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Thomas von Arx, Paola Maldonado, Michael M. Bornstein

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Occurrence of vertical root fractures after apical surgery: A retrospective analysis.

Thomas von Arx[a] (thomas.vonarx@zmk.unibe.ch)
Paola Maldonado[a] (paola.maldonado@students.unibe.ch)
Michael M. Bornstein[b] (michael.bornstein@unibas.ch)

[a]Department of Oral Surgery and Stomatology, School of Dental Medicine, University of Bern, Freiburgstrasse 7, CH-3010 Bern, Switzerland
[b]Department of Oral Health & Medicine, University Center for Dental Medicine Basel UZB, University of Basel, Mattenstrasse 40, CH-4058 Basel, Switzerland

Correspondence author: Prof. Dr. T. von Arx, Department of Oral Surgery and Stomatology, School of Dental Medicine, University of Bern, Freiburgstrasse 7, CH-3010 Bern, Switzerland.
Phone +41-31-632-2566
Fax +41-31-632-2503
Email thomas.vonarx@zmk.unibe.ch

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Occurrence of vertical root fractures after apical surgery: A retrospective analysis.

Abstract

Introduction

Vertical root fractures (VRFs) are among the most frequent causes of tooth loss, mainly of endodontically treated teeth. However, very little data is available about the occurrence of VRFs following apical surgery.

Methods

Patient charts from 864 patients with 1058 teeth treated with apical surgery (September 1999 to December 2018) were retrospectively evaluated, if a VRF had occurred after surgery. The following, possibly influencing factors were analyzed: sex and age, type of treated tooth, primary versus re-surgery, technique of root-end preparation, and timepoint of VRF diagnosis. Endpoints were either tooth extraction or the last follow-up.

Results

The study cohort (55% females, 45% males) had a mean age of 52 ±13.97 years (range 9 – 93 years). The overall rate of VRFs after apical surgery was 4% (42 out of 1058 teeth). Among these 42 teeth, 33.3% were mandibular first molars and 26.2% were maxillary second premolars. The most frequently affected root was the mesial root of mandibular first molars (28.6%). With regard to the study parameters, significant differences of VRF rates were only observed for the type of tooth treated.

Conclusions

A low VRF rate of 4% was observed in this study. VRFs commonly occurred in maxillary premolars and mandibular molars, with the mesial root of mandibular first molars affected most frequently. This is in line with previous reports about VRFs in endodontically treated teeth without additional apical surgery.

Keywords

Vertical root fracture; Apical surgery; Risk factor; Retrospective analysis.

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Introduction

Apical surgery, today also known as endodontic microsurgery, is a well-established treatment modality to preserve teeth with persistent or recurrent endodontic infection. In the last three decades, important diagnostic (three-dimensional radiography) and therapeutic inventions (surgical microscope, microtips for root-end cavity preparation, biocompatible root-end filling materials) have contributed to higher success rates of endodontic microsurgery compared to the traditional surgical technique[1-3]. Yet, the fact that a tooth treated with apical surgery has had previous endodontic and restorative or reconstructive therapy may jeopardize its long-term prognosis.

One major concern in dentistry is the occurrence of vertical root fractures (VRFs), mainly in association with root-canal treatment (RCT)[4-8]. However, the causes of VRFs include a variety of factors that are not limited to endodontic issues (Table 1)[4-14]. In almost every case, VRFs result in the extraction of the affected teeth. Indeed, VRFs are among the three most common causes of tooth loss – the other two are dental caries and periodontal disease[15,16]. Therefore, knowledge of the condition is important to avoid heroic attempts of endodontic and/or periodontal therapy[6,17].

In contrast to tooth cracks that originate in the crown, VRFs develop within the root. Therefore, VRFs are difficult to detect. VRFs usually develop slowly and unnoticed by the patient until clinical signs and symptoms become apparent[18]. Common diagnostic factors associated with VRFs include: isolated periodontal pocket > 5 mm, sinus tract close to gingival margin, periodontal swelling or abscess, spontaneous pain, and radiologic image of J-shaped or “halo” radiolucency[18-22]. However, according to a systematic review by Tsesis et al.[23], evidence-based data regarding the diagnostic accuracy of VRFs is still lacking.

The objective of this retrospective study was to analyze the occurrence of VRFs in a cohort of teeth that were treated with apical surgery. The null-hypothesis was that the VRF rates did not differ across the various tooth groups.

Materials and methods

Patient charts from 864 individuals with 1058 teeth treated with apical surgery (September 1999 to December 2018) were retrospectively evaluated, if a VRF had occurred after apical surgery. The surgical technique has been described previously in a number of papers[24-26]. All surgeries were performed by a single surgeon. The charts were evaluated by a postgraduate student not involved in the treatment of the patients. The study was approved by the Institutional Review Board (KEK # 2020-00824).

Surgical technique

All surgeries were carried out in a dedicated surgical room, under local anesthesia, and using a surgical microscope. Triangular or trapezoidal flaps were raised and osteotomy performed with rotary burs to access the root apices. Following debridement of the pathological tissue and root-end resection, hemostasis was obtained. The cut root face was stained with methylene blue and was inspected with a rigid endoscope. Subsequently, root-end cavities were prepared and obturated with one of the following techniques: microtips either driven by sonic, ultrasonic or piezo devices for root-

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end filling (SuperEBA, MTA, or BCRRM), or with rotary instruments in case of root-end sealing (adhesive composite). After thorough wound cleansing, the flap was repositioned and sutured.

Follow-up

Patients were recalled 1, 5 and 10 years after apical surgery. Due to the retrospective nature of the study, follow-up periods differed among the included individuals. Endpoints were either tooth extraction or the longest follow-up.

Diagnosis of VRFs

The presence of a VRF was confirmed clinically (staining with methylene blue, Fig. 1F)) and/or histologically (serial cross-sectioning of roots, Fig. 1G/H and Fig. 2L/M) of the extracted or surgically removed teeth. Details about the histologic processing have been reported previously[18].

Statistics

Chi-square test or Fisher's exact test was performed to investigate the impact of different factors (Table 2) on the occurrence of VRFs individually. If a significant result was found, further comparisons of VRF proportions were done using Bonferroni adjustment. All of the tests performed were two-tailed tests with a 0.05 significance level. The analyses were done using IBM SPSS Statistics for Windows Version 26 (IBM Corp. Armonk, NY, USA).

Results

The study sample (55% females, 45% males) had a mean age of 52 ±13.97 years (range 9 – 93 years). All 1058 studied teeth had a minimal follow-up of 1 year; 466 were followed for 5 years and 124 teeth for 10 years. The overall rate of VRFs after apical surgery was 4% (Table 2). Among these 42 teeth, 33.3% were mandibular first molars and 26.2% were maxillary second premolars (Fig. 1 and 2). The most frequently affected root was the mesial root of mandibular first molars (28.6%).

Males and females presented similar occurrence rates of VRFs. However, individuals from the two older age groups had higher rates of VRFs compared to those from the two younger age groups, but without reaching statistical significance ($p = 0.121$). Considering the treated teeth, maxillary premolars demonstrated the highest VRF rate (9.3%), whereas maxillary anteriors had the lowest rate (0.6%). This difference was found to be of statistical significance ($p < 0.001$). After Bonferroni adjustment, maxillary premolars, mandibular anteriors and mandibular molars all exhibited a significant higher VRF proportion than maxillary anteriors (Table 3). Therefore, the null-hypothesis was rejected.

With regard to the type of surgery, VRFs tended to occur more frequently in re-surgeries compared to first-time surgeries. Some differences were also noted when the VRF rate was calculated concerning the method of root-end preparation. The use of sonic-driven microtips resulted in a higher VRF rate compared to the other root-end preparation techniques. But overall, the technique of root-end preparation did not appear to have a significant impact ($p = 0.961$). Two thirds of VRFs occurred within the first year after apical surgery (28 out of 42).

Discussion

The present study retrospectively assessed the occurrence of VRFs following apical surgery. Previous pertinent studies have looked at VRF rates in extracted teeth or in endodontically treated teeth, but not specifically in teeth treated with apical surgery (Table 4).

In the present cohort, the overall rate of VRFs after apical surgery was low (4%), similar to the 4.3% reported in a study by Riis et al.[28]. In contrast, the latter study found 12.5% of VRFs in teeth that had been retreated with conventional RCT. In a study of 200 extracted teeth with VRFs, only 6.5% of those teeth had been treated with apical surgery, but 31.3% had undergone an endodontic retreatment, and 62.3% had a combination of endodontic retreatment and apical surgery[29]. Therefore, endodontic retreatment appears be a risk factor for the development of VRFs. This assumption was further substantiated in an experimental study by Shemesh et al.[9]. Root-canal retreatment procedures significantly damaged the roots and resulted in cracks and fractures. In a clinical study, Tawil et al.[30] evaluated the presence of cracks following root resection using methylene blue and LED transillumination during apical surgery of 122 teeth. Results were correlated with the previous RCT: primary versus retreatment. Retreated teeth presented significantly ($p < 0.001$) more cracks (64.7%) compared to teeth with primary root-canal treatment (22.5%). The authors concluded that a microsurgical approach toward non-healed root canals with a good coronal seal might be a more prudent approach over endodontic retreatment. In the present study, the information about the status of endodontic retreatment prior to apical surgery was not available.

With regard to sex, some studies have reported a higher rate of VRFs in endodontically treated teeth in females than in males[19,20,29]. In the present study, no such difference was observed. Previous studies also correlated the occurrence of VRFs with age. An analysis of 227 teeth with VRFs found that 86.8% of the evaluated teeth were from patients older than 40 years[17]. Another study demonstrated that patients older than 40 years had a significantly higher rate of VRFs compared to patients younger than 40 years (OR = 6.3; 95% CI, 1.91–185.53)[19]. The present study also found higher VRF rates in patients older than 40 years compared to younger patients.

When considering tooth groups with a predilection for development of VRFs, the data from the literature is consistent and unambiguous (Table 5). Maxillary premolars (22.8 – 38.1%) and mandibular molars (12.5 – 44.6%) generally constitute the highest proportions among teeth with VRFs. Pradeep Kumar et al.[19] retrospectively analyzed 197 root-filled (no posts!) and crowned teeth with suspected VRF. Posterior teeth had a significantly higher rate of VRFs than anterior teeth (OR = 5.22; 95% CI, 1.79–109.67). In a study of VRFs in Chinese patients, VRFs occurred mostly in mandibular molars (44.6%) followed by maxillary premolars (24.6%). The occurrence of VRFs in the mandibular molars was 6 times higher than that in the maxillary molars. VRFs were mostly observed in the mesial root of mandibular molars (57.14%) in both endodontically and non-endodontically treated teeth[20]. Also in the present study, the mesial root of mandibular molars was the most frequently affected root. Tamse et al.[31] noted that mesial roots of mandibular molars had fractures more often (17 of 22) than distal roots. Similarly, Chan et al.[12] reported a predilection of 3:1 comparing mesial and distal roots of mandibular molars with regard to VRFs. The narrow mesio-distal root anatomy as well as the presence of an isthmus, both typical features of mesial roots of mandibular molars, are considered predisposing factors for VRFs[33].

When the technique of ultrasonic root-end preparation was introduced, there was some concern about an elevated risk for crack/fracture formation due to the oscillating microtips within the fragile portion of the resected root apex[34]. However, *in vitro* studies using extracted teeth for evaluation of crack formation in conjunction with ultrasonic root-end preparation have limitations: extraction forces, storage and laboratory conditions, as well as the absent cushioning effect of the periodontium may distort the results. In fact, *ex vivo* studies in cadavers have demonstrated less crack development in cadaveric teeth compared to extracted teeth[35,36]. It appears that the periodontal ligament and the surrounding bone have the capacity to attenuate the effects of ultrasonic preparation on crack formation[37].

Two clinical studies have evaluated crack formation following ultrasonic root-end preparation[37,38]. Morgan & Marshall[38] used *in vivo / in situ* impressions after root-end resection and again after ultrasonic root-end preparation of 25 roots in 20 patients. There was no evidence of cracks after root-end resection, and only one incomplete canal crack was observed after root-end preparation. Tawil[37] assessed 84 teeth during apical surgery with transillumination of root apices following root-end resection as well as after ultrasonic root-end preparation. In intact roots, root-end preparation was safe without new crack formation. However, in roots with preexisting cracks, 54% of partial defects were propagated into full defects by ultrasonic root-end preparation.

Some authors have evaluated if a post presents a risk factor for a VRF. In a study of 944 root-filled teeth with endodontic failures, VRFs occurred significantly more frequently ($p < 0.001$) in teeth with posts (16.2%) compared to teeth without posts (1.2%). Furthermore, threaded or cast posts were significantly more involved than fiber, silica or carbide posts ($p < 0.001$)[21]. Riis et al.[28] evaluated long-term survival (> 10 years) of teeth after surgical or nonsurgical endodontic retreatment. VRFs were significantly ($p = 0.036$) more frequent in the nonsurgical group when retreatment included post removal. In the present study, it was not possible to assess whether teeth treated with apical surgery had a post or screw due to the retrospective nature of the analysis.

With regard to the period from apical surgery to VRF diagnosis, 66.7% of the VRFs occurred within 1 year after surgery. In a retrospective study of 944 teeth subjected to apical surgery, the follow-up duration (< 1 year vs. 1-5 years vs. > 5 years) since endodontic treatment did not have a significant relation with the occurrence of VRFs[21]. In another retrospective evaluation of 197 endodontically treated teeth with suspected VRFs, a mean postoperative time period of 4.35 ±1.96 years was reported before the presentation of VRFs[19].

In conclusion, a low VRF rate of 4% was calculated for 1058 teeth treated with apical surgery. Highest risk rates of VRFs were observed in maxillary premolars and mandibular molars, with the mesial root of mandibular first molars affected most frequently. Based on the present findings, apical surgery seems not to result in a higher rate of VRFs than conventional RCT. However, due to the retrospective nature of the analysis and the limited number of teeth with VRFs, the results must be interpreted with caution.

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References

1. Setzer FC, Shah SB, Kohli MR, et al. Outcome of endodontic surgery: A meta-analysis of the literature – part 1: Comparison of traditional root-end surgery and endodontic microsurgery. J Endod 2010;36:1757-65.

2. Tsesis I, Rosen E, Taschieri S, et al. Outcomes of surgical endodontic treatment performed by a modern technique: An updated meta-analysis of the literature. J Endod 2013;39:332-9.

3. Tortorici S, Difalco P, Caradonna L, et al. Traditional endodontic surgery versus modern technique: A 5-year controlled clinical trial. J Craniofac Surg 2014;25:804-7.

4. Fuss Z, Lustig J, Katz A, et al. An evaluation of endodontically treated vertical root fractured teeth: Impact of operative procedures. J Endod 2001;27:46-8.

5. Shemesh H, Wesselink PR, Wu MK. Incidence of dentinal defects after root canal filling procedures. Int Endod J 2010;37:995-1000.

6. Haueisen H, Gärtner K, Kaiser L, et al. Vertical root fractrure: Prevalence, etiology, and diagnosis. Quintessence Int 2013;44:467-74.

7. Ossareh A, Rosentritt M, Kishen A. Biomechanical studies on the effect of iatrogenic dentin removal on vertical root fractures. J Conserv Dent 2018;21:290-6.

8. Pradeep Kumar AR, Shemesh H, van Loveren C, et al. Impact of apical extent of root canal filling on vertical root fracture: A case-control study. Int Endod J 2019;52:1283-9.

9. Shemesh H, Roeleveld AC, Wesselink PR, et al. Damage to root dentin during retreatment procedures. J Endod 2011;37:63-6.

10. Garcia-Guerrero C, Parra-Junco C, Quijano-Guauque S, et al. Vertical root fractures in endodontically-treated teeth: A retrospective analysis of possible risk factors. J Investig Clin Dent 2018;9:e12273.

11. Jain A, Nikhil V, Bansal P. Effect of root canal preparation, obturation, and retreatment on the induction of dentinal microcracks: A microcomputed tomography study. J Conserv Dent 2018;21:521-5.

12. Chan CP, Lin CP, Tseng SC, et al. Vertical root fracture in endodontically versus nonendodontically treated teeth: A survey of 315 cases in Chinese patients. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1999;87:504-7.

Journal Pre-proof

13. Tang W, Wu Y, Smales RJ. Identifying and reducing risks for potential fractures in endodontically treated teeth. J Endod 2010;36:609-17.

14. Yan W, Montoya C, Oilo M, et al. Reduction in fracture resistance of the root with aging. J Endod 2017;43:1494-8.

15. Kishen A. Mechanisms and risk factors for fracture predilection in endodontically treated teeth. Endod Topics 2006;13:57-83.

16. Yoshino K, Ito K, Kuroda M, et al. Prevalence of vertical root fracture as the reason for tooth extraction in dental clinics. Clin Oral Investig 2015;19:1405-9.

17. Cohen S, Berman LH, Blanco L, et al. A demographic analysis of vertical root fractures. J Endod 2006;32:1160-3.

18. von Arx T, Bosshardt D. Vertical root fractures of endodontically-treated posterior teeth: A histologic analysis with clinical and radiographic correlates. Swiss Dent J 2017;127:14-23.

19. Pradeep Kumar AR, Shemesh H, Jothi Latha S, et al. Diagnosis of vertical root fractures in restored endodontically treated teeth: A time-dependent retrospective cohort study. J Endod 2016;42:1175-80.

20. Liao WC, Tsai YL, Wang CY, et al. Clinical and radiographic characteristics of vertical root fractures in endodontically and nonendodontically treated teeth. J Endod 2017;43:687-93.

21. Maddalone M, Gagliani M, Citterio CL, et al. Prevalence of vertical root fractures in teeth planned for apical surgery. A retrospective cohort study. Int Endod J 2018;51:969-74.

22. See WK, Ho JC, Huang CF, et al. The association between clinical diagnostic factors and the prevalence of vertical root fracture in endodontic surgery. J Formos Med Assoc 2019;118:713-20.

23. Tsesis I, Rosen E, Tamse A, et al. Diagnosis of vertical root fractures in endodontically treated teeth based on clinical and radiographic indices: A systematic review. J Endod 2010;36:1455-8.

24. von Arx T, Jensen SS, Hänni S. Clinical and radiographic assessment of various predictors for healing outcome 1 year after periapical surgery. J Endod 2007;33:123-8.

25. von Arx T, Hänni S, Bürgin W, et al. Clinical results of two different methods of root-end preparation and filling in apical surgery: Mineral trioxide aggregate and adhesive resin composite. J Endod 2010;36:1122-9.

Journal Pre-proof

26. von Arx T, Janner SF, Hänni S, et al. Bioceramic Root Repair Material (BCRRM) for root-end obturation in apical surgery – an analysis of 174 teeth after 1 year. Swiss Dent J 2020;130:390-6.

27. Fuss Z, Lustig J, Tamse A. Prevalence of vertical root fractures in extracted endodontically treated teeth. Int Endod J 1999;32:283-6.

28. Riis A, Taschieri S, del Fabbro M, et al. Tooth survival after surgical or nonsurgical endodontic retreatment: Long-term follow-up of a randomized clinical trial. J Endod 2018;44:1480-6.

29. Karygianni L, Krengel M, Winter M, et al. Comparative assessment of the incidence of vertical root fractures between conventional versus surgical endodontic retreatment. Clin Oral Invest 2014;18:2015-21.

30. Tawil PZ, Arnarsdottir EK, Phillips C, et al. Periapical microsurgery: Do root canal-retreated teeth have more dentinal defects? J Endod 2018;44:1487-91.

31. Tamse A, Fuss Z, Lustig J, et al. An evaluation of endodontically treated vertically fractured teeth. J Endod 1999;25:506-8.

32. Sugaya T, Nakatsuka M, Inoue K, et al. Comparison of fracture sites and post lengths in longitudinal root fractures. J Endod 2015;41:159-63.

33. Chai H, Tamse A. The effect of isthmus on vertical root fracture in endodontically treated teeth. J Endod 2015;41:1515-9.

34. von Arx T, Walker W. Microsurgical instruments for root-end cavity preparation following apicoectomy. A literature review. Endod Dental Traumatol 2000 ;16:47-62.

35. Calzonetti KJ, Iwanowski T, Komorowski R, et al. Ultrasonic root end cavity preparation assessed by an in situ impression technique. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1998;85:210-5.

36. de Bruyne MA, de Moor RJ. SEM analysis of the integrity of resected root apices of cadaver and extracted teeth after ultrasonic root-end preparation at different intensities. Int Endod J 2005;38:310-9.

37. Tawil PZ. Periapical microsurgery. Can ultrasonic root-end preparations clinically create or propagate dentinal defects? J Endod 2016;42:1472-5.

38. Morgan LA, Marshall JG. A scanning electron microscopic study of in vivo ultrasonic root-end preparations. J Endod 1999;25:567-70.

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Figures

Fig. 1 Referral of a 54-year-old female for apical surgery of her right maxillary first premolar.

(A) The preoperative periapical radiograph shows a diffuse apical radiolucency.

(B) The coronal CBCT-image demonstrates a distinct periapical lesion. A post is visible in the buccal root canal, and the roots are fused in the cervical portion, but separate in the apical part.

(C) The sagittal CBCT-image along the palatal root exhibits the periapical lesion.

(D) The postoperative periapical radiograph shows the resected roots and the root-end filling.

(E) Periapical radiograph taken 3 months after surgery: the patient complained of pain, and a small putrid swelling as well as an isolated deep pocket were noted on the buccal aspect of the tooth.

(F) The tooth was removed and stained with methylene blue confirming a VRF (black arrows) on the buccal aspect. Also note the deep indentation (white arrowhead) and the extent of the root-end filling (dotted white line).

(G) Histologic section (stain: toluidine blue - fuchsin) at the level of the root-end filling (*) demonstrates the VRF (black arrowhead) on the buccal aspect.

(H) Another section located more cervically shows the unfilled isthmus (white arrowhead) connecting the two filled root-canals. The VRF (black arrowhead) on the buccal aspect is also clearly visible.

Fig. 2 Referral of a 33-year-old female for apical surgery of her right mandibular first molar.

(A) The preoperative radiograph shows a periapical lesion associated with the mesial root.

(B) Postoperative periapical radiograph.

(C) Intraoperative endoscopic view of the cut root face following root-end resection.

(D) Intraoperative endoscopic view of the root-end cavity prepared with piezo-driven microtips.

(E) Intraoperative endoscopic view after root-end filling with MTA.

(F) The 1-year periapical radiograph shows excellent healing around the mesial root.

(G) The 5-year periapical radiograph demonstrates stable bone conditions around the mesial root, but the periodontal ligament space is slightly widened on the mesial aspect in the crestal part.

(H) The 10-year periapical radiograph clearly exhibits a J-shape lesion (widened periodontal ligament space) along the mesial aspect of the mesial root. The tooth was sensitive and a small swelling was clinically visible at the buccal aspect of the mesial root.

(I) The sagittal CBCT shows a distinct recurrent apical lesion at the mesial root (black arrow).

(J) The coronal CBCT demonstrates the bone loss of the buccal cortex (white arrowhead).

(K) In the axial CBCT (level of root-end filling), a dentinal defect is clearly visible (white arrow) in the buccal aspect of the mesial root.

(L) Histologic section (stain: toluidine blue - fuchsin) at the level of the root-end filling (*) demonstrates the dentinal defect (black arrow) on the buccal aspect of the mesial root. The fracture line appears to run along the root-end filling and reaches the lingual cementum (white arrow).

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(M) Another section located more cervically shows an isthmus (white arrowhead) connecting the two filled root-canals. The VRF (white arrows) completely crosses the mesial root. In the distal root, a crack (black arrow) is visible on the lingual aspect.

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Table 1

Risk factors for VRFs

Endodontic[4-11]	Occlusal[6,12,13]	Other[6,14]
- root canal preparation (mechanical and chemical) - (over-) filling - root canal retreatment - root canal posts (wedging effect, corrosion, expansion) - intracanal restoration	- occlusal overload (loss of mechanoreceptors) - excessive masticatory forces - chewing habits - abutment teeth (for removable or fixed partial dentures)	- aging (leading to reduction in damage tolerance of radicular dentin) - root morphology (oval cross-section) - Asian origin (teeth have predisposed morphology with protruding crowns and delicate roots)

VRFs = vertical root fractures

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Table 2

Study parameters and subcategories

Study parameter	Subcategories
Sex	- Male - Female
Age group	- ≤ 20 years - 21 – 40 years - 41 – 60 years - ≥ 61 years
Treated tooth	- Maxillary anteriors (incisors, canines) - Maxillary premolars - Maxillary molars - Mandibular anteriors (incisors, canines) - Mandibular premolars - Mandibular molars
Type of apical surgery	- Primary surgery - Re-surgery
Root-end preparation technique	- Sonic (Airscaler SONICflex and SONICretrotips, KaVo GmbH, Biberach, Germany) - Ultrasonic (Endo Success Apical Surgery Kit, Satelec Acteon, Merignac, France) - Piezo (Piezosurgery®, Mectron S.p.A., Loreto, Italy) - Rotary (round diamond burs in a straight hand piece
Timepoint of VRF diagnosis after apical surgery	- ≤ 1 year - 1.1 – 5 years - 5.1 – 10 years

VRF = vertical root fracture

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Table 3

Rates of VRFs per study parameter and subcategories (N = 1058)

Parameter	Subcategories	N treated	N VRFs	% VRFs	Statistics
All	-	1058	42	4.0	-
Sex	Male	498	21	4.2	Chi-square test:
	Female	560	21	3.8	p = 0.698
Age group	≤ 20 years	24	0	0	Chi-square test:
	21- 40 years	216	4	1.9	p = 0.121
	41- 60 years	559	23	4.1	
	≥ 60 years	259	15	5.8	
Treated tooth	Maxillary anterior	354	2	0.6[a,b,c]	Chi-square test:
	Maxillary premolar	172	16	9.3[a]	p < 0.001*
	Maxillary molar	164	4	2.4	
	Mandibular anterior	68	4	5.9[b]	
	Mandibular premolar	81	1	1.2	
	Mandibular molar	219	15	6.8[c]	
Type of surgery	Primary surgery	962	37	3.8	Fisher's exact test:
	Re-surgery	96	5	5.2	p = 1.000
Technique of root-end preparation	Sonic	292	15	5.1	Chi-square test:
	Ultrasonic	435	15	3.4	p = 0.691
	Piezo	117	4	3.4	
	Rotary	195	8	4.1	
	None	19	0	0	
Timepoint of VRF diagnosis	≤ 1 year	592	28	4.7	Chi-square test:
	1.1 - 5 years	342	12	3.5	p = 0.235
	5.1 - 10 years	124	2	1.6	

VRFs = vertical root fractures

*For overall significant results, same superscript letters denote a subset of categories showing significant differences of VRF rates from each other at the 0.05 level with Bonferroni adjustment

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Table 4

Frequency of VRFs in different studies

Author(s) year	Study design	N study sample	N VRFs	% VRFs	Comments
Fuss et al. 1999[27]	Prospective	147 endodontically treated teeth referred for extraction over a period of 6 months	16	10.9	Extracted teeth were inspected with loupes for VRFs
Maddalone et al. 2018[21]	Retrospective	944 root-filled teeth with endodontic failures subjected to endodontic microsurgery	68	7.2	32 VRFs detected preoperatively (no surgery), and 36 VRFs detected during surgery; *p < 0.001
		thereof 377 teeth with a post	61	16.2*	
		thereof 567 teeth without a post	7	1.2*	
		thereof 177 incisors/canines	14	7.9	
		thereof 480 premolars	40	8.3	
		thereof 287 molars	14	4.9	
Riis et al. 2018[28]	RCT	47 root-filled teeth with endodontic failures treated with endodontic surgery	2	4.3	VRFs detected during follow-up (~10 years) as reason for failure
		48 root-filled teeth with endodontic failures treated with endodontic retreatment	6	12.5	
See et al. 2019[22]	Retrospective	330 root-filled teeth with endodontic failures subjected to endodontic microsurgery	61	18.5	VRFs detected during surgery
Present study	Retrospective	1058 teeth that were treated with apical surgery	42	4.0	VRFs confirmed at the time of tooth extraction

RCT = randomized clinical trial
VRFs = vertical root fractures

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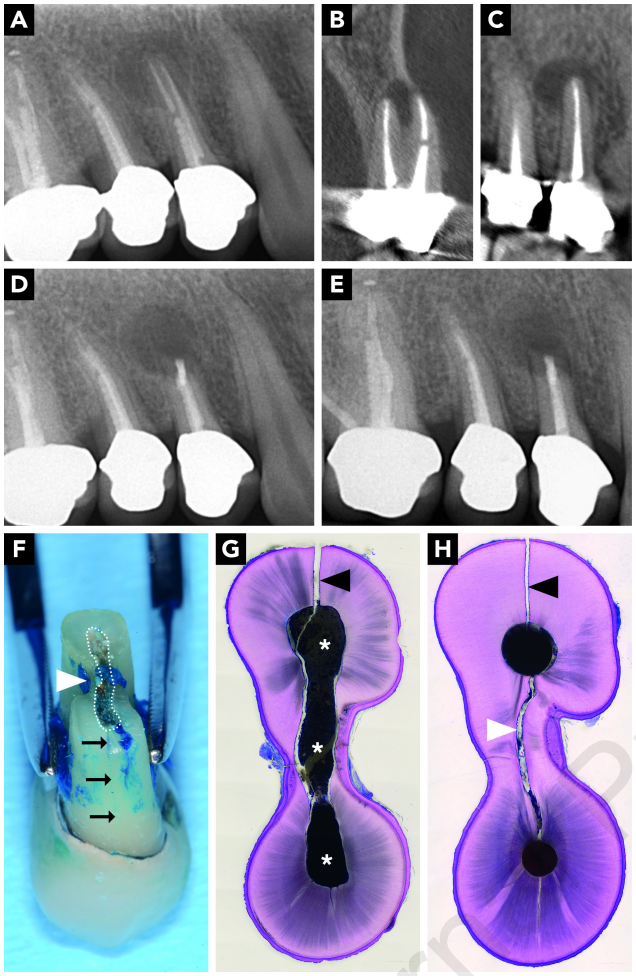
Table 5

Frequency distribution (%) among teeth with VRFs

			Maxilla			Mandible		
Author(s) Year	**Study sample**	**N sample**	**% incisors, canines**	**% premolars**	**% molars**	**% incisors, canines**	**% premolars**	**% molars**
Tamse et al 1999[31]	Extracted endodontically treated teeth	92	10.9	38.0	9.8	3.3	14.1	23.9
Cohen et al. 2006[17]	Extracted teeth: 12.3% were vital; 39% were non-vital and had no RCT; 48.7% had RCT	227	8.8	23.4	17.2	7.9		42.8
Karygianni et al. 2014[29]	Extracted endodontically treated teeth: 31.2% with endodontic retreatment; 6.5% with apical surgery; 62.3% with endodontic retreatment as well as apical surgery	200	Incisors: 12.0 Canines: 11.5	34.0	6.5	3.0	20.5	12.5
Sugaya et al. 2015[32]	Teeth with VRFs detected clinically and/or radiographically: 2.3% were vital; 0.7% were non-vital and had no RCT; 97% had a RCT	304	Incisors: 9.5 Canines: 6.9	32.9	10.2	3.0	16.8	20.7
Pradeep Kumar et al. 2016[19]	Endodontically treated teeth; VRFs confirmed after surgical flap elevation	197	9.6	22.8	17.3	3.0	13.2	34.0
Liao et al. 2017[20]	Extracted teeth: 56 were endodontically treated; 9 were not endodontically treated	65	12.3	24.6	7.7	3.1	7.7	44.6
Present study	All teeth with EMS	42	4.8	38.1	9.5	9.5	2.4	35.8

EMS = endodontic microsurgery
RCT = root canal treatment
VRFs = vertical root fractures



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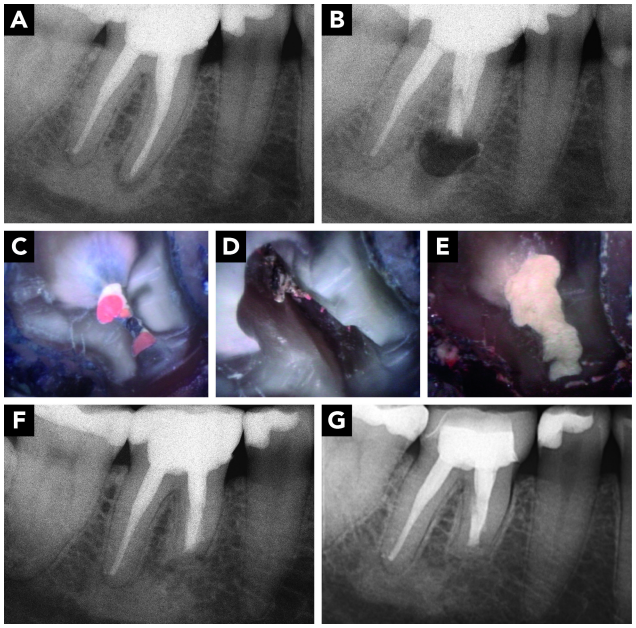

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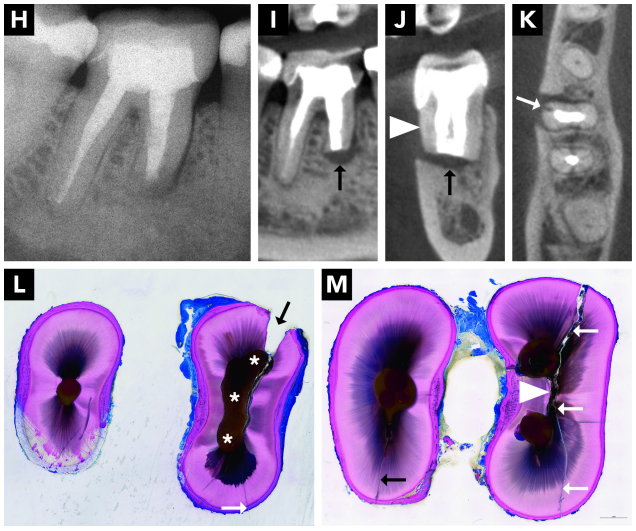

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Credit author statement:

T. VON ARX: study design, surgeries, case documentations, manuscript

P. MALDONADO: study design, data collection, revision of manuscript

M.M. BORNSTEIN: statistics, revision of manuscript

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