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Apical surgery: endoscopic findings at the resection level of 168 consecutively treated roots

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Abstract

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Aim Endoscopic evaluation of the cut root face after root-end resection during apical surgery.

Methodology Consecutive cases undergoing apical surgery from June 2006 to May 2008 were enrolled. After root-end resection, the cut root face was inspected with a rigid endoscope and the following findings were assessed: number of canals, presence of isthmus, presence and location of craze lines/cracks, frosted dentine, and gaps between root filling material and dentine. Craze lines/cracks, frosted dentine and gaps were further correlated with the age group of the patient (<45 vs. ≥45 years), the type of treated tooth and the presence or absence of a post/screw.

Results The final material included 168 resected roots. The highest frequency of isthmuses was found in mesial roots of mandibular first molars (88.5%). A craze line/crack was seen in 9.5%, frosted dentine in 79.8% and gaps in 83.3% at the cut root faces. Significant differences were observed for the location of the microfindings at the resected root surfaces (buccal vs. mesial vs. lingual vs. distal, $P > 0.0001$). Premolars had significantly more craze lines/cracks than anterior teeth ($P = 0.006$) and molars ($P = 0.000$). Frosted dentine was significantly more frequently seen in premolars ($P = 0.027$) and molars ($P = 0.001$) compared to anterior teeth. The age groups and the presence or absence of a post/screw did not significantly influence the findings.

Conclusions Frosted dentine and gaps were frequently observed with endoscopy at the resected root surfaces. The type of tooth appeared to affect the occurrence of a craze line/crack and of frosted dentine.

Keywords: apical surgery, cut root face, endoscopy, microfindings.

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Introduction

The goal of apical surgery is to create suitable conditions for healing by sealing any path from the root canal to the periradicular tissues (European Society of Endodontology 2006). This objective is usually accomplished by root-end resection, preparation of a root-end cavity and its subsequent filling. Because apical surgery is undertaken on exceptionally small and complex structures, undertaking treatment without magnification is no longer recommended (Kim & Kratchman 2006). Hence, use of a surgical microscope has become the standard of care in conventional and surgical endodontics. The combination of magnification, focused illumination and methylene blue staining is a prerequisite to effectively identify anatomical details at the cut root face, such as accessory canals or isthmuses. The key to success in apical surgery is to prevent reinfection by accurately identifying and managing potential bacterial pathways. There is consensus that to obtain a successful outcome, apical surgery requires effective and precise root-end preparation with subsequent root-end filling (Christiansen *et al.* 2009). Other bacterial pathways for reinfection include an

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obvious gap between the existing root filling material and the adjacent dentine wall as well as dentinal cracks. However, the clinical significance of dentinal cracks identified at the cut root surface following root-end resection remains unclear. It has been speculated that radicular dentinal cracks may enlarge during function and in this way result in future leakage pathways or root fractures (de Bruyne & de Moor 2005). Other frequent findings of cross-section surfaces of root filled teeth are opaque areas within the root dentine. Opaque or frosted dentine has been associated with areas of strain, and it has been hypothesized that frosted dentine might be a precursor to a crack (Slaton *et al.* 2003), and therefore, warrants further investigation.

With regard to the detection of extremely fine anatomical details, such as dentinal cracks, the surgical microscope may have limitations (von Arx *et al.* 2010). An additional tool for magnification is the endoscope; however, the endoscope has not yet gained the same acceptance and wide use in dentistry as the surgical microscope. The advantage of an endoscope over other visualization techniques for the identification of artificially created cracks was documented in an experimental study (Slaton *et al.* 2003). In a new experimental study using extracted human teeth, endoscopy ×64 proved the most accurate visual aid for the identification of dentinal cracks after root-end resection, compared to endoscopy ×8 and microscopy ×16 and ×24 (von Arx *et al.* 2010). No clinical paper has been published comparing endoscopy and microscopy in apical surgery. In contrast, one clinical study evaluating the outcome of apical surgery compared the endoscope and magnification loupes (Taschieri *et al.* 2006). Another clinical study assessing healing after apical surgery compared the endoscope and the naked eye (von Arx *et al.* 2003b).

Clinical papers on apical surgery mostly focus on the healing outcome in relation to the root-end management and filling material (Tsesis *et al.* 2009). *In vivo* information is scanty with regard to microscopic or endoscopic findings following root-end resection and preparation, respectively. Morgan & Marshall (1999) assessed root ends for cracks during apical surgery of 25 roots in 20 patients. Impressions were made after root-end resection and again after ultrasonic root-end preparation. Scanning electron micrographic examination of the root-end replicas found only one incomplete canal crack after root-end preparation. Another clinical study assessed the frequency of canal isthmuses at the resection level in first molars (von Arx 2005). The cut root faces were stained with methylene blue and inspected with a rigid endoscope. In maxillary first molars, 76% of resected mesio-buccal roots had two canals and an isthmus, whereas 83% of mesial roots in mandibular first molars had two canals with an isthmus. That study did not report data regarding the presence of gaps or cracks at the cut root face.

The objective of this clinical study was to document and analyse macro- and microfindings detected with endoscopic inspection at the cut root face after root-end resection during apical surgery.

Material and methods

Patient selection

Patients undergoing apical surgery from June 2006 to May 2008 were enrolled consecutively. Patients were instructed about the surgical procedure, postoperative care, follow-up examinations and alternative treatment options. Each patient signed a consent form according to the Declaration of Helsinki. The included material comprised 144 teeth in 120 patients.

Surgical technique

Apical surgery was performed under local anaesthesia (articaine 4% with 1 : 100 000 epinephrine, Ultracain® 4% D-S forte; Sanofis-Aventis, Meyrin, Switzerland) in an operating room and using a surgical microscope (Möller Denta 300; Haag-Streit International, Köniz, Switzerland). Following the elevation of a full-thickness mucoperiosteal flap, osteotomy was carried out with round burs under copious saline irrigation. Affected roots were then resected approximately 3 mm from the apex. Following debridement of the pathological tissue, haemostasis of the bony crypt was achieved with aluminium chloride (Expasyl™; Produits Dentaires SA, Vevey, Switzerland) and/or ferric sulphate (Stasis®; Belport Co., Camarillo, CA, USA). After staining of the surgical area with methylene blue and root-end inspection (for details, see below), root-end cavities were prepared with sonic-driven microtips (KaVoSONICretro; KaVo Dental GmbH, Biberach, Germany) or with ultrasonic retro-tips (Piezotome/Newtron; Satelec/Acteon, Merignac, France). Root-end fillings were made with MTA (ProRoot®; Dentsply Tulsa Dental, Tulsa, OK, USA). After the wound area had been cleaned, primary wound closure was accomplished with multiple interrupted sutures.

Collection of data

After root-end resection, the cut root face was inspected using a rigid endoscope (rod-lens system) with the largest possible magnification (approximately ×80 to ×100). The endoscope was a 6-cm-long and 3-mm-wide telescope with a viewing angle of 70° (TeleOtoscope with Hopkins 70° optics; Karl Storz GmbH, Tuttlingen, Germany). With a camera (Endovision Telecam SL; Karl Storz GmbH) mounted onto the ocular of the endoscope, the captured endoscopic images were transferred to a monitor in the operating theatre and were recorded on a digital videotape (DVCAM digital medical recorder; Sony Corporation, Tokyo, Japan) (von Arx *et al.* 2002). Video sequences were subsequently transferred to an iMac computer for further image analysis. The following primary study parameters were assessed at the cut root face (Fig. 1):

Macrofindings:

number of canals per root and

presence of isthmus per root.

Microfindings:

presence and location of a craze line: dark line that appears to disrupt the integrity of the dentine;

presence and location of a crack: apparent fissure within the dentine;

presence and location of area with 'frosted dentine': whitish or opaque dentine in contrast to the normal greyish or yellowish dentine and

presence and location of a gap: a space (stained with methylene blue) between the root canal filling material and the adjacent dentinal wall.

For location of microfindings at the resected root face, a 12-sector grid was superimposed on a still image of the video sequence, and the elements were allocated to one or more sectors. Sector No. 12 was always oriented to the buccal, sector No. 3 to the mesial, sector No. 6 to the lingual and sector No. 9 to the distal aspect of the root. The centre of the grid was placed in the middle of the root canal, or, in teeth with two canals, in the middle of a line connecting the root canals (Fig. 2). To ensure correct mesial and distal orientation, the numbering of the sectors was clockwise for teeth in the maxillary left and mandibular right quadrants, and counter-clockwise for teeth in the maxillary right and mandibular left quadrants.

Secondary study parameters included the age of the patient (<45 vs. ≥45 years), the type of treated tooth (anterior teeth = incisors and canines vs. premolars vs. molars) and the presence or absence of a post/screw within the assessed root.

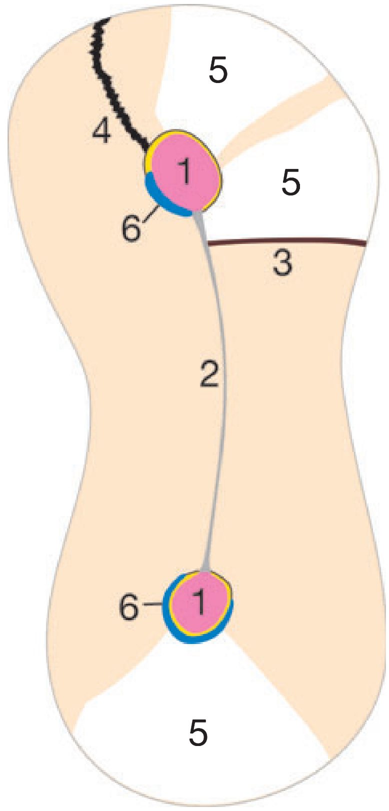

Figure 1 Schematic illustration of macro- and microfindings that were assessed at the cut root face: (1) canal(s), (2) isthmus, (3) craze line, (4) crack, (5) frosted dentine and (6) gap(s).

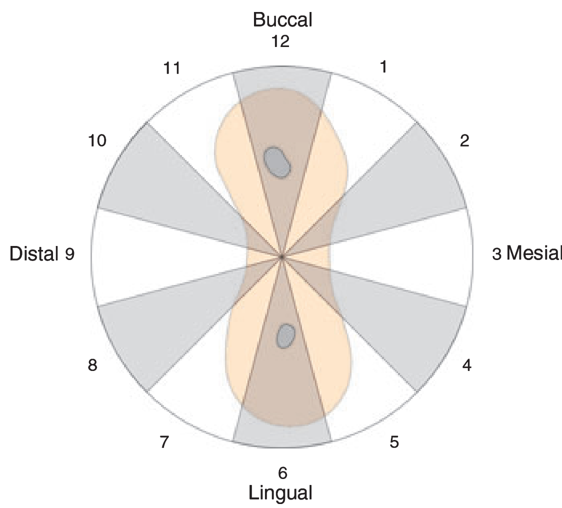

Figure 2 Schematic illustration of a root with two canals and 12-sector grid with clockwise sector numbering.

Evaluation of data

To simplify data evaluation and statistical comparisons, the sectors were pooled as follows: buccal segment of cut root face = sectors No. 11, 12 and 1; mesial segment = sectors No. 2, 3 and 4; lingual segment = sectors No. 5, 6 and 7; distal segment = No. 8, 9 and 10. The macrofindings 'canal' and 'isthmus' were assessed per root. The microfindings 'craze line', 'crack', 'frosted dentine' and 'gap' were assessed per root and per root segment. The microfindings were further correlated with the secondary study parameters, i.e. age of patient, type of treated tooth and presence/absence of post/screw.

Statistical analysis

Descriptive statistics are presented as frequency tables. Associations in two-by-two tables were tested by Fisher's exact tests (Table 2). For proportions of segments per microfinding in Table 3, exact two-sided 95% confidence intervals (Clopper–Pearson) were computed and the null hypotheses of equal proportions within each microfinding were tested by chi-squared goodness-of-fit tests. Because of the exploratory nature of the data analysis, no correction for multiple testing of *P* values and confidence intervals was applied. The analysis was performed using R 2.9.1. (The R Foundation for Statistical Computing, Vienna, Austria).

Results

From the initial material, six teeth in six patients had to be excluded for the following reasons: incomplete data set (three teeth), roots were fused at the resection level (two teeth) and filling of a latero-buccal perforation (one tooth). The final material consisted of 138 teeth with 168 treated roots in 114 patients. The mean age of the patients was 48.4 years (range 20–81 years). Fifty-eight patients were men (50.9%) and 56 patients were women (49.1%).

The distribution of included teeth and treated roots is shown in Table 1. The teeth most often included were mandibular first molars ($n = 30$, 21.7%). With regard to individual roots, the most frequently assessed root was the mesial root of mandibular first molars ($n = 26$, 15.5%). Eleven of 13 maxillary first premolars had only one root, whereas in the remaining two premolars with two roots, only the buccal root was treated. With regard to the three mandibular second molars, two teeth had two roots, but only the mesial root was treated, and in one second molar, the tooth had only one root.

Multiple canals per root were mainly found in premolars and molars, but not exclusively (Table 1). Three incisors – one central and one lateral maxillary incisor and one central mandibular incisor – demonstrated two canals at the resection level (Fig. 3). Three canals per root were only observed in three mesial roots of mandibular first molars (Fig. 4a,b). The highest frequency of isthmuses was seen in mesial roots of mandibular first molars (88.5%) (Fig. 5). No isthmuses were detected in mandibular premolars (Table 1); in contrast, 41.4% of maxillary premolar roots had an isthmus at the cut root face (Fig. 6). The overall presence of an isthmus in posterior teeth including all premolar and molar roots was 44.1%.

With regard to detection of microfindings at the cut root face, 11 of 168 roots (6.5%) had a total of 18 craze lines (Fig. 7) in a total of 27 sectors (six roots had one craze line, four roots had two and one root had four). Regarding cracks (Fig. 8a,b), five of 168 roots (3.0%) had one or more cracks (four roots had one crack and one root had two cracks in a total of nine sectors). Because of the low number of roots with craze lines or cracks, these were pooled for further evaluation. Overall, 16 of 168 roots (9.5%) had a craze line or crack, with a total of 36/2016 (1.8%) sectors affected (Tables 2 and 3). The majority of craze lines/cracks were located in the buccal segment (63.9%). The distribution of craze lines/cracks per segment was statistically highly significant ($P < 0.0001$) (Table 3).

Frosted dentine was observed in 79.8% of roots (Fig. 9), and in 733/2016 sectors overall (36.4%), most often in the buccal segment (39.6%). The distribution of frosted dentine per segment was statistically highly significant ($P < 0.0001$) (Table 3).

Amongst the assessed microfindings, a gap (Fig. 10-a,b) between the root filling material and the dentine wall was the most frequent finding; it was present in 83.3% of roots. Overall, a gap was observed in 967/2016 sectors (48.0%). Again, a gap was more frequently found in the buccal segment (29.7%) compared to the other segments. The distribution of gaps per segment was highly significant ($P < 0.0001$) (Table 3).

Occurrence of microfindings and association with secondary study parameters

Age of patient

No significant differences were found for the occurrence of craze lines/cracks ($P = 0.848$), frosted dentine

Table 1 Distribution of treated teeth (n = 138) and treated roots (n = 168), and frequency of canals and isthmuses per group of roots

Jaw	Teeth	Roots		Roots with single canal	Roots with two canals	Roots with three canals	Roots with isthmus
			N (%)	N (%)	N (%)	N (%)	N (%)
Maxilla	Central incisors (n = 17)		17 (10.3)	16 (94.1)	1 (5.9)	–	–
	Lateral incisors (n = 20)		20 (11.9)	19 (95.0)	1 (5.0)	–	–
	Canines (n = 6)		6 (4.3)	6 (100)	–	–	–
	First premolars (n = 13)	Only one root	11 (6.5)	6 (54.5)	5 (45.5)	–	4 (36.4)
		Buccal root	2 (1.2)	2 (100)	–	–	–
	Second premolars (n = 16)		16 (9.5)	6 (37.5)	10 (62.5)	–	8 (50.0)
	First molars (n = 15)	Mesio-buccal root	14 (8.3)	8 (57.1)	6 (42.9)	–	6 (42.9)
		Disto-buccal root	9 (5.4)	9 (100)	–	–	–
		Palatal root	2 (1.2)	2 (100)	–	–	–
	Second molars (n = 5)	Mesio-buccal root	5 (3.0)	1 (20.0)	4 (80.0)	–	3 (60.0)
		Disto-buccal root	3 (1.8)	3 (100)	–	–	–
	Total maxillary teeth (n = 92)	Maxillary roots	105 (62.5)	78 (74.3)	27 (25.7)	–	21 (20.0)
Mandible	Central incisors (n = 4)		4 (2.4)	3 (75.0)	1 (25.0)	–	–
	Lateral incisors (n = 2)		2 (1.2)	2 (100)	–	–	–
	Canines (n = 1)		1 (0.6)	1 (100)	–	–	–
	First premolars (n = 1)		1 (0.6)	1 (100)	–	–	–
	Second premolars (n = 5)		5 (3.0)	5 (100)	–	–	–
	First molars (n = 30)	Mesial root	26 (15.5)	1 (3.8)	22 (84.6)	3 (11.5)	23 (88.5)
		Distal root	21 (12.5)	14 (66.7)	7 (33.3)	–	7 (33.3)
	Second molars (n = 3)	Mesial root	2 (1.2)	1 (50)	1 (50)	–	1 (50.0)
		Only one root	1 (0.6)	1 (100)	–	–	–
	Total mandibular teeth (n = 46)	Mandibular roots	63 (37.5)	29 (46.0)	31 (49.2)	3 (4.8)	31 (49.2)
	Total teeth (n = 138)	Total roots	168 (100)	107 (63.7)	58 (34.5)	3 (1.8)	52 (31.0)

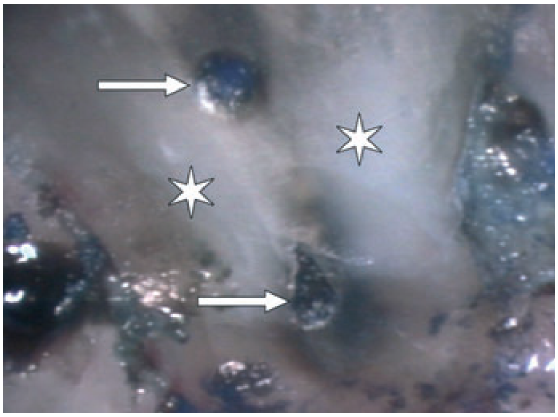

Figure 3 Mandibular lateral incisor with two canals (⇨). In addition, frosted dentine (☆) can be seen on mesial and distal aspects of the cut root face.

(P = 0.559) or gaps (P = 0.836), respectively, when comparing younger (<45 years) and older (≥45 years) patients (Table 2).

Type of treated tooth

Roots of premolars had significantly more craze lines/cracks than roots of anterior teeth (P = 0.006) and molars (P = 0.000). With regard to frosted dentine, roots of premolars (P = 0.027) and molars (P = 0.001) were significantly more frequently affected than roots of anterior teeth. The occurrence of gaps was similar (no statistically significant differences) for all types of treated roots.

Presence or absence of post/screw

No significant difference was found for craze lines/cracks (P = 0.166), for frosted dentine (P = 0.156) or for gaps (0.189) when their occurrence was correlated with the presence or absence of a post/screw.

Discussion

The objectives of the present clinical study were (i) to perform endoscopic inspection of the cut root face following root-end resection in teeth undergoing apical surgery for the presence of macro- and microfindings and (ii) to correlate the occurrence of these findings with the patient's age, type of treated tooth and presence/absence of a post/screw. Data acquisition was based on images captured with a camera mounted on a rigid endoscope. The advantages of endoscopy compared to surgical microscopy in apical surgery mainly include the rapid and easy

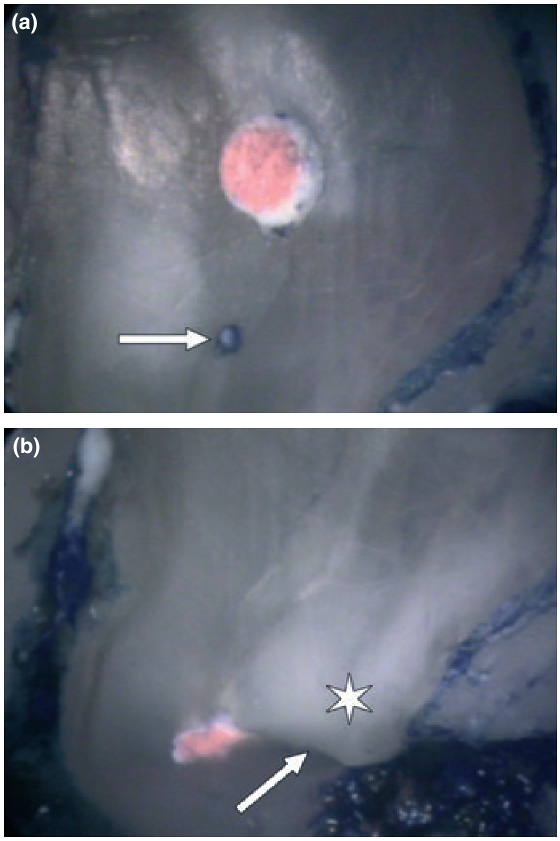

Figure 4 (a) Buccal part of the cut root face of a mesial root of a mandibular first molar. An unfilled accessory 'third' canal (⇨), stained with methylene blue, is present lingual to the buccal canal that is filled. (b) The lingual part of the cut root face of the same root shows the filled lingual canal and a craze line (⇨) originating from the lingual canal and running to the distal root aspect. The craze line also delineates frosted dentine (☆) on the distal aspect.

adjustment of the viewing angle, and the direct viewing of the cut root face (no mirrors are required). In addition, the endoscope is a readily transportable, versatile and expandable system. A shortcoming of the endoscope is the repeated necessity of cleaning the lens because of fogging (patient's breath) or soiling with blood, tissue or cooling agent (von Arx *et al.* 2002).

An experimental study demonstrated the superiority of endoscopy versus other visualization techniques (P = 0.0007) for correct identification of artificially created dentinal cracks in resected root ends of extracted human maxillary incisors (Slaton *et al.* 2003). The accuracy of correct identification was

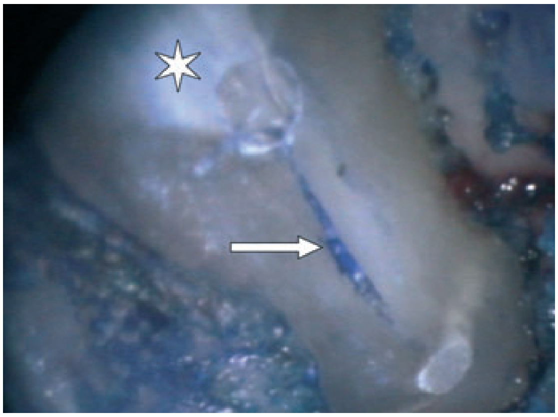

Figure 5 Cut root face of a mesial root in a mandibular first molar. The two filled root canals are connected by an unfilled isthmus (⇨) that is stained with methylene blue. Frosted dentine (☆) is visible in the buccal segment.

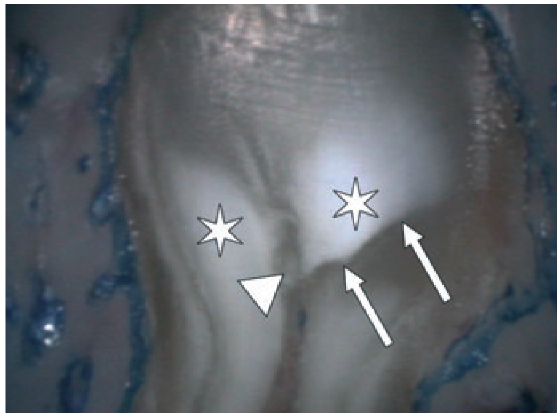

Figure 7 Mesial root of a mandibular first molar with a craze line (⇨) that is stained with methylene blue. Frosted dentine (☆) originating from an unfilled buccal canal (Δ). The craze line runs diagonally and demarcates frosted dentine (☆) that expands to the buccal segment.

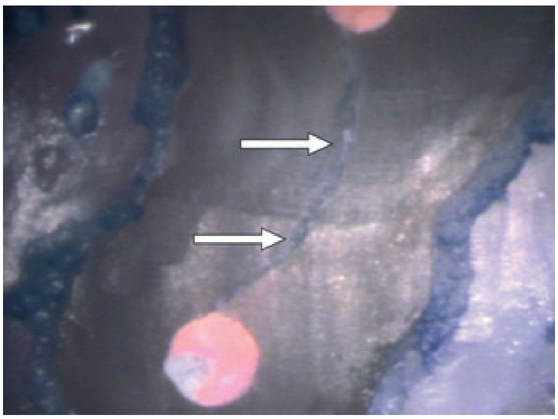

Figure 6 Cut root face of a maxillary first premolar with two filled canals. The connecting isthmus (⇨) is stained with methylene blue.

39% for unaided/corrected vision, 45% for loupes, 53% for the microscope and 58% for the endoscope. However, the authors concluded that even with the endoscope, the accuracy (sensitivity 53%, specificity 63%) of identifying dentinal cracks was lower than expected. They further speculated that the low accuracy was caused by the relatively low (×35) magnification used and the type of endoscope (fibre-optic bundle containing glass fibres for transmission of light and images). The resolution capacity of a flexible endoscope is determined by the number of fibres contained in the image transmission system. In contrast, the resolution capacity of a rigid endoscope (as used in the present study) is limited only by the wavelength and is therefore considerably higher than the resolution of a flexible endoscope (Reling 1989). In fact, relatively high accuracy in diagnosis of incomplete and complete canal cracks at resected root ends was reported in an experimental study comparing a rigid endoscope and scanning electron microscopy (von Arx *et al.* 2003a). An experimental study comparing microscopy (×16 and ×24) and endoscopy (×8 and ×64) with scanning electron microscopy for detection of dentinal cracks after root-end resection reported the highest sensitivity (78.9%) for endoscopy ×64 (von Arx *et al.* 2010).

Identification of unnegotiated canals and isthmuses is the first and most important step after root-end resection. If these findings remain undetected, recurrence of infection and failure of apical surgery are unavoidable. A special problem is the presence of a hairline-type connection between two canals, the so-called type-II isthmus according to the classification of Hsu & Kim (1997). The present study clearly demonstrated that the presence of an isthmus is a frequent finding in roots with two canals in posterior teeth, in particular in mesial roots of mandibular first molars. This is in accordance with previous data from laboratory studies (Weller *et al.* 1995, Hsu & Kim 1997, Tam & Yu 2002, Teixeira *et al.* 2003). The majority of those hairline-type isthmuses are 'partial isthmuses' (Weller *et al.* 1995, Teixeira *et al.* 2003), which are partially obliterated by calcified or sclerotic dentine (Mannocci *et al.* 2005). It is also noteworthy that in the present study, an isthmus was found in 50% of maxillary

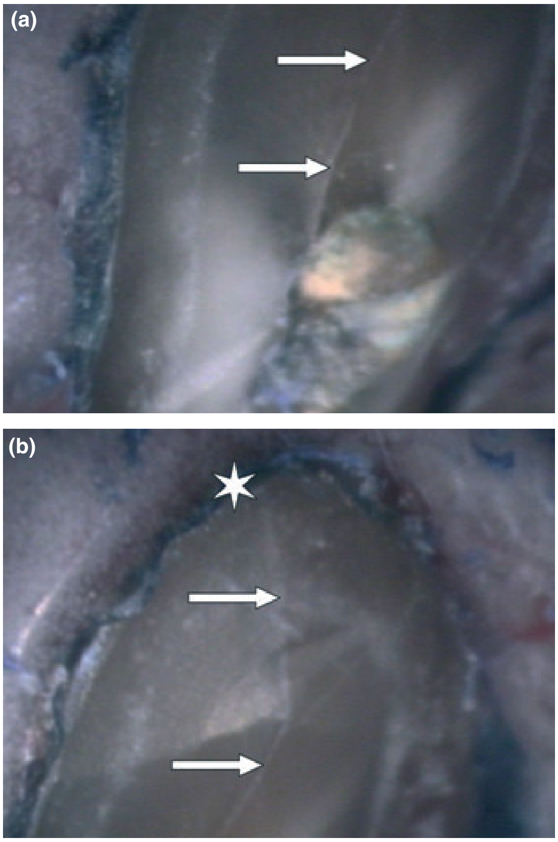

Figure 8 (a) Cut root face of a mandibular lateral incisor with a complete canal crack (⇨) progressing from the partially filled root canal towards the buccal segment. (b) The crack (⇨) crosses the cut root face in a bucco-lingual direction towards the periodontal ligament space (☆) on the buccal root aspect.

second premolars. Therefore, the recognition and management of the canal isthmus is an important factor that improves the success rate of apical surgery in posterior teeth (Rubinstein & Kim 1999, 2002). Interestingly, the present material also demonstrated the presence of two canals in three incisor teeth (two maxillary incisors, one mandibular incisor) at the resected root surface. The use of methylene blue is highly recommended because the dye stains the (necrotic) tissue residing in unnegotiated canals, and accessory canals become visible.

Only 16 roots had a craze line or crack. To date, there is only one clinical study evaluating cracks in root after root-end resection (Morgan & Marshall 1999). That study examined the cut faces of 25 roots with scanning electron microscopy (SEM), using resin replicas fabricated from *in vivo* impressions of the resected root surfaces. There was no evidence of cracks after root resection. One incomplete canal crack was observed with SEM only after ultrasonic root-end preparation. It is noteworthy that this crack was not detected clinically with either methylene blue dye or the operating microscope. This calls for the use of higher magnification, such as the endoscope. An *ex vivo* study comparing microscopy (×16 and ×24) and endoscopy (×8 and ×64) for detection of root-end dentinal cracks showed higher sensitivity for the endoscope ×64 compared to the other tested visual aids. However, the sensitivity never surpassed 80% (78.9% for complete canal cracks and 64.7% for incomplete canal cracks) (von Arx *et al.* 2010). The clinical significance of canal cracks is speculative, but they may be of concern if there are residual bacteria present, or if coronal leakage occurs, with subsequent bacterial colonization (Wright *et al.* 2004). A recent experimental study on extracted human teeth demonstrated that cracks originating from the root canal adversely affected the seal of root-end filling materials (de Bruyne & de Moor 2008). Another concern is that a canal crack may leak during function or may progress to a vertical root fracture (Morgan & Marshall 1999, de Bruyne & de Moor 2005). Hence, it is not clear whether an incomplete canal crack should be included in the preparation of the root-end cavity. Likewise, it is debatable whether a complete canal crack (or even an incomplete canal crack) is a contraindication for apical surgery. The present study did not assess if root canal preparations were centred or not centred in the root cross section, and if this aspect influenced crack observation for the following reasons: (i) the analysis was performed only at one specific root level, i.e. at the resection level, (ii) the original root canal(s) may not have been in the centre of the root and (iii) different bevels of resection planes might influence such an analysis.

Grooves or irregularities caused by the bur on the resected root end can cause a change in the reflection of light, creating the illusion of a crack (Wright *et al.* 2004). Moreover, the difference between a craze line and a crack is not well defined and may be interpreted differently by clinicians.

In the present study, significantly more craze lines/cracks were seen in premolars than in other teeth. The reason for this remains unclear. The presence of a post/screw was associated with a higher occurrence of craze lines/cracks (six of 10 premolars with craze lines/cracks had a post/screw). In contrast, the age of the patient was not associated with the occurrence of craze lines/cracks. Interestingly, when a craze line/crack was

Table 2 Presence of microfindings per group of roots related to secondary study parameters (n = 168)

	Microfindings		
	Craze line/cracks	Frosted dentine	Gaps
	N (%)	*N* (%)	*N* (%)
Age of patient			
Roots in patients <45 years (*n* = 69)	6/69 (8.7)	57/69 (82.6)	57/69 (82.6)
Roots in patients ≥45 years (*n* = 99)	10/99 (10.1)	77/99 (77.8)	83/99 (83.8)
Total (*n* = 168)	16/168 (9.5)	134/168 (79.8)	140/168 (83.3)
Type of tooth			
Roots of anterior teeth[a] (*n* = 50)	3/50 (6.0)*	31/50 (62.0)[†,‡]	40/50 (80.0)
Roots of premolars (*n* = 35)	10/35 (28.6)*,**	30/35 (85.7)[†]	30/35 (85.7)
Roots of molars (*n* = 83)	3/83 (3.6)**	73/83 (88.0)[‡]	70/83 (84.3)
Total (*n* = 168)	16/168 (9.5)	134/168 (79.8)	140/168 (83.3)
Presence of post/screw			
Roots with post/screw (*n* = 56)	8/56 (14.3)	41/56 (73.2)	50/56 (89.3)
Roots without post/screw (*n* = 112)	8/112 (7.1)	93/112 (83.0)	90/112 (80.4)
Total (*n* = 168)	16/168 (9.5)	134/168 (79.8)	140/168 (83.3)

[a]Incisors and canines.
Statistically significant differences: *P = 0.006; **P = 0.000; [†]P = 0.027; [‡]P = 0.001.

Table 3 Distribution of craze lines/cracks (n = 36), frosted dentine (n = 733) and gaps (n = 967) per root segment

	Craze lines/cracks		Frosted dentine		Gaps	
	N (%)	Exact 95% confidence interval (lower/upper boundary)	*N* (%)	Exact 95% confidence interval (lower/upper boundary)	*N* (%)	Exact 95% confidence interval (lower/upper boundary)
Buccal segment (sectors No. 11, 12, 1)	23 (63.9)	46.2/79.2	290 (39.6)	36.0/43.2	287 (29.7)	26.8/32.7
Mesial segment (sectors No. 2, 3, 4)	2 (5.6)	0.7/18.7	157 (21.4)	18.5/24.6	186 (19.2)	16.8/21.9
Lingual segment (sectors No. 5,6,7)	10 (27.8)	14.2/45.2	176 (24.0)	21.0/27.3	268 (27.7)	24.9/30.7
Distal segment (sectors No. 8, 9, 10)	1 (2.8)	0.0/14.5	110 (15.0)	12.5/17.8	226 (23.4)	20.7/26.2
Total	36 (100)		733 (100)		967 (100)	
P value (chi-squared goodness of fit test)	<0.0001		<0.0001		<0.0001	

present, it was more likely to be found in the buccal segment, particularly in premolars. This phenomenon has also been reported in the literature, with most fracture lines observed in a bucco-lingual direction (Lam *et al.* 2005, Versluis *et al.* 2006). The development of cracks has been associated with root canal preparation and filling, or post placement (Boyarsky & Davis 1992, Onnink *et al.* 1994). Whilst Versluis *et al.* (2006) found high concentrations of intracanal stress and subsequent fractures at the buccal and lingual canal extensions of oval canals when placed under compaction load, they also observed that after preparation, the loads were more equally distributed, even in roots where fins remained. Lam *et al.* (2005) discovered that taper and apical size did not increase susceptibility to fracture in treated roots. However, Kim *et al.* (2010), showed that less flexible file designs lead to higher stress in curved canals and raised the risk of preparation errors that may lead to apical cracking. Other cracks may be inherent in the root and are not caused by preparation of the root canal system (Altshul *et al.* 1997). In summary, the microfinding 'crack' at the cut root face remains a problem for clinical diagnosis and management. The crack geometry (length, incomplete versus complete) may also be different depending on the plane of sectioning along the root.

Frosted dentine was another microfinding studied. The term describes a change in the colour of dentine from the characteristic yellow or grey to white. Slaton *et al.* (2003) assessed artificially created dentinal cracks in resected root ends of extracted human maxillary incisors. With a video microscope, they observed the

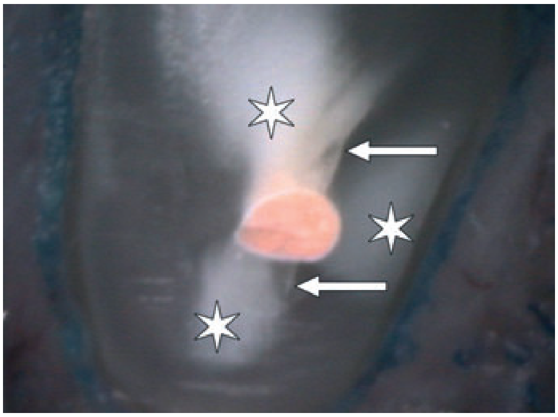

Figure 9 Frosted dentine (☆) of buccal, mesial and lingual segments are visible in a maxillary lateral incisor. Two incomplete canal cracks (⇨) that run in a bucco-lingual direction can also be seen.

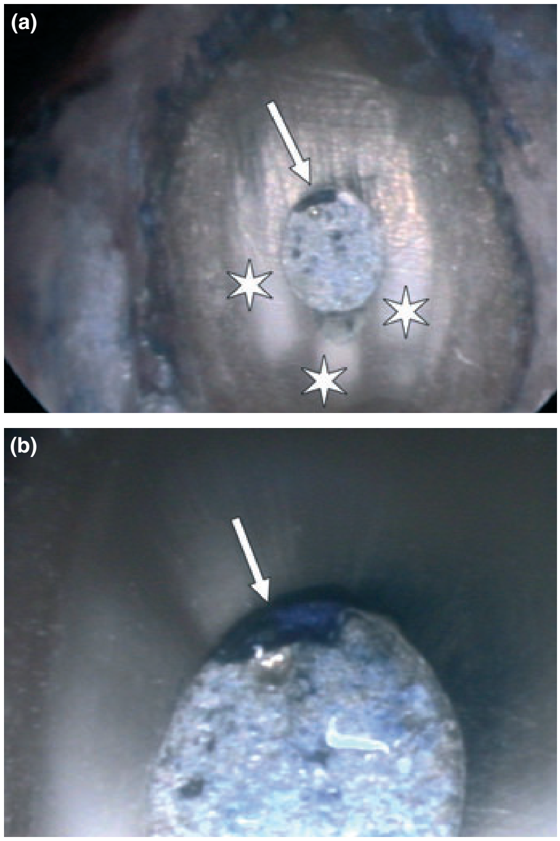

Figure 10 (a) A large gap (⇨) (stained with methylene blue) between the root filling material and the dentinal wall can be seen in a maxillary canine. Frosted dentine (☆) is visible on mesial, distal and lingual aspects of the cut root face. (b) Higher magnification of (a) shows leakage (⇨) at the site of the stained gap.

cracks as they developed in the apical dentine. As a load was being applied, the dentine around the area of strain became opaque or frosted in appearance before a crack developed. The authors speculated that the frosted dentine was caused by the formation of many microscopic cracks that had not yet coalesced into a macro-crack. In the present study, frosted dentine was observed in 134 of 168 roots (79.8%) and was more frequently found in the buccal segment (39.6%) compared to the other root segments (15–24%).

The regions of the cut root surface containing frosted dentine in the present study corresponded with the root dentine located at similar canal levels that was differentially stained by a dye of larger molecular size using a trichrome stain in histological sections (Susin *et al.* 2010). Thus, an alternative explanation for the observation of frosted dentine is that the dentinal tubules in these regions are patent instead of being filled with sclerotic casts (Paqué *et al.* 2006). Similar sclerotic casts in the apical third of the canal walls have been illustrated by Tay *et al.* (2007). It is well known that dentine permeability is markedly reduced in the presence of dentinal tubule occlusion (Senawongse *et al.* 2008, Komabayashi *et al.* 2010). As the dentine is stressed during load application, such as in the study by Slaton *et al.* (2003), water may have moved out of the surface layer of the partially severed tubules and evaporated, thereby producing an opaque or frosted appearance. In the present study, air-drying of the severed root end prior to create a clear field for examination and photography or evaporation could have likewise removed water from the open tubules. Replacement of the water in patent dentinal tubules with air changes the refractive index of the tubules and generates an overall frosty appearance. Such a phenomenon should not occur in those regions containing sclerotic dentine, as the tubules are filled with sclerotic casts that have a refractive index similar to that of the adjacent intertubular radicular dentine. Thus, the interpretation of frosted dentine by Slaton *et al.* (2003) as regions with increased strain and increased risk of developing a crack or a root fracture is unfounded and should be challenged. Interestingly, roots of premolars and molars presented more frequently with frosted dentine than roots of anterior teeth. This may simply represent that the premolars and molars contain more patent tubules than the anterior teeth, particularly along the bucco-lingual direction (Susin *et al.* 2010). Neither the age of the patient nor the presence/absence of a post/screw was found to be associated with the development of frosted dentine in the present study. Because current data do not prove a relationship between frosted dentine and subsequent crack formation, a cautious approach is recommended to avoid overtreatment, such as enlarged root-end preparations or tooth extractions. On the contrary, the mechanical properties of sclerotic dentine have recently been shown by nanoindentation and nanoscratch testing to be inferior to those of normal dentine (Martín *et al.* 2010). Hence, it is proposed that one has to exhibit caution when using ultrasonic instruments for preparing root-end cavities in the event that non-frosted apical root dentine is encountered to minimize the chance of creating cracks in these regions. This hypothesis has to be validated in future studies.

One of the primary causes of failed root canal treatment is inadequate filling of the root canal system; in other words, the presence of gaps between the root canal filling material and the dentinal walls. Following coronal leakage, bacteria may spread along these gaps and cause periapical re-infection. The microfinding 'gap' was the most frequently seen anomaly (83.3%) at the resection plane in the present study. No correlation was found between gaps and the age of the patient, the type of treated tooth or the presence/absence of a post/screw. Gaps were more often located in the buccal (29.7%) and lingual (27.7%) segments than in the mesial (19.2%) and distal (23.4%) segments. One may speculate that the instrumentation and/or filling of canals is easier to perform in the mesial and distal areas of the canals compared to the buccal and lingual zones; hence, gaps appear to be more frequently produced in the buccal and lingual aspects of the root canals. Another potential reason is that the buccal and lingual aspects represent locations that contain a higher incidence of canal fins, as a rotary instrument is likely to create a round preparation within an oval-shaped canal (Metzger *et al.* 2010).

Conclusions

Within the limits of this clinical observational study assessing macro- and microfindings at the cut root face following root-end resection during apical surgery, the following conclusions can be drawn:

Multiple canals per root were mainly found in premolars and molars, but not exclusively.

Mesial roots of mandibular first molars had the highest frequency of a canal isthmus (in 88.5%).

Craze lines or cracks were an infrequent finding (9.5%), mostly oriented in a bucco-lingual direction and mostly seen in premolar roots.

Roots with a post/screw demonstrated twice as many craze lines or cracks (14.3%) as roots without a post/screw (7.1%).

Frosted dentine was found in 79.8% of treated roots; it was observed more frequently in buccal and lingual root segments (63.6%) than in mesial and distal root segments (36.4%).

Roots of molars (88%) and premolars (85.7%) demonstrated a greater occurrence of frosted dentine than roots of anterior teeth (62%).

The present study could not demonstrate a correlation of crack formation and frosted or non-frosted dentine, but further studies are warranted to clarify this open question.

A gap between the existing root canal filling material and the dentinal wall was the most frequently observed anomaly at the cut root face (83.3%).

Gaps were more often seen in buccal and lingual segments than in mesial and distal segments.

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