Stop Function' that operates in a similar way to the 'auto reverse function'.

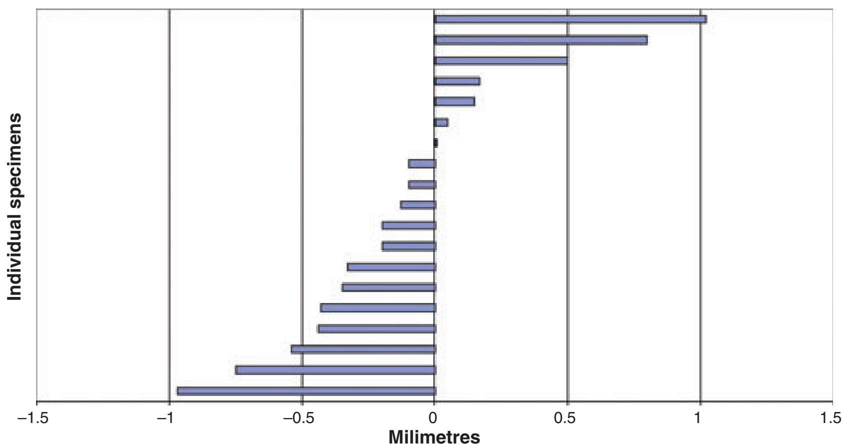

Figure 4 Differences (mm) between the true length (TL2) and the length measured when instrument was inserted passively (EL2) as determined by the TCM Endo V®.

In the present study, the accuracy of electronic detection of the canal terminus and 'auto reverse function' of the devices was evaluated during penetration of gutta-percha.

One of the primary aims of any working length determination technique, including ERCLMDs, is measuring the distance between the file tip and the coronal landmark that should be adjusted to a stable coronal reference point. ElAyouti & Löst (2006) suggested evaluating the repeatability of the operator in an attempt to reduce the probability of false readings as a source of error in clinical and laboratory experiments. Weiger *et al.* (1999) suggested a definite coronal reference point should be prepared, using stable rubber stops and taking the mean of repeated measurements to minimize inaccurate readings. It is also critical that the instrument is inserted perpendicular to the rubber stop so that the orientation of the instrument against the measuring device does not influence the reading.

In the present study to minimize inaccuracies in the length reading procedure, a definite coronal reference point was prepared by decoronating teeth at the CEJ to provide a flat, horizontal surface. Moreover, Aeliteflo® (Bisco Inc.), a flowable light cured resin, was used to stabilize the rubber stops. In addition, all readings were repeated with a digital calliper three times and the mean value of three measurements was taken as the definitive reading.

The speed of rotation and torque level of the TCM Endo V® device are adjustable whereas the speed of the Tri Auto ZX® is not adjustable and is set at 250 rpm. However, the torque level of the latter device is adjustable to high or low levels. In the present study, to obtain the most comparable results, the speed of the TCM Endo V® was adjusted to the preset speed of the Tri Auto ZX®. To avoid misreading of the 'auto torque function', both devices were adjusted to the maximum torque level. In addition, gutta-percha was also softened by using chloroform.

Based on the classification of Nekoofar *et al.* (2006) both of the ERCLMD integrated in the devices are 'impedance ratio' or 'quotient' type. In the impedance ratio-based ERCLMDs, the AC source is a two-frequency source, i.e. it comprises two sine waves with a high and a low frequency, 500 Hz and 7.5 kHz in the TCM EndoV® (http://www.endodontology.ch/Programm%202007.pdf) and 400 Hz and 8 kHz in the Tri Auto ZX® (http://oceania.morita.com/products/p07tri.html). The impedance of the teeth is measured at each frequency and the position of the file is determined from the ratio between these two impedances (Kobayashi & Suda 1994).

Topuz *et al.* (2007) compared the accuracy of the electronic root-end terminus detection functions of the TCM Endo V® and Root ZX®. They reported that at the tolerance limit ±0.50 mm, the TCM Endo V® was as reliable as the Root ZX®. In the present study at the same tolerance, the auto reverse function of the Tri Auto ZX® was accurate in 80% of cases and significantly more accurate than the TCM Endo V® device ($P < 0.001$). The auto reverse function of the TCM Endo V® was accurate in 37% of measurements. This finding is in accordance with Alves *et al.* (2005) who evaluated the accuracy of the Tri Auto ZX® in nonsurgical treatment of root-filled teeth and reported that within a tolerance limit of ±0.5 mm the electronic length and true length measurement were coincident in 76% of samples.

In the present study, the lengths measured with the 'auto reverse function' of the Tri Auto ZX® and TCM Endo V® (ARL1/ARL2) were beyond the foramen in 60% and 95% of cases respectively. The time elapsed between detection of the length by the devices (0.5 setting) and the operator stopping the rotary motion may be the reason for these 'long' readings. It may also be related to the speed of the devices and the amount of pressure applied by the operator. In the present study to obtain the most comparable results, both of the devices were adjusted to the same speed (250 rpm) and to the highest torque level. Both devices were also used by the same experienced operator without applying excessive pressure.

Grimberg *et al.* (2002) in an *in-vivo* study evaluated the clinical performance of the Tri Auto ZX®. They compared the 'auto reverse function' length, electronic length and true length of 25 cases. However, the auto reverse function length and electronic length were coincident in all cases and these measurements coincided with the true length in 40% of cases. The true length measurements were shorter than the electronic length and auto reverse function length in only one case. Therefore, Grimberg *et al.* (2002) concluded that the TriAuto ZX® was a reliable device against over preparation.

Carneiro *et al.* (2006) evaluated the accuracy of the ERCLMD integrated into the TriAuto ZX® and its auto reverse function when used with Protaper® instruments and set to reverse at the preset distance of 1 and 2 respectively. Using a preset distance of 1 provided a distance of 0.669 mm, whereas the setting of 2 resulted in a distance of 1.384 mm. They considered the Tri Auto ZX® as an acceptable device for determining working length during instrumentation. In the present study, the accuracy of the automatic apical reverse mechanism of the Tri Auto ZX® and TCM Endo V®, preset to start at the 0.5 setting, were evaluated during removal of gutta-percha. There were significant differences between their accuracy in active (rotating) and passive (not-rotating) modes; both devices were more accurate when used in passive mode.

Conclusions

- During the removal of gutta-percha and sealer from root-filled teeth the auto reverse function of the Tri Auto ZX® and TCM Endo V® device, set to start at 0.5 setting, were initiated beyond the foramen in 60% and 95% of samples respectively. Thus, this automatic function must be used with caution when removing gutta-percha root fillings.
- At a tolerance limit of ±0.50 mm there was a statistically significant difference between the measurements at which the auto reverse function of the Tri Auto ZX® and TCM Endo V® devices were initiated ($P < 0.001$); the former was more accurate.
- In the Tri Auto ZX® group, when using the auto reverse function (ARL1), 80% of measurements were within ±0.50 mm of true length. In this group whilst the instrument was not rotating (EL1), 90% of electronic measurements were within ±0.50 mm of the true length. There was no statistically significant difference between ARL1 and EL1.
- In the TCM Endo V® group, 37% of measurements at which the auto reverse function was initiated (ARL2) were within ±0.50 mm of true length. In this group whilst the instrument was not rotating (EL2), 74% of electronic measurements were within ±0.50 mm of true length. There was a significant difference between ARL2 and EL2; the latter was more accurate.

References

Alves AM, Felippe MC, Felippe WT, Rocha MJ (2005) Ex vivo evaluation of the capacity of the Tri Auto ZX to locate the apical foramen during root canal retreatment. *International Endodontic Journal* **38**, 718–24.

Aurelio JA, Nahmias Y, Gerstein H (1983) A model for demonstrating an electronic canal length measuring device. *Journal of Endodontics* **9**, 568–9.

Burch JG, Hulen S (1972) The relationship of the apical foramen to the anatomic apex of the tooth root. *Oral Surgery Oral Medicine, and Oral Pathology* **34**, 262–8.

Campbell D, Friedman S, Nguyen HQ, Kaufman A, Keila S (1998) Apical extent of rotary canal instrumentation with an apex-locating handpiece *in vitro*. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **85**, 319–24.

Carneiro E, Bramante CM, Picoli F, Letra A, da Silva Neto UX, Menezes R (2006) Accuracy of root length determination using Tri Auto ZX and ProTaper instruments: an *in vitro* study. *Journal of Endodontics* **32**, 142–4.

de Carvalho Maciel AC, Zaccaro Scelza MF (2006) Efficacy of automated versus hand instrumentation during root canal retreatment: an ex vivo study. *International Endodontic Journal* **39**, 779–84.

Chugal NM, Clive JM, Spangberg LSW (2003) Endodontic infection: some biologic and treatment factors associated with outcome. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **96**, 81–90.

Dummer PM, McGinn JH, Rees DG (1984) The position and topography of the apical canal constriction and apical foramen. *International Endodontic Journal* **17**, 192–8.

ElAyouti A, Löst C (2006) A simple mounting model for consistent determination of the accuracy and repeatability of apex locators. *International Endodontic Journal* **39**, 108–12.

Grimberg F, Banegas G, Chiacchio L, Zmener O (2002) *In vivo* determination of root canal length: a preliminary report using the Tri Auto ZX apex-locating handpiece. *International Endodontic Journal* **35**, 590–3.

Hepworth MJ, Friedman S (1997) Treatment outcome of surgical and non-surgical management of endodontic failures. *Journal of the Canadian Dental Association* **63**, 364–71.

Katz A, Tamse A, Kaufman AY (1991) Tooth length determination: a review. *Oral Surgery Oral Medicine, and Oral Pathology* **72**, 238–42.

Kaufman AY, Keila S, Yoshpe M (2002) Accuracy of a new apex locator: an *in vitro* study. *International Endodontic Journal* **35**, 186–92.

Kobayashi C, Suda H (1994) New electronic canal measuring device based on the ratio method. *Journal of Endodontics* **20**, 111–4.

Kuttler Y (1955) Microscopic investigation of root apexes. *Journal of the American Dental Association* **50**, 544–52.

Kuttler Y (1958) A precision and biologic root canal filling technic. *Journal of the American Dental Association* **56**, 38–50.

Morfis A, Sylaras SN, Georgopoulou M, Kernani M, Prountzos F (1994) Study of the apices of human permanent teeth with the use of a scanning electron microscope. *Oral Surgery, Oral Medicine, and Oral Pathology* **77**, 172–6.

Nekoofar MH, Sadeghi K, Akha ES, Namazikhah MS (2002) The accuracy of the Neosono Ultima EZ apex locator using files of different alloys: an *in vitro* study. *Journal of the California Dental Association* **30**, 681–4.

Nekoofar MH, Ghandi MM, Hayes SJ, Dummer PMH (2006) The fundamental operating principles of electronic root canal length measurement devices. *International Endodontic Journal* **39**, 595–609.

Paik S, Sechrist C, Torabinejad M (2004) Levels of evidence for the outcome of endodontic retreatment. *Journal of Endodontics* **30**, 745–50.

Ricucci D (1998) Apical limit of root canal instrumentation and obturation, part 1. Literature review. *International Endodontic Journal* **31**, 384–93.

Ricucci D, Langeland K (1998) Apical limit of root canal instrumentation and obturation, part 2. A histological study. *International Endodontic Journal* **31**, 394–409.

Saad AY, Al-Hadlaq SM, Al-Katheeri NH (2007) Efficacy of two rotary NiTi instruments in the removal of gutta-percha during root canal retreatment. *Journal of Endodontics* **33**, 38–41.

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

Topuz O, Uzun O, Tinaz AC, Sadik B (2007) Accuracy of the apex locating function of TCM Endo V in simulated conditions: a comparison study. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **103**, e73–6.

Weiger R, John C, Geigle H, Löst C (1999) An *in vitro* comparison of two modern apex locators. *Journal of Endodontics* **25**, 765–8.

Wu MK, Dummer PMH, Wesselink PR (2006) Consequences of and strategies to deal with residual post-treatment root canal infection. *International Endodontic Journal* **39**, 343–56.

Zmener O, Grimberg F, Banegas G, Chiacchio L (1999) Detection and measurement of endodontic root perforations using a newly designed apex-locating handpiece. *Endodontics & Dental Traumatology* **15**, 182–5.

