Prevalence and Clinical Aspects of Cracks and Fractures in Teeth

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A.R. Pradeep Kumar

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CHAPTER 1

General Introduction

Root canal treatment is done in order to maintain healthy periradicular tissues when the dental pulp is diseased or injured. In the presence of apical periodontitis, root canal treatment is specifically focused on restoring health of the periradicular tissues (European Society of Endodontology, 2006). The aim of root canal treatment is to eliminate microorganisms in the root canal system and to prevent reinfection (Nair et al., 1990). Root canal treatment generally consists of tooth isolation, access cavity preparation, working length determination, root canal preparation and irrigation, inter-appointment medication when necessary, and root canal filling.

A systematic review has reported that the weighted pooled success rates of primary root canal treatment ranged between 68% to 85% (Ng et al., 2007) when strict criteria were applied. Success rates of primary root canal treatment were reported to be improved by four conditions: absence of a pre-operative periapical radiolucency, root filling without voids, root filling which extends to within 0-2 mm from the radiographic apex, and placement of a satisfactory coronal restoration (Ng et al., 2008). The highest pooled success rates of 92% were reported in teeth with flush root fillings (within 0-2 mm from the apical-most point of the radiographic apex) and without pre-operative periapical lesions (Ng et al., 2008).

One of the important causes of failure of root canal treatment is persistent root canal infection or reinfection (Nair et al., 1990). Apart from infection, vertical root fracture (VRF) is one of the commonly reported causes of failure in root canal treated teeth (Versiani et al., 2015). VRF is defined as a complete or incomplete fracture initiated at the root and is usually directed bucco-lingually (American Association of Endodontists, 2008). VRF is a type of fracture which is not caused by impact trauma. These fractures usually involve the root canal and may be caused by propagation of an initial defect in root dentin such as a microcrack or craze line (Versiani et al., 2015). It may extend the entire length of the root or occur as a short crack in the cervical, mid root or apical part of the root. VRF can extend to both buccal and lingual surfaces as a complete fracture or may be present only on one surface as an incomplete fracture (Walton et al., 1984). However, VRF is most commonly associated with root canal treated teeth (American Association of Endodontists, 2008). Other types of longitudinal tooth fractures reported are craze lines, fractured cusps, cracked tooth and split tooth.

The clinical signs and symptoms of VRF may be evident only a few years (Fuss et al., 2001) after root canal treatment and usually leads to extraction of the affected tooth or root. VRF can lead to inflammation in periodontal tissues adjacent to the fracture (Walton et al., 1984). Granulation tissue and a bony defect overlying the fractured root surface (Walton, 2017) can be present.

Root canal treatment procedures and the use of intra-radicular posts are two iatrogenic factors which can be associated with VRF. Therefore, removal of dentin during treatment procedures should be minimised to maintain sufficient radicular thickness to withstand masticatory forces (Tamse, 2006).

Outline of the thesis

Chapter 2

VRFs can be difficult to diagnose as the clinical and radiologic features can be similar to root canal treatment failure and periodontal disease (American Association of Endodontists, 2008). However, a rapid/early diagnosis is essential to avoid further bone loss around the fractured root (Tamse, 2006). Patients may complain of mild symptoms. Pain on percussion and palpation may be present. A narrow periodontal pocket and a sinus tract in association with a root canal treated tooth can be indicative of VRF (American Association of Endodontists, 2008). Radiographs may not help in diagnosing VRF unless there is separation of root fragments (American Association of Endodontists, 2008). Fractures without separation may be visible in the radiograph if the fracture plane is within 4 degrees of the x-ray beam (Rud & Omnell, 1970). Cone beam computed tomography can be useful in the diagnosis of VRF in unfilled roots but may have poor sensitivity and specificity for VRF diagnosis in root filled teeth (Talwar et al., 2016). Surgical flap elevation and evaluation of the root with a dental operating microscope can be the ideal method to confirm a diagnosis of VRF (Walton, 2017).

In this chapter, patients with a history of root canal treatment and a diagnosis of VRF were assessed. The signs, symptoms, and radiographic features of VRF were evaluated along with tooth type, age and gender of the patients and root canal treatment related data. Specifically, the time taken from root filling to a clinical diagnosis of VRF was evaluated. Diagnosis of VRF was confirmed by surgical flap elevation and examination of the root with a dental operating microscope.

Chapter 3

VRF has been reported in teeth without endodontic treatment (Chan et al., 1999). A 13 year survey of 315 VRF cases in a Chinese population reported that 40% of VRF cases occurred in teeth without root canal treatment (Chan et al., 1999). Pre-existing radicular microcracks have been reported (Arias et al., 2014; De-Deus et al., 2014) in non-endodontically treated teeth. Such preexisting microcracks can progress to a VRF (Versiani et al., 2015). However, a recent paper has reported that preexisting microcracks in teeth without root canal treatment may be a result of extraction trauma or storage conditions (De-Deus et al., 2018).

In this chapter, the presence of microcracks in teeth without root canal treatment was investigated. Freshly extracted teeth with no prior history of root canal treatment that were atraumatically extracted for reasons not related to the study were collected. They were evaluated for the presence/absence of root dentinal microcracks using non-invasive micro-computed tomographic imaging technology.

Chapter 4

In vitro research has indicated that root canal preparation to (Adorno et al., 2009) or beyond (Adorno et al., 2011) the apical foramen can result in the formation of apical root microcracks. Therefore, apical extent of root canal preparation can play a role in the initiation of microcracks which can lead to a VRF. However, there was a need for clinical research investigating apical extent of root canal preparation and VRF.

In this chapter, the apical extent of root filling and its association with VRF was examined using a case-control study design. Teeth with VRF and a history of root canal treatment were designated as cases and matched with teeth with root canal treatment and without VRF which were designated as controls. The apical extent of the root canal filling was evaluated as the dependent variable and its association with VRF was determined.

Chapter 5

Laboratory research has indicated that root dentin microcracks/defects may develop after routine root canal treatment procedures such as root canal preparation, root canal filling and retreatment (Shemesh et al 2009 ;Versiani et al., 2015). Recent research on VRF done in human cadaver models and micro-computed imaging technology does not support the theory that mechanical preparation of the root canal can cause the formation of root dentin microcracks (De-Deus et al., 2014; 2017).

In this chapter, the impact of root canal instrumentation on the formation of root dentinal microcracks was evaluated by an *in vivo* study design. Patients who required extraction of contra-lateral premolars for orthodontic purposes participated in this study. Contra-lateral premolars were instrumented with either hand or rotary instruments, extracted atraumatically and evaluated by micro-computed tomographic imaging technique for root dentinal microcracks.

Since the prognosis for a tooth with VRF is questionable, it is prudent to take measures to prevent VRF. Prevention of VRF involves the preservation of radicular dentin during root canal/restorative treatment procedures, and minimization of intra-canal wedging forces (Rivera & Walton, 2015).

Objectives of the thesis

The aim of this thesis was to specifically report on signs, symptoms and radiographic features of VRF, and to report on VRF etiology. The four specific approaches undertaken were:

1. Diagnostic features of teeth with VRF after root canal treatment.
2. Evaluation of freshly extracted teeth for the presence of preexisting root dentinal microcracks.
3. Evaluation of apical extent of root filling as an etiological factor for VRF.
4. *In-vivo* research on root dentinal microcrack formation after root canal instrumentation.

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CHAPTER 2

Diagnosis of vertical root fractures in root filled teeth

This chapter was published in the Journal of Endodontics: PradeepKumar AR, Shemesh H, Jothilatha S, Vijayabharathi R, Jayalakshmi S and Anil Kishen (2016). Diagnosis of vertical root fractures in restored endodontically treated teeth: a time-dependent retrospective cohort study. *Journal of Endodontics* **42**, 1175–80.

Abstract

Introduction: The purpose of this study was to examine different patient and treatment-related factors associated with the time of presentation of vertical root fractures (VRFs) in endodontically treated teeth restored with crowns.

Methods: One hundred and ninetyseven root filled, crowned teeth with no post and suspected of VRFs were included in the study. Patient details with relevance to endodontic treatment and clinical signs/symptoms were documented, and radiographs were taken. A diagnosis of a VRF was confirmed after surgical flap elevation. Frequency distributions were determined, and statistical analyses were performed using Pearson chi-square analysis, Fisher exact test, cross tabulation, Pearson correlation, and multiple logistic regression.

Results: Mandibular molars (34%) and maxillary premolars (22.8%) were the most frequently affected teeth. The postoperative time to the diagnosis of a VRF was 4.35 (±1.96) years. Female patients, posterior teeth, overfilled canals, and patients older than 40 years were associated with the presentation of VRFs within 5 years of the postoperative period. Clinical findings most frequently observed were pain on percussion (60%), pain on palpation (62%), presence of a deep narrow pocket (81%), and sinus tract/swelling (67%). ‘‘Halo’’-type radiolucency (48.7%) was the most common radiographic feature related to VRFs.

Conclusions: Pain on palpation/percussion, deep narrow pocket, sinus tract, and halo-type radiolucency are characteristic features of VRFs. Posterior teeth, overfilled canals, female patients, and older patients (>40 years) presenting with the previously described clinical features in endodontically treated teeth restored with crowns are more likely to present with VRFs within 5 years postoperatively.

Significance: This study highlights the average time taken for the clinical presentation of VRFs in endodontically treated teeth restored with crowns and without posts. It looks at the association between the length of obturation and VRFs and describes the characteristic clinical and radiographic features of VRFs in endodontically treated teeth restored with crowns and without posts.

Key Words: Crown, overfilled canals, post, root canal treatment, vertical root fracture.

Introduction

A vertical root fracture (VRF) is defined as a complete or incomplete, longitudinally oriented fracture of the root, which is usually directed in the buccolingual plane. This fracture usually initiates in the tooth root and may extend coronally (American Association of Endodontists, 2008). In most instances, a VRF leads to tooth extraction (Tang et al., 2010). Clinical surveys and follow-up studies of endodontically treated teeth suggest a variable prevalence of 3.6% (Morfis, 1990), 4.3% (Vire, 1991), 11% (Fuss et al., 1999), 13.4% (Touré et al., 2011), and 20% (Coppens & DeMoor, 2003) for VRFs. A recent retrospective clinical study that examined the 10 year survival of endodontically treated teeth observed root fractures in 6% of the extracted teeth (Borén et al., 2015). These inconsistencies in the reported prevalence of VRFs may be attributed to several risk factors, ambiguous clinical presentations, and challenges involved in the diagnosis. Several predisposing factors have been known to increase the predilection of root filled teeth to VRFs. The morphology of the root (Kishen, 2006), root canal anatomy (Chai & Tamse, 2015), amount of remaining dentin (Kishen, 2006), and age changes in dentin (Kinney et al., 2015) were also suggested to increase the predilection of VRFs in root filled teeth. In addition, iatrogenic causes such as the degree of dentin removed during operative procedures or root canal preparation (Cohen et al., 2006), dentinal defects induced during instrumentation and obturation procedures (Shemesh et al., 2009), and post space preparation (Kishen, 2006) were also suggested as predisposing factors. It has also been suggested that endodontically treated abutment teeth are at high risk for fracture (Tang et al., 2010). Previous clinical studies have examined different diagnostic and clinical parameters associated with VRFs. Nevertheless, the diagnostic accuracy of clinical and radiographic features of VRFs in root filled teeth is still uncertain (Tsesis et al., 2010).

Typically, a VRF has been suggested to be a fatigue failure in an endodontically treated tooth (Kishen et al., 2006; Yahyazadehfar et al., 2014). A VRF may be initiated during root canal treatment or restorative treatment. Yet, it is usually diagnosed years after the completion of treatment, when significant degrees of bone loss have already occurred (Fuss et al., 2001). Nonetheless, only a few clinical studies have investigated the postoperative time to the diagnosis of VRFs in crowned endodontically treated teeth. Schwarz et al. (2012) evaluated 32 endodontically treated and crowned teeth with VRFs and reported an average of 7.8 years. Fuss et al. (2001) and Morfis (1990) reported 1 to 5 years and 3 years postoperatively, respectively. However posts were present in more than 50% of these cases. The purpose of the current retrospective study was to determine the postoperative period taken for the confirmative diagnosis of VRFs and to examine the related clinical and diagnostic features of VRFs in crowned endodontically treated teeth restored with a crown and no post.

Material and Methods

The Institutional Ethical Review Board of the Dr. MGR Educational and Research Institute University, Chennai, India, approved the study. Patients with previously endodontically treated teeth presenting with signs and/or symptoms of VRFs in the university dental hospital and 2 private dental surgeries between 2009 and 2015 were assessed for this study. Informed consent was obtained from all the patients, and a documentation form was prepared. The collection of patient/tooth-related data included the age, sex, tooth type, history of root canal treatment (primary or retreatment), date and technique of root canal obturation, and details of the postendodontic restoration. The history and treatment related details were obtained from the case records of the dentist who had performed the root canal treatment.

Radiographs were taken using a paralleling cone technique, and findings were recorded. Radiographic assessment was performed based on the classification of Tamse et al. (2006). The recorded radiographic features were categorized as follows:

1. Normal periapical region: No periapical rarefaction detected.
2. Periapical radiolucency: Radiolucency/rarefaction located in the periapical region of the affected tooth and extending to less than 2 mm of the root coronally.
3. Isolated perilateral radiolucency: Radiolucency/rarefaction limited to the lateral aspect of the affected root, without involving the coronal or apical regions.

4. ‘‘Halo’’-radiolucency (Fig.1): A periradicular rarefaction/radiolucency observed on the lateral aspect of the affected root, which extended apically and to the opposite side of the root.
5. Periodontal radiolucency: A lateral radiolucency/rarefaction observed extending from the crestal bone to the apical (mesial, distal, or both) aspect of the root but did not involve the periapical area.
6. Vertical bone loss: Interproximal angular bone loss exists in the mesial or distal side or both sides of the root.
7. Furcation radiolucency: Radiolucency/rarefaction observed in the furcation area only.
8. Uniform widening of the periodontal ligament space.

The presenting clinical features recorded were pain on palpation, pain on percussion, presence of sinus tract/swelling, and presence of a buccal or lingual deep, narrow periodontal pocket. A diagnosis of a VRF was confirmed after surgical flap elevation (Fig. 2) using a microscope. A surgical flap was elevated for 294 teeth, with VRFs being identified in 289 teeth (97.6%). Under local anaesthesia, a mucoperiosteal flap was elevated, and granulation tissue in the areas of bone dehiscence or fenestration was removed.

Figure 1. A periapical radiograph showing ‘halo’’-type radiolucency around the root suggestive of a VRF.

The exposed root surface was examined under a microscope to confirm the presence of a VRF. A total of 289 extracted root filled teeth with VRFs were evaluated for this study. Teeth that were not crowned (n=14), underwent retreatment (n=26), received a post and core restoration (n=16), served as an abutment (n=35), and third molars (n=1) were excluded from the study, leaving 197 teeth for the analysis.

Statistical Methods

The data were combined, and statistical analysis was performed using the Statistical Package for the Social Sciences software, version 18.0 (SPSS Inc, Chicago, IL). The frequency distributions of all the parameters were obtained. In order to determine the association between various parameters, Pearson chi-square analysis, Fisher exact test, and cross tabulation were carried out for various combinations of parameters as follows: postoperative time before extraction versus apical extent of root canal filling, tooth type, radiographic presentation, and sex. To analyze the correlation between age of the patients and the postoperative time before extraction, Pearson correlation was conducted. To determine the influence of various factors on the postoperative time before extraction, multiple logistic regression analysis was performed to determine the odds ratio.

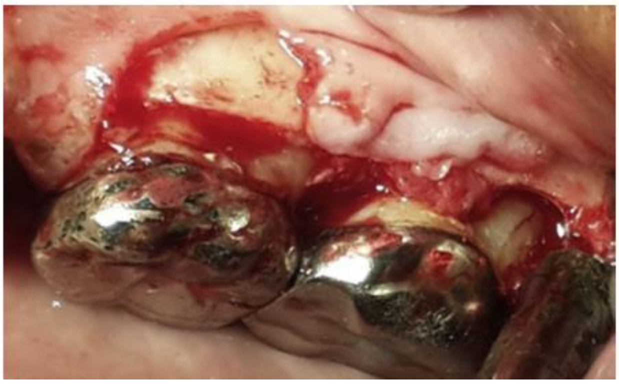

Figure 2. A clinical photograph confirming the diagnosis of a VRF after surgical flap elevation.

Results

The age of the patients (Fig. 3A) and the postoperative time before the diagnosis (Fig. 3B) of VRFs and extraction showed a normal distribution with a mean (±standard deviation) of 54.34 (±12.69) years and 4.35 (±1.96) years, respectively. Among the recorded cases, mandibular molars had the highest occurrence of VRFs (34%) followed by maxillary premolars (22.8%) (Fig. 4A). The characteristic clinical findings in teeth with VRFs were pain on percussion (60%), pain on palpation (62%), presence of a deep/narrow pocket (81%), and sinus tract/swelling (67%).

The most common (Fig. 3C) radiographic presentation was D (‘‘halo’’-type radiolucency (48.7%)) followed by H (thickened periodontal ligament space (23.4%)). When the treatment features of teeth with VRFs were analyzed, it was noted that most of the teeth (Fig. 3D) showed overfilled root canals (79.2%). It was also observed that the obturation technique followed in all the teeth was lateral compaction technique using gutta-percha. When combinations of different parameters were examined, a significant association was observed between the tooth type versus postoperative time before extraction (P=0.03) and sex versus postoperative time before extraction (P=0.04). Cross tabulation of data showed that the majority of mandibular molars (67.2%) and maxillary premolars (68.9%) were detected with a VRF 2 to 5 years after root canal treatment. Most of the teeth in females (63.9%) and in males (56.1%) were detected with a VRF 2 to 5 years after root canal treatment, as were most teeth with overfilled root canals (59.6%). Analysis of the age of patients versus postoperative time before extraction showed a weak positive correlation (r=0.09), which was not statistically significant (P=0.17).

The results were further analyzed in multiple logistic regression models with the odds of ‘‘postoperative time before extraction ≤ 5 years’’ as the dependent variable (Table 1). The sex and age of the patients, the presence of overfilled canals, and tooth type were found to significantly influence postoperative time before extraction. Female patients had 1.95 times higher odds for the presentation of VRFs within 5 years postoperatively (odds ratio (OR) = 1.95; 95% confidence interval (CI: 1.43-3.49) compared with male patients. The presence of overfilled root canals significantly increased the odds by 2.72 times (OR = 2.72; 95% CI: 1.59-8.62). Posterior teeth had 5.22 times higher odds than anterior teeth (OR = 5.22; 95% CI: 1.79-109.67). When the patients were categorized based on the age as "up to 40 years" and "over 40 years", patients older than 40 years had 6.3 times higher odds of VRF than patients younger than 40 years (OR = 6.3; 95% CI: 1.91-185.53).

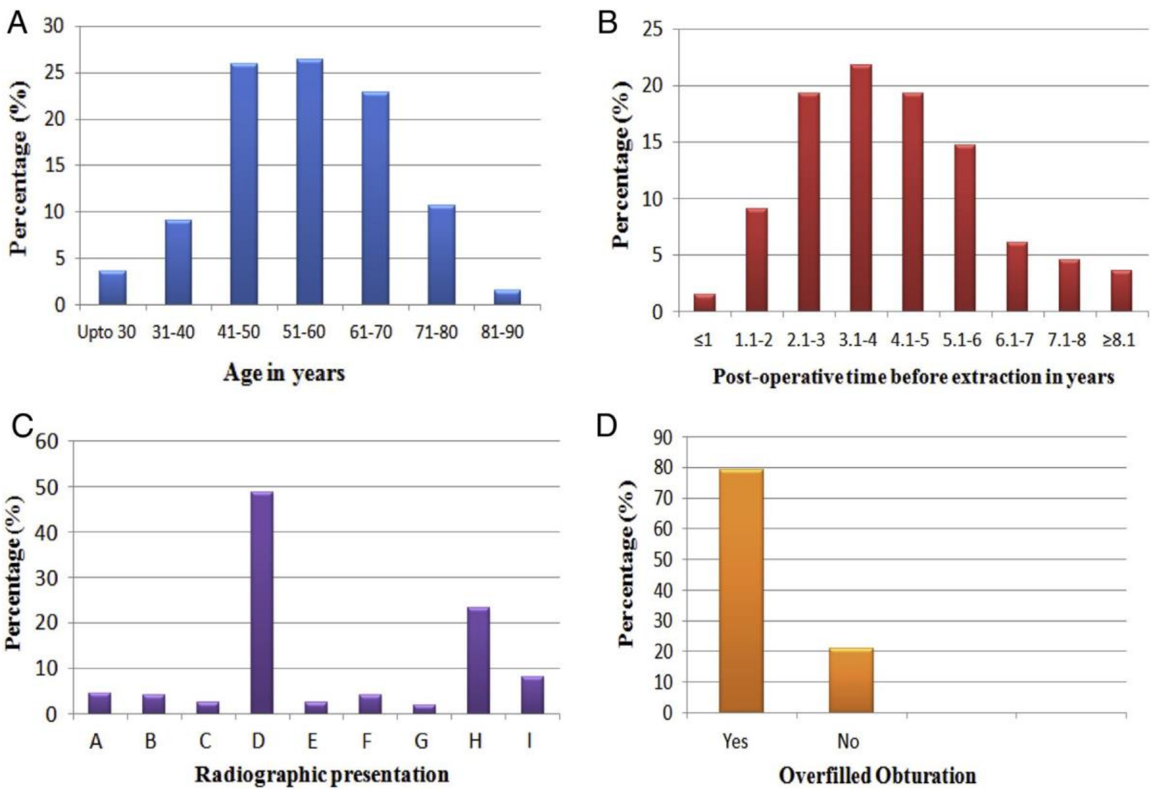

Figure 3. A graphic representation of the frequency distribution of the (A) age of the patients, (B) postoperative time before extraction, (C) radiographic presentation (Tamse et al., 2006), and (D) overfilled obturation in teeth with a VRF.

Discussion

Although a definite identification of a VRF is challenging in most clinical situations, an accurate diagnosis is usually possible based on the associated signs and symptoms. Various studies have evaluated the clinically relevant factors (Fuss et al., 2001; Cohen et al., 2006; Sugaya et al., 2015) and radiographic features associated with VRFs (Chavda et al., 2014). Some studies have included both endodontically treated as well as nonendodontically treated teeth in their analysis (Chan et al., 1999; Cohen et al., 2006). Studies that limited their samples to endodontically treated teeth usually included a limited number of cases (i.e., 36 teeth (Testori et al., 1993), 25 (Llena-Puy et al., 2001), and 32 teeth (Schwarz et al., 2012)). Others have surveyed a larger number of VRF cases, but the majority of their samples had a post and core restoration (Fuss et al., 2001; Sugaya et al., 2015). It has been reported that post space preparation could weaken the remaining tooth structure (Kishen, 2006). The exclusion of teeth with post and core restoration, retreatment cases, abutment teeth, and third molars minimized the influence of confounding factors in the current study. Furthermore, teeth with VRFs were confirmed by surgical examination and were immediately, atraumatically extracted. Thus, the possible role of tooth extraction on root fracture was discounted.

Llena-Puy et al.(2001) highlighted that the mean postoperative time period for a clinical presentation of a VRF was 54 months. Fuss et al. (2001) indicated that 50% of the teeth with VRFs were extracted 1 to 5 years after root canal treatment, whereas Schwarz et al. (2012) observed VRFs 7 to 8 years after root canal filling. Of the 197 teeth included in the current study, 138 teeth with VRFs were extracted 4.35 ±1.96 years after root canal treatment. It was also observed that the majority of mandibular molars (67.2%) and maxillary premolars (68.9%) were detected with a VRF 2 to 5 years after root canal treatment. These observations further emphasize that a VRF is likely a fatigue process (Yahyazadehfar et al., 2014), and the actual failure or crack resulting in a VRF would have been initiated much earlier than the date of extraction
(Fuss et al., 2001).

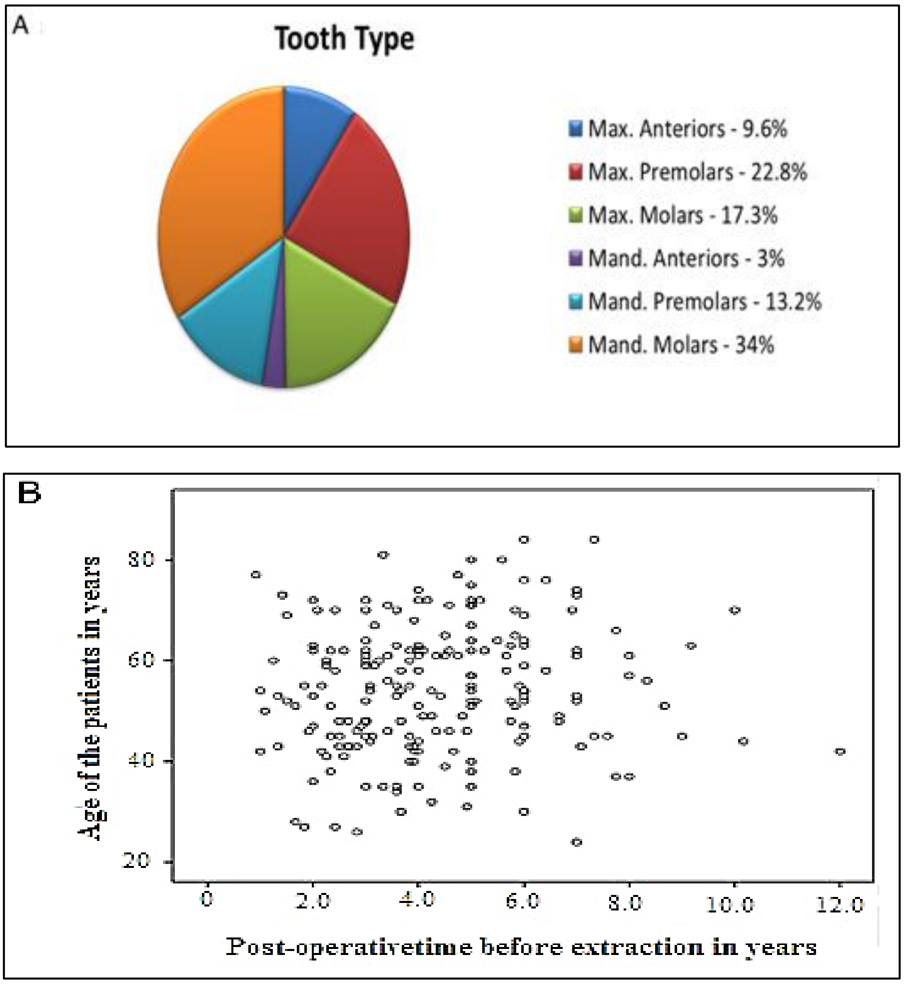

Figure 4. A graphic representation of (A) frequency distribution of tooth type in teeth with a VRF, (B) A scatter plot depicting the absence of linear correlation between the age of patients and postoperative time before extraction of VRF teeth.

Table 1. The outcomes of the multiple logistic regression model.

Explanatory variable (test category vs reference category)	**Odds ratio (OR)**	**95% confidence interval for OR**
Sex (female vs male)	1.95	1.43-3.49
Presence of overfilled root canals vs not overfilled	2.72	1.59-8.62
Tooth type (posteriors vs anteriors)	5.22	1.79-109.67
Age of the patient (over 40 years vs up to 40 years)	6.3	1.91-185.53

The significant clinical signs/symptoms that presented with VRFs in this study were pain on percussion (60%), pain on palpation (62%), and presence of a deep, narrow periodontal pocket (81%). These findings corresponded with previous studies, which reported that 70% of VRF cases presented with pain on percussion (Cohen et al., 2006) and reported localized deep pockets in 67% of the root filled teeth associated with VRFs (Tamse et al., 1999). Sinus tract/swelling adjacent to the gingival margin was observed in 67% of the root filled teeth with VRFs in the current study. This observation was more frequent in the present study than previous reports that observed sinus tracts only in 35% (Tamse et al., 1999) or 18.4% (Cohen et al., 2006) of the cases with VRFs. Furthermore, in concurrence with the previous studies (Chan et al., 1999; Cohen et al., 2006), mandibular molars showed the highest occurrence of VRFs (34%) followed by maxillary premolars (22.8%). The narrow mesiodistal width of the roots would have increased the risk of VRFs in premolars and mandibular molars (Chan et al., 1999). The OR showed that posterior teeth had 5 times more odds for the presentation of VRFs within 5 years of root canal treatment in comparison with anterior teeth. The reason for the earlier presentation of VRFs in posterior teeth may be attributed to the root anatomy and the higher masticatory loads acting on them (Ferrario et al., 2004). Thus, the narrow mesiodistal width of the root and magnitude and direction of masticatory forces may be suggested as potential risk factors influencing the time of presentation of VRFs.

The findings from this study showed that female patients had 2 times higher odds for the clinical presentation of VRFs within 5 years postoperatively.This increased propensity of VRFs in females is in agreement with previous findings (Cohen et al., 2006; Sugaya et al., 2015). Conversely, Chan et al. (1999) reported that males have 1.4 times more VRFs than females in endodontically treated teeth. The exact reasons for an increased predilection of VRFs in females in this study and others are not clear. Contrary to the observed predilection in sex, there was no significant linear correlation between the age of patients (Fig. 4B) and postoperative time before extraction. However, we did observe that patients older than 40 years had a 6 times higher chance for the clinical presentation of VRFs within 5 years of root canal treatment than the younger counterparts.

Similarly, Cohen et al. (2006) and Mireku et al. (2010) have also reported more VRFs in patients aged over 40 years and 60 years, respectively. The reason for the increased predilection of VRFs in older patients could be attributed to the age-related physical effects on the tooth (Cohen et al., 2006), and/or alterations to the fracture toughness (Kinney et al., 2015), and tensile fatigue strength of dentin (Tonami & Takahashi, 1997). Hence, caution should be exercised while performing endodontic procedures in older patients, especially when the remaining dentin thickness is minimal.

Clinical evidence concerning the application of radiographs for the early determination of VRF is inadequate (Tsesis et al., 2010). Both conventional digital radiography and advanced imaging techniques such as cone-beam computed tomographic imaging have been suggested to present limitations in the detection of VRFs (Patel et al., 2013; Long et al., 2014; Chavda et al., 2014). In later stages, with the progression of VRFs, root separation may transpire, which would facilitate the determination of VRFs. In this study, a ‘‘halo’’-type of radiolucency (D) was found to be a significant indicator and was observed in 48.7% of cases. This finding corresponds with earlier reports that the ‘‘halo’’-type radiolucency was one of the most typical radiographic findings associated with VRFs (Pitts & Natkin 1983; Tamse et al., 2006). The next most common radiographic characteristic detected in the current study was a uniform widening of the periodontal ligament space (23.4%). The remaining 6 radiographic presentations combined together comprised only 27.9%, which may not be contributory to the diagnosis of VRFs.

Analysis of the prevalence of endodontic treatment features showed that most of the teeth with VRFs exhibited dense overfilled root canals (79.2%). This finding significantly increased the odds for VRFs by 2.72 times. The relationship between the apical extent of root canal instrumentation and the formation of apical cracks was studied previously using *in vitro* experiments (Adorno et al., 2009; 2011). Those studies concluded that instrumentation of the root canal up to the apical foramen resulted in an increased likelihood of apical crack formation rather than when instrumentation was performed at least 1 mm short (Adorno et al., 2009). Thus, it may be inferred that the overfilled root canals observed in this study were associated with over instrumentation beyond the minor constriction, which may have contributed to apical cracks and subsequent VRFs. In this study, when the overfilled root apices were visually examined, gutta-percha points were observed to project beyond the major apical foramina, whereas the apical foramina were damaged. It is important to acknowledge that in this study, all the teeth with VRFs were filled using the lateral compaction technique and gutta-percha points. Earlier *in vitro* experimentation showed that VRFs may occur under spreader loads of 1.5 kg (Holcomb et al., 1987), whereas dentinal defects and craze lines can occur after lateral compaction (Shemesh et al., 2009). Although it has not been proven that lateral compaction can be a trigger for VRFs, it has been reported that lateral compaction is the most used technique of obturation in endodontically treated teeth with VRFs (Versiani et al., 2015). However, the current study did not compare the influence of different root canal filling techniques on VRFs.

Conclusion

The retrospective design and the lack of information on preexisting cracks before root canal treatment were some of the limitations of this study. Within the limitations of this retrospective study, it can be concluded that the mean postoperative time period before the presentation of VRFs in endodontically treated teeth with crowns and without posts is 4.35 (±1.96) years. The presence of deep, narrow periodontal pockets and halo-type radiolucency are strongly suggestive of VRFs in crowned endodontically treated teeth. Posterior teeth, female patients, older patients (>40 years), and overfilled canals are all potential risk factors for the presentation of VRF within 5 years postoperatively.

Acknowledgments

The authors deny any conflicts of interest related to this study.

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CHAPTER 3

Root dentinal microcracks in teeth without root canal treatment

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Abstract

Introduction: This study evaluated the prevalence, location, and pattern of preexisting dentinal microcracks in roots of extracted teeth without endodontic treatment in patients from two age groups using micro-computed tomographic imaging.

Methods: Six hundred and thirtythree nonendodontically treated teeth extracted using an atraumatic procedure because of reasons unrelated to this study were collected and divided into groups based on the patient age. Teeth were scanned with micro-computed tomographic (micro-CT) imaging (resolution of 26.7 μm) to examine the presence of preexisting dentinal microcracks in roots. The characteristic features of preexisting dentinal microcracks determined were location, extent, length, and coronoapical distribution. Chi-square bivariate analysis was performed to assess the association between various parameters.

Results: Fortyfive of 633 nonendodontically treated teeth exhibited preexisting microcracks in roots with a prevalence of 7.1%. The prevalence of preexisting microcracks was found to be 8.3% in older patients (40–70 years) compared with 3.7% in younger patients (20–39 years) ($P < 0.05$). A significant association was found between the preexisting microcracks in mandibular teeth (10.3%) when compared with maxillary teeth (2.9%) ($P < 0.001$). All preexisting microcracks were located mesiodistally. 66% occurred in the cervical and middle thirds of root. Only 33% of the preexisting microcracks were complete in nature, showing canal involvement. Complete dentinal microcracks exhibited a mean length of 6.9 mm, whereas incomplete cracks had a mean length of 3.75 mm ($P < 0.001$).

Conclusions: Preexisting dentinal microcracks in roots of nonendodontically treated teeth occurred more often in older patients (40–70 years) in the mesiodistal direction. They were predominantly found in the cervical and middle thirds of root and were more likely to be incomplete in nature.

Significance: This micro-CT based analysis of 633 teeth showed a 7.1% prevalence of preexisting dentinal microcracks in roots of nonendodontically treated teeth. The preexisting microcracks were more common in mandibular teeth of older patients, typically in the cervical and middle regions of root surface in the mesiodistal direction. Understanding the nature and prevalence of preexisting dentinal cracks in teeth would

emphasize the potential risk of fractures in such teeth before and after endodontic treatment.
Key Words: Dentinal microcracks, micro–computed tomography, nonendodontically treated teeth.

Introduction

Vertical root fracture (VRF) and a cracked tooth are 2 separate entities based on their specific characteristics and clinical presentation. VRF is a complete or incomplete fracture initiating from the root at any level, usually in the buccolingual direction and progressing toward the crown under the influence of function. In contrast, cracked or split teeth are initiated from the crown, usually in the mesiodistal direction and progressing subgingivally toward the root (American Association of Endodontists, 2008). VRFs have been reported to be more prevalent in maxillary premolars and mandibular molars (Cohen et al., 2006; PradeepKumar et al., 2016). Because of poor treatment prognosis, VRFs usually lead to extraction of the tooth or root (American Association of Endodontists, 2008).

Coronal cracks have been reported to be associated with restorations, occlusal interferences, and parafunctional habits (Ratcliff et al., 2001). Berman and Kuttler (2010) reported pulpal necrosis in the absence of restorations, dental caries, and traumatic injuries. This form of pulp necrosis, termed fracture necrosis, is associated with longitudinal fractures extending from the occlusal surface into the pulp space. Although endodontic treatment has been considered as an important predisposing factor (Tang et al., 2010), VRF has also been reported in teeth without endodontic treatment (Cohen et al., 2006). Root morphology and behavioural factors that resulted in excessive and repetitive occlusal forces are risk factors for VRF in teeth without endodontic treatment (Chan et al., 1998; 1999).

Preexisting dentinal microcracks in the roots of teeth are clinically difficult to diagnose and treat (Versiani et al., 2015). These preexisting dentinal microcracks may be attributed to noniatrogenic factors such as age changes, the effect of functional or parafunctional stresses (Yang et al., 1995; Chan et al., 1998), or iatrogenic factors such as restorative procedures (Kishen, 2006; Shemesh et al., 2009). It has been suggested that preexisting dentinal microcracks in endodontically treated teeth under chewing loads may progress to VRF with time (Barreto et al., 2012). Although age changes have been reported to negatively impact dentin toughness (Nazari et al., 2009), there have been no studies evaluating the influence of age changes on the occurrence of preexisting dentinal microcracks in nonendodontically treated teeth. Preexisting dentinal microcracks in roots of nonendodontically treated teeth have been previously studied using destructive techniques, such as the sectioning method (Arias et al., 2014), as well as non-destructive techniques, such as the micro–computed tomographic (micro-CT) based method (De-Deus et al., 2014).

Micro-CT imaging has been currently used in endodontic research for the non-destructive assessment of the presence, location, and extent of VRFs (Versiani et al., 2015). However, some concerns were raised regarding the scanning resolution of micro-CT imaging, which may not be adequate to detect smaller cracks (Shemesh, 2015), and the effect of environmental conditions on specimens before and during analysis (Kishen & Rafique, 2006).The objective of the current study was to evaluate the prevalence, location, and pattern of preexisting dentinal microcracks in roots of extracted teeth without endodontic treatment from patients in two different age groups using micro-CT based analysis.

Material and Methods

The Institutional Ethical Review Board of the Dr MGR Educational and Research Institute University, Chennai, India, approved the protocol for this study. Patients who opted for tooth extractions as part of their treatment plan but did not have any previous endodontic treatment were recruited from the university dental hospital and 5 collaborating private dental clinics for the study. Informed consent was obtained before extraction, and a documentation form was prepared. Seven hundred extracted maxillary and mandibular human teeth with completely formed roots and without endodontic treatment were obtained. Patient/tooth-related data, including age, sex, tooth type, and radiographs were collected. The common reasons for tooth extraction were chronic periodontitis, carious teeth associated with irreversible pulpitis or necrotic pulps, and apical symptomatic/asymptomatic periodontitis or periapical abscess wherein the patient did not prefer to save the tooth. The extractions were performed atraumatically to prevent cracks during extraction. The mucoperiosteum was initially separated by an intrasulcular incision. Periotomes were then used to sever the periodontal ligament from the root (Fernandes et al., 2011), whereas the extraction was completed using luxators and forceps.

Immediately after extraction, all root surfaces were gently cleaned using an ultrasonic bath to remove calculus and soft tissue debris. Third molars and retained roots were excluded as well as teeth that were extracted because of a diagnosis of VRF/cracked tooth. The remaining samples were subsequently inspected under a stereomicroscope at 12x magnification and transillumination to detect and exclude teeth with root caries, incomplete root formation, fracture, or resorptions. Sixtyseven teeth were excluded, and 633 teeth were finally selected and stored in 0.1% thymol solution at 5° C until further evaluation.

The teeth were divided according to the age of the patient as follows: group 1 (n=164), between 20 and 39 years old, and group 2 (n=469), between 40 and 70 years old. All specimens were scanned using a micro-CT system (SkyScan 1172; Bruker-micro-CT, Kontich, Belgium) at 80 kV and 100 mA with an isotropic resolution of 26.73 µm with 360° rotation around the vertical axis, a rotation step of 1°, a camera exposure time of 1159 milliseconds, and frame averaging of 2. X-rays were filtered with a 1 mm thick aluminum + copper filter. Images were reconstructed with NRecon v.1.6.9 software (Bruker- micro-CT) using 40% beam hardening correction and ring artifact correction of 10, resulting in the acquisition of 37 transverse cross sections per millimeter (De-Deus et al., 2014).

Two precalibrated examiners screened the crosssectional images of teeth from the cementoenamel junction to the root apex. Dataviewer software (Bruker-micro-CT) was used to identify the presence and nature of preexisting dentinal microcracks in root dentin. Crack identification was performed according to previously published methodology. The presence of radiolucent lines in micro-CT sections were identified as cracks (Berman & Kuttler 2010; De-Deus et al., 2014; 2015). The identification of a crack was based on the following definition: a crack is a break or disruption in tooth structure without the separation of parts (Ratcliff et al., 2001). The image analysis was repeated twice at 2 week intervals to evaluate the reproducibility of measurements.

In case of any discrepancies, the images were examined together until an agreement was reached. The preexisting dentinal microcracks in group 1 and group 2 were examined using the following parameters:

1. The direction of the crack: mesiodistal or buccolingual.
2. The location of the crack (i.e., cervical, middle, or apical thirds of the root). The coronoapical distribution of cracks was based on the classification by Sugaya et al. (2015). A cervical crack is a crack seen in the cervical and middle thirds. A middle crack is a crack seen in the middle third only, and an apical crack is a crack observed in the apical and middle thirds of the root. Continuous cracks are present in the cervical, middle, and apical thirds.
3. The presence of complete and incomplete cracks: cracks were classified as a complete crack (Fig. 1A and B) when they extended from the external surface to the root canal or as an incomplete crack (Fig. 1C and D) when they did not extend to the root canal (Wilcox et al., 1997).

Statistical Analysis

Data analysis was performed using the Statistical Package for the Social Sciences software (Version 21.0; SPSS Inc, Chicago, IL). Bivariate analysis was performed using the chi-square test to determine the association between various parameters. An independent T-test was used to compare the mean crack lengths between complete and incomplete cracks. The α value was set at <0.05 for statistical significance.

Results

Six hundred and thirtythree nonendodontically treated teeth had the following distribution: 217 anterior teeth, 159 premolars, and 257 molars. Three hundred thirteen (49.5%) men and 320 (50.5%) women were included. After micro-CT examination, it was found that 48 of the 633 teeth evaluated showed preexisting dentinal microcracks in the root; 3 were excluded because the microcrack crossed the cementoenamel junction into the enamel, leaving 45 teeth (7.1%). Interobserver variability was determined using the Kappa statistic, and reliability was found to be 0.81.

The prevalence of cracks (Table 1) was found to be significantly higher in older patients (40–70 years) (8.3%) compared with younger patients (20–39 years) (3.7%) ($P < 0.050$). A significant association was found between the prevalence of cracks in mandibular teeth (10.3%) compared with maxillary teeth (2.9%) ($P < 0.001$). Fortyfive teeth with preexisting dentinal microcracks were distributed among 32 patients (15 (46.9%) men and 17 (53.1%) women). Nine patients had more than 1 tooth with a microcrack, and all were older patients (40–70 years). The distribution of teeth with cracks was 19 anteriors, 11 premolars, and 15 molars. All preexisting dentinal microcracks in roots were oriented in the mesiodistal direction.

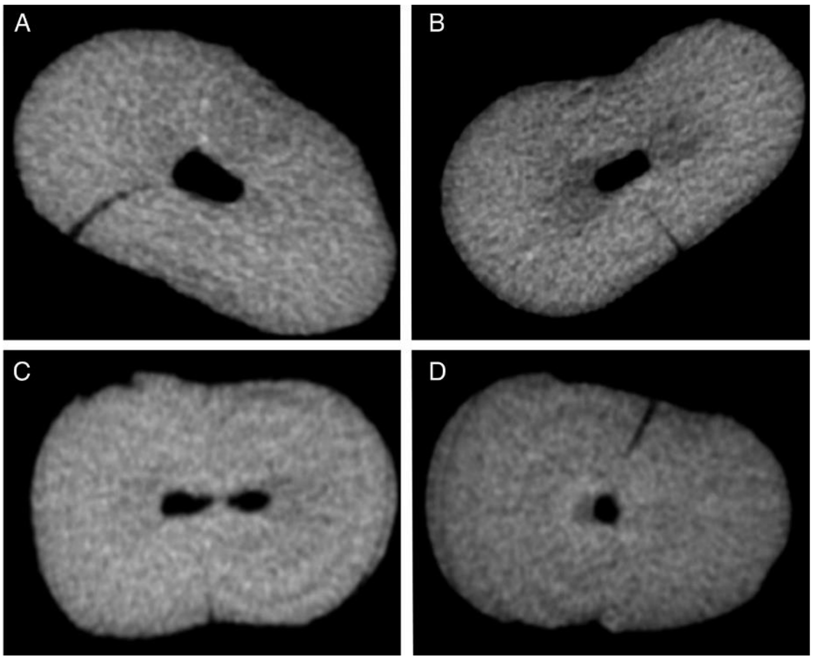

Figure 1. Micro-CT images showing typical preexisting microcracks in roots of non-endodontically treated teeth. (A and B) Complete microcracks and (C and D) incomplete microcracks.

In addition, 8 (17.8%) of the preexisting dentinal microcracks were present in the cervical aspect, 30 (66.6%) (Table 2) were located in the cervical and middle aspect of the root, 3 (6.7%) were continuous cracks, 2 (4.4%) were located in the middle third of the root, and 2 (4.4%) were apical cracks. Image analysis also showed that out of 45 teeth (Table 3) with preexisting radicular dentinal micro-cracks, 15 teeth (33.3%) showed complete cracks, whereas 30 teeth (66.6%) showed incomplete cracks. The mean length of preexisting dentinal microcracks was determined to be 4.82 mm. There was a significant difference in the mean length of complete cracks (6.9 mm) versus incomplete cracks (3.75 mm) ($P < 0.001$). However, the mean length of cracks observed in the different age groups was not found to be statistically significant.

Table 1: Distribution of teeth and microcracks based on location and age.

	Samples	Maxilla	Mandible	10–39 y	40–70 y
Total samples	633	273	360	164	469
Microcracks, n (%)	45 (7.1)	8 (2.9)	37 (10.3)	6 (3.7)	39 (8.3)

y=years.

Table 2: Distribution of 45 teeth with microcracks based on the location of microcracks.

	Cervical	Cervical & middle	Middle	Apical	Continuous	Total
Microcracks, n (%)	8 (17.8)	30 (66.6)	2 (4.4)	2 (4.4)	3 (6.7)	45

Table 3: Distribution of 45 teeth with microcracks based on canal extension.

	Complete	Incomplete	Total
Microcracks, n (%)	15 (33.3)	30 (66.6)	45

Discussion

VRFs occurred in endodontically treated teeth as well as in nonendodontically treated teeth (Chan et al., 1998; 1999; Cohen et al., 2006). Although root canal treatment predisposed teeth to VRFs, it has been suggested to have a multifactorial etiology (Cohen et al., 2006). Many iatrogenic and noniatrogenic factors have been suggested to increase the risk of fracture in endodontically treated teeth (Wilcox et al., 1997; Cohen et al., 2006; Kishen, 2006; Tang et al., 2010). Preexisting microcracks and iatrogenic microcracks in root dentin of endodontically treated teeth may progress to VRFs, indicating a typical fatigue type of failure mechanism (Versiani et al., 2015). Similarly, in nonendodontically treated teeth, fracture may be preceded by preexisting dentinal microcracks (Ratcliff et al., 2001). Thus, understanding the nature and prevalence of preexisting dentinal cracks in teeth would emphasize the potential risk of fractures in such teeth before and after endodontic treatment.

The prevalence of VRFs in endodontically treated teeth was suggested to range from a minimum of 3.69% (Morfis, 1990) or 6.19% (Borén et al., 2015) to a maximum of 13.4% (Touré et al., 2011). However, these studies did not take into account the presence of preexisting dentinal microcracks before endodontic treatment. Some studies have assessed the distribution of VRFs in both endodontically and nonendodontically treated teeth. In their investigation, Cohen et al. (2006) found 51.3% (12.3% in teeth with vital pulp and 39% in nonvital teeth) of VRFs in nonendodontically treated teeth, whereas 48.7% of VRFs occurred in teeth with previous root canal treatment. Chan et al. (1999) concluded that VRFs in nonendodontically treated teeth are not uncommon in Chinese patients. Along similar lines, in their study, Kang et al. (2016) highlighted cracks in 34% of intact teeth.

Preexisting dentinal microcracks in nonendodontically treated teeth were reported in certain *in vitro* studies by examining teeth before the planned experiments (Barreto et al., 2012; Arias et al., 2014; De-Deus et al., 2014). Barreto et al. (2012) reported dentin defects in 2 of 5 intact teeth, whereas Arias et al. (2014) reported preexisting microcracks in 4 of 6 teeth in their control group. Micro-CT analysis reported that 27.6% (De-Deus et al., 2014) and 34.6% (De-Deus et al., 2015) of all dentin slices had some form of defect before experiments. These *in vitro* studies were conducted on a limited number of teeth. In our micro-CT–based study, a total of 633 extracted nonendodontically treated teeth were examined, and preexisting dentinal microcracks were observed in 45 teeth with a prevalence of 7.1%.

Any excessive force on teeth as in tooth extraction (Barreto et al., 2012) or environmental changes on dentin as in dehydration (Kishen & Rafique, 2006) may result in dentinal microcracks. In the current study, extractions were performed atraumatically, and the samples were stored in 0.1% thymol to maintain hydration. The low percentage of microcracks (7.1%) as well as the mesiodistal direction of preexisting microcracks may indicate that extraction stresses or environmental changes may not have drastically influenced the observations in this study. This finding may be supported by previous reports of much higher numbers of microcracks in control teeth (Barreto et al., 2012; Arias et al., 2014; De-Deus et al., 2014; De-Deus et al., 2015). Sex did not play a significant role in the distribution of preexisting dentinal microcrack in our study. Comparable results were obtained in a study on VRFs by Cohen et al. (2006), who reported a distribution of 52.4% in females and 47.5% in males. On the contrary, Chan et al. (1999) reported that 78% of VRFs in nonendodontically treated teeth occurred in males, whereas only 22% occurred in females. In the same study, 58% of VRFs in endodontically treated teeth were in males and 42% in females. Because other determinants such as the presence of pain/temporomandibular disorders, parafunctional habits, craniofacial morphology, and occlusion would influence the magnitude and nature of bite forces (Waltimo & Könönen, 1993; Koc et al.,2010), further studies may be required to compare the propensity of preexisting dentinal microcracks between patients of either sex.

In our study, a significant association was found between the prevalence of preexisting dentinal microcracks and tooth position in the dental arch. Preexisting root dentinal microcracks in mandibular teeth (10.3%) were significantly higher than in maxillary teeth (2.9%). Previous studies have reported a similar predisposition of VRFs in nonendodontically treated mandibular teeth (Yang et al., 1995; Chan et al., 1998). However, Sugaya et al. (2015), who mainly studied post and core restored endodontically treated teeth, reported more chance of VRFs in maxillary teeth compared with mandibular teeth. Another study, which evaluated both endodontically and nonendodontically treated teeth, reported no clear propensity for VRFs between maxillary and mandibular teeth (Cohen et al., 2006).

Dentin from older individuals may be less resistant to fracture than dentin from younger individuals (Arola et al., 2005). In this study, a cut off of 40 years was used to evaluate the difference between young and aged dentin. This cut off was based on previous studies. According to Shinno et al. (2016), aged crown and root dentin (age ≥ 40) exhibited significantly lower flexural strength and toughness than young dentin (age <40). PradeepKumar et al. (2016) reported that patients older than 40 years had a higher chance of clinical presentation of VRFs within 5 years of root canal treatment. Cohen et al. (2006) reported that 87% of all root fractures in their study were observed in patients older than 40 years. Similarly, Chan et al. (1999) reported that most fractures occurred in the 40 to 49 year age group in men and in the 50 to 59 year age group in women.

These studies attributed the increased propensity of VRFs in older patients to the more years of physical use and the exposure to more extensive restorative treatment procedures. In addition, it should be noted that the fatigue strength, flexural strength, and fracture toughness of dentin might be reduced with age (Arola et al., 2005; Nazari et al., 2009). In the present study, the prevalence of preexisting dentinal microcracks was found to be 8.3% in patients in the 40 to 70 year age group compared with 3.7% in patients in the 20 to 39 year age group. Furthermore, 9 patients had more than 1 tooth with microcracks, and all were older patients (40–70 years). Therefore, root cracks and fractures may be more anticipated in older patients irrespective of whether the tooth was endodontically treated or not.

We categorized the preexisting dentinal microcracks as complete and incomplete (Wilcox et al., 1997). It was observed that of 45 teeth with a crack, 33.3% were complete cracks, extending from the canal wall to the root surface, whereas 66.6% were incomplete cracks, initiating from the root surface. The lengths of preexisting dentinal microcracks were found to correlate with its extension into the pulp. The mean length of cracks extending into the root canal, was 6.96 mm, whereas the mean length of cracks that did not extend to the root canal was only 3.75 mm. All the cracks had a width of less than 30 µm. The crack width was measured according to the method reported by Huang et al. (2014). This study highlighted that preexisting dentinal microcracks may extend into the root canal space and serve as a portal of entry for microbes, which could compromise the status of the root canal or the health of the pulp (Berman & Kuttler, 2010).

All incomplete preexisting dentinal cracks observed in this study extended from the root surface toward the root canal. There were no incomplete cracks extending from the root canal wall toward the surface.This finding indicated that preexisting dentinal microcracks in nonendodontically treated teeth occurred at the root surface, contrary to the current understanding of VRFs in endodontically treated teeth which frequently originated from the root canal wall (Roh & Lee, 2006). Microcracks originating from the canal wall were also reported after root canal instrumentation in a cadaver model (Arias et al., 2014). Moreover, experiments involving post and core restored teeth have shown fractures originating from the root canal wall. This finding was attributed to the increase in tensile stresses and regions of stress concentration associated with a stiff post/core system in endodontically treated teeth (Kishen & Asundi, 2002; Kishen et al., 2004). The observed difference in the origin of preexisting cracks and VRFs may be caused by the difference in the biomechanical principles underlying crack initiation in endodontically treated teeth and nonendodontically treated teeth.

VRFs have been reported to generally be in the buccolingual direction (American Association of Endodontists, 2008). Arias et al. (2014) evaluated microcracks formed after root canal instrumentation using a cadaver model and found that all the microcracks were in the buccolingual direction. In the current study, all preexisting dentinal microcracks in the root were found to be in the mesiodistal direction. Based on their investigations on VRFs in endodontically treated teeth, Sugaya et al. (2015) reported that most apical fractures were in the buccolingual direction, whereas cervical fractures may be in the buccolingual or mesiodistal direction (Sugaya et al., 2015). Mesiodistal cracks were also described commonly in the coronal aspects of intact teeth with no restoration (Roh & Lee, 2006). Nevertheless, further studies may be required to elucidate the presence of preexisting dentinal microcracks in the mesiodistal direction.

The distribution of dentinal microcracks in the coronoapical direction of the root was based on a previous study (Sugaya et al., 2015), which examined endodontically treated teeth and found that the majority of fractures were either at the cervical or apical aspect of the root, both occurring at a similar frequency. In our study, most cracks (66.6%) were located at the cervical and middle aspect of the root followed by 17.8% in the cervical region. This may be explained by previous *in vivo* strain gauge experiments, which reported maximum functional strain distribution at the cervical root surface (Asundi & Kishen, 2000).

A micro-CT system with a resolution of 26.73 µm was used in this study. A previous study by Huang et al. (2014) highlighted that a micro-CT system with a resolution of 9 µm was better than 80 µm resolution for the evaluation of VRFs. They reported fracture widths from 10 µm to 1070 µm. In their study, only 7 of 37 teeth (20%) had fractures smaller than 30 µm. Thus, the percentage of cracks under 30 µm may be less in number. The samples in this study were stored in 0.1% thymol to maintain hydration and to avoid cracks, which may be formed because of dehydration. Although the application of a higher resolution micro-CT system may not produce any significant changes in the nature of preexisting dentinal microcracks reported in this study, future studies with a higher resolution micro-CT system may be beneficial.

Conclusion

In summary, the present micro-CT–based analysis of 633 teeth showed a 7.1% prevalence of preexisting dentinal microcracks in roots of nonendodontically treated teeth. These preexisting dentinal microcracks were more common in the mandibular teeth of older patients (>40 years) and were typically found in the cervical and middle regions of root surface in the mesiodistal direction.

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The authors deny any conflicts of interest related to this study.

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CHAPTER 4

Apical extent of root canal filling and vertical root fracture

This chapter was published in the International Endodontic Journal: PradeepKumar AR, Shemesh H, van Loveren C, JothiLatha S, Shireen F, VijayaBharathi R, Kishen A. (2019). Impact of apical extent of root canal filling on vertical root fracture: a case–control study. *International Endodontic Journal*, **52**, 1283–89.

Abstract

Introduction: The aim of this case-control study was to investigate the impact of apical extent of root filling on vertical root fracture (VRF).

Methods: Eightysix patients (119 roots) diagnosed with VRF in crowned root filled anterior and posterior teeth were selected. The cases were matched individually with control teeth in a ratio of 1:1 for age (±5 years), gender, tooth type, canal instrumentation method, master apical file (MAF) size and taper, technique of canal filling and time period after root filling. All root canals had been prepared using nickel–titanium (NiTi) rotary instruments and filled using the lateral compaction technique. The apical extent of root filling (overfilled: to or beyond the radiographic apex or not overfilled: short of the radiographic apex) was recorded as the dependent variable by two individual examiners. Inter-examiner agreement was obtained using Kappa statistics. Recorded numbers of overfilled and not overfilled canals in cases and controls were analyzed using chi-square tests and conditional logistic regression, and an odds ratio was calculated. In addition, the frequency distribution of vertical and cross-sectional extensions and the course of VRFs were evaluated.

Results: The mean age of patients with VRFs was 50±10 years with 27 (31%) males and 59 (69%) females. The Kappa score for inter-observer agreement was 0.83. There was a significant difference between cases and controls with respect to apical extent of root filling ($P < 0.0001$).When compared to roots not overfilled, overfilled roots had 11.5 times higher odds for occurrence of VRF (OR=11.5; CI: 4.99-26.48). Most VRFs had a complete corono-apical longitudinal extension and were present bucco-lingually/palatally.

Conclusions: After matching for age, gender, tooth type, MAF size and taper, canal filling technique and time period after root filling, root canals filled to or beyond the radiographic apex following lateral compaction had a greater association with VRF than canals filled short of the radiographic apex.

Significance: Avoiding overinstrumentation/overfilling beyond the apical constriction can reduce the risk of VRF.

Keywords: case-control study, overfilled root canals, root canal filling, vertical root fracture, VRF.

Introduction

Vertical root fracture (VRF) is a complete or incomplete longitudinal root fracture, usually located in the bucco-lingual plane (American Association of Endodontists, 2008). VRFs are one of the most important causes of tooth loss after root canal treatment (Versiani et al., 2015) due to their poor prognosis (Fuss et al., 2001; Walton, 2017). Although VRF may be caused by excessive wedging forces that exceed the binding strength of root dentine (Rivera & Walton, 2015), there may be multiple risk factors for fracture initiation and propagation in a root filled tooth (Kishen, 2006; Tamse, 2006). Increased loss of radicular dentine (Wilcox et al.,1997), post-core restorations (Fuss et al., 2001) and root morphology (Tamse et al., 1999) have all been suggested as risk factors that increase the predilection of VRF in root filled teeth. Mandibular molars and maxillary premolars have been reported to be most frequently diagnosed with VRF after root canal treatment (PradeepKumar et al., 2016).

Root canal treatment procedures have been investigated as key risk factors for VRF in root filled teeth (Tamse, 2006). Root canal instrumentation and filling procedures have been reported to cause dentinal defects and cracks/craze lines, which may have the potential to develop into a VRF (Bier et al., 2009; Shemesh et al., 2009). However, this is controversial as studies have not consistently found a direct correlation between instrumentation and appearance of cracks in root canal dentine (De-Deus et al., 2014; 2015). Effect of the length of apical instrumentation on the formation of cracks has also been evaluated with the suggestion that instrumentation to the major foramen (Adorno et al., 2009) or beyond (Adorno et al., 2011) can result in more crack formation than if done 1 mm short of the major foramen.

A recent paper has suggested that microcracks reported in stored extracted teeth subjected to laboratory root canal procedures may be due to the extraction process or storage conditions (De-Deus et al., 2019). Therefore, there is a need for clinical studies to evaluate the aetiological factors of VRF in root filled teeth, particularly with respect to endodontic and restorative treatment procedures. It has been reported that the apical extent of root canal instrumentation can correlate with the extent of root filling (Ng et al., 2011). A recent clinical study evaluating VRF cases reported that overfilled root canals may be associated with a greater clinical presentation of VRF within 5 years of root canal treatment (PradeepKumar et al., 2016). However, there are no clinical studies evaluating risk factors for root filled teeth with VRF in comparison with similar teeth without VRF. Case-control is a study design used to identify the association of a risk factor with an outcome (Barborka et al., 2017). Hence, this retrospective case-control study aimed to investigate the relationship between length of root fillings and the occurrence of VRFs. The null hypothesis tested was that there is no difference in the occurrence of VRF in overfilled or not overfilled root canals.

Material and Methods

A case-control study was designed comparing crowned teeth which had undergone root canal treatment and were diagnosed with VRF to similar teeth without VRF. The study protocol followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for case-control studies (von Elm et al. 2007) and was approved by the Dr M.G.R Educational and Research Institute's Institutional Ethical Committee. The sample size was calculated based on a pilot investigation, by setting α error at 5% and power at 90%. The study was conducted from 2015 to 2017 in the Thai Moogambigai Dental College and Hospital and two private dental surgeries in the city of Chennai, India. Informed consent was obtained from all the patients. Patients who had undergone root canal treatment followed by full crown restorations were selected for participation. Endodontically treated teeth with evidence of periapical/periodontal pathosis, without full crown restorations, with post, with root resorption, teeth serving as abutment, cracked teeth, retreatment cases, teeth with poor quality root filling (presence of voids), patients with bruxism or traumatic occlusion, and third molars were excluded.

Out of 900 patients examined clinically and radiographically, 98 were provisionally diagnosed with VRF. Twelve were excluded as they declined to continue as participants in the study whilst 86 were included as cases. Diagnosis of VRF was suspected by clinical signs such as the presence of sinus tract, deep narrow periodontal pocket, symptoms like pain on percussion and palpation and radiographic findings of J-shaped or halo-type radiolucency (von Arx & Bosshardt, 2017). VRF was confirmed by surgical flap elevation and direct observation of fracture under a dental operating microscope (American Association of Endodontists, 2008; Walton 2017). Following atraumatic extraction of teeth with VRF, the apices were examined under a stereomicroscope (NSZ-606, Magnus Analytics, New Delhi, India) for evaluation of apical foramen deformation in the form of transportation and/orVRF passing through the foramen. The corono-apical extent of VRF was evaluated and serial ground sections of the roots were prepared and evaluated under a stereomicroscope for bucco-lingual/mesio-distal extensions of VRF according to the criteria reported by von Arx & Bosshardt (2017).

Patient details such as age, gender, tooth type, root canal instrumentation system used, master apical file (MAF) size and taper, technique of root filling, post-endodontic restoration and time period from root filling to a diagnosis of VRF were documented. Overall, 119 fractured roots were identified from 86 teeth with VRF. Data were recorded individually for each fractured root. Patients with crowned root filled teeth without VRF or periapical/periodontal disease were selected as controls. Cases were individually matched with controls in a ratio of 1:1 for age (±5 years), gender, tooth type, instrumentation system, MAF size and taper (Table 1), technique of canal filling and time period from canal filling (similar or more for controls). Cases and controls were selected from a pool of patients treated by three qualified endodontists with more than 10 years of experience. VRF cases were matched with controls treated by the same operator.

Root canal treatment in both cases and controls was completed in 1 to 3 appointments. Working length was established using an electronic apex locator (Pagavino et al., 1998) at zero-point minus 1 mm (Root ZX, J Morita, Tokyo, Japan) and radiographs followed by rotary instrumentation of the canals. Apical patency was maintained throughout the procedure by passing a size 10 K-file (Mani Inc., Tokyo, Japan) passively through the apical foramen. Apical gauging was done before selection of master cones. Canal filling was achieved using 2% taper gutta-percha points and AH-Plus sealer (Dentsply De Trey, Konstanz, Germany) with the lateral compaction technique using 2% taper stainless steel finger spreaders (Mani Inc., Tokyo, Japan) size 25 and 30. After removal of excess gutta-percha, the root fillings were covered by a glass–ionomer cement layer and a composite core restoration. Porcelain fused to metal full crown restorations were placed within 1 month. Adequate ferrule design (either three or four-walled ferrule) was maintained. Two blinded calibrated examiners assessed the apical extent of root filling (overfilled: to or beyond the radiographic apex or not overfilled: short of the radiographic apex) by viewing three digital intra-oral periapical radiographs: straight, mesial-angled and distal-angled (Dürr Dental, VistaScan, Bietigheim-Bissingen Germany), which was recorded as a dependent variable. If there was more than one canal in the root with VRF, the canal with the longer root filling was recorded. Final consensus was obtained between examiners in case of variation.

Statistical Analysis

Recorded numbers of overfilled and not overfilled canals in cases and controls were analyzed using chi-square tests and conditional logistic regression with SPSS software (SPSS Statistics for Windows, Version 22.0, IBM Corp., Armonk, NY, USA). An odds ratio (OR) was calculated to determine the association between extent of root filling and VRF. Inter-examiner agreement for radiographic length of root filling was obtained using Kappa statistics. The frequency distributions of all parameters were obtained.

Table 1: The tooth types and the range of master apical file (MAF) sizes and taper in the cases and controls.

Tooth Type	MAF Size	MAF Size & Taper	
		ProTaper	Mtwo &RaCe*
Maxillary anteriors	40-50	F4 (40–6%), F5 (50–5%)	40–6%
Maxillary premolars	30-40	F3 (30–9%)	30, 35,40–6%
Maxillary molars			
Mesiobuccal	30-35	F3 (30–9%)	30, 35,40–6%
Distobuccal	30-35		
Palatal	30-40		
Mandibular anteriors	30-35	F3 (30–9%)	30, 35–6%
Mandibular Premolars	30-40	F3 (30–9%)	30, 35,40–6%
Mandibular molars			
Mesiobuccal	30-35	F3 (30–9%)	30, 35,40–6%
Mesiolingual	30-35		
Distal	30-40		

*Mtwo and RaCe have common sizes and are placed in the same column.

Table 2: Extent and course of VRF.

Variables	Subgroups	Percentage
Vertical extent of VRF	Complete	82
	Cervical	14
	Mid root	1
	Apical	3
Horizontal extent of VRF	Complete Bucco-lingual/Palatal	56
	Buccal only	16
	Lingual/Palatal only	14
	Buccal and Lingual/Palatal	3
	Complete Mesio-distal	11
Axial course of VRF	Straight	47
	Oblique	23
	Curved	20
	Zig zag	10
Isthmus (Posterior teeth)	Present (VRF involving isthmus)	37
	Present (VRF not involving isthmus)	5
	Absent	58

Results

The mean age of patients with VRF (cases) was 50±10 years with 71% of patients aged between 40 and 60 years. The time period from root filling to a VRF diagnosis ranged from 11 months to 13 years and 5 months; 66% of VRF cases were diagnosed 2 to 5 years after canal filling. Amongst 86 cases, 27 (31%) were male and 59 (69%) were female. The distribution of tooth type amongst 119 roots with VRF was 6 (5%) maxillary anteriors, 16 (13%) maxillary premolars, 36 (30%) maxillary molars, 1 (1%) mandibular anterior, 8 (7%) mandibular premolars and 52 (44%) mandibular molars. Amongst the two-rooted teeth (maxillary premolars and mandibular molars), 64% (n=32) and 36% (n=18) of teeth presented with single root fracture and two root fracture, respectively. Amongst the three-rooted teeth (maxillary molars), 52% (n=11), 24% (n=5) and 24% (n=5) had single root fractures, two root fractures and three root fractures, respectively. Roots that most commonly fractured were mesial roots (n=29) and distal roots (n=23) of mandibular molars, palatal roots of maxillary molars (n=16) followed by single-rooted maxillary premolars (n=15), and mesiobuccal roots (n=12) and distobuccal roots (n=8) of maxillary molars. Descriptive statistics of three rotary nickel–titanium file systems used were ProTaper Universal 54% (n=64), Race 44% (n=52) and Mtwo 3% (n=3).

The Kappa score for inter-examiner agreement evaluating overfilled/not overfilled root canals was 0.83. All roots with overfilled canals had deformed/transported apical foramen with gutta-percha extrusion on stereomicroscopic evaluation. VRFs involved the apical foramen in 50% of cases. Deformed apical foramen including VRF through the foramen was present in 89% of cases. Data representing the extent and course of VRF are presented in Table 2. An isthmus was present in 42% of posterior roots with VRF amongst which VRFs were found to involve 37%.

There was a significant difference ($P< 0.0001$) between cases and controls with respect to the extent of root fillings. In controls, 21% roots were overfilled and 79% were not overfilled. But in VRF cases, 74% roots were overfilled and only 26% were not overfilled. When compared to roots not overfilled, overfilled roots had 11.5 times higher odds for occurrence of VRF (OR=11.5; 95% confidence interval (CI), 4.99-26.48).

Discussion

VRF is one of the catastrophic complications which can occur after root canal treatment. The current case-control study was designed to investigate a possible association between root filling length and VRF. In order to minimize the effect of confounding factors, teeth without crowns, with posts, teeth serving as abutment and retreatment cases were excluded (Reeh et al., 1989; Fuss et al., 2001; PradeepKumar et al., 2016). Root filled teeth with evidence of periapical/periodontal disease were excluded as controls since VRF could mimic root canal treatment failure/periodontal disease (American Association of Endodontists, 2008).

VRF cases were matched with controls to reduce the effect of confounding risk factors. Age and gender of the patient have been previously reported as risk factors for VRF (PradeepKumar et al., 2016). The tooth type with VRF represented mainly in the current study was mandibular molars, which also corroborated with previous studies (PradeepKumar et al., 2016).

A microcrack, which acts as an initiator of VRF, may be introduced during endodontic or restorative procedures. However, clinical signs and symptoms of VRF may take a much longer time to emerge (Fuss et al., 2001). The time period from root canal treatment to a diagnosis of VRF ranged from 11 months to 13 years and 5 months, which was matched with a similar or longer time period in controls. The lag phase prior to the appearance of clinical signs/symptoms suggests the influence of several factors for the progression of subclinical features to VRFs with obvious clinical indicators (Kishen, 2006; Tamse, 2006). In the current study, 66% of VRF cases were diagnosed

2 to 5 years from completion of root canal treatment which corroborates with previous reports (Fuss et al., 2001; PradeepKumar et al., 2016).

All teeth included in this study (cases and controls) exhibited acceptable, radiographically dense root fillings. At the recall visit, the length of canal filling was recorded as either short of (not overfilled) or to and beyond the radiographic apex (overfilled). Apical constriction and foramen may be located several millimetres short of the anatomic apex (Gutierrez & Aguayo, 1995) and radiographic apex (ElAyouti et al., 2001). Therefore, radiographic evaluation of root filling length may underestimate the number of overfills beyond the apical constriction. Since this study evaluated the presence of VRF at the recall visit, radiographic length of root filling was evaluated as a risk factor for VRF. Better three-dimensional evaluation of root filling (Liang et al., 2012) and overfill (Song et al., 2017) may require CBCT images. Due to ethical considerations, only conventional radiographic evaluation of root filling length was undertaken.

Since rotary instrument design can influence stress concentration on root dentine (Kim et al., 2010), the rotary system used (including MAF size and taper) in VRF cases was matched with controls (Table 1). Laboratory studies have reported more apical root cracks when rotary instrumentation is done to the major apical foramen (Adorno et al., 2009) or beyond (Adorno et al., 2011) compared to 1 mm short. Apical overinstrumentation can result in various patterns of apical fracture (Gutierrez et al., 1999). Conversely, a recent micro-computed tomographic study concluded that root canal instrumentation either up to the apical foramen or 1 mm short did not result in the formation of microcracks (de Oliveira et al., 2017).

Apical extent of root filling has been reported to correlate with apical extent of instrumentation (Ng et al., 2011). Instrumentation through the apex is more likely to be associated with overfilling (Bergenholtz et al., 1979). Laboratory experiments have reported that lateral compaction can cause the formation of dentine defects (Shemesh et al., 2009) and that VRFs can occur with spreader loads as low as 1.5 kg (Holcomb et al., 1987). In this study, all root fillings were done using stainless steel spreaders. Using NiTi spreaders may have reduced compaction forces (Gharai et al., 2005). In this clinical study, deformed apical foramen including fracture lines through foramina were present in the majority of VRF cases. Apical foramen deformation could be the result of inadvertent overinstrumentation irrespective of using an apex locator. A recent clinical study has reported that 79% of teeth with VRF had dense overfilled root canals (PradeepKumar et al., 2016). Hence in this study, the length of root filling, which can act as a surrogate for instrumentation length, was evaluated as a potential risk factor.

In the present study, to eliminate operator variability, VRF cases were matched with controls performed by the same operator. However, in VRF cases 74% roots were overfilled, whilst in controls, only 21% were overfilled. The aetiology for VRF is multifactorial in nature (Kishen, 2006; Tamse, 2006). In the present study, it was also found that VRFs were present to a significantly lesser frequency (26%) in roots that were not overfilled. The higher odds for occurrence of VRF in overfilled roots suggest that root canals filled to or beyond the radiographic apex using cold lateral compaction are a potential risk factor for VRF. Hence, the null hypothesis was rejected.

When the bucco-lingual/mesio-distal extent of VRF was evaluated, 89% of VRFs were in a bucco-lingual/palatal direction corresponding to previous reports (Tamse, 2006; von Arx & Bosshardt, 2017). Complete fractures extending from the buccal to the lingual/palatal surfaces were seen in 56% of VRFs whilst the rest were incomplete. Several previous studies reported 50% and 90% prevalence of complete fractures in VRF cases (Walton et al., 1984; von Arx & Bosshardt, 2017). However, due to the dynamic nature of VRF, an incomplete VRF may propagate to a complete VRF with time under the influence of masticatory forces (von Arx & Bosshardt, 2017). An isthmus connecting root canals may promote VRF propagation in the horizontal plane as it can be considered as a natural weak plane (Chai & Tamse, 2015). Similarly, in the present study, fracture lines propagated horizontally through the isthmus in the majority of the VRF cases with isthmus. More than 80% of the VRFs evaluated in this study had a complete corono-apical extension and were present in cervical, middle and apical third of the roots. Therefore, it was not possible to identify whether the fractures had originated coronally or apically, which may be important when evaluating their aetiology (Sugaya et al., 2015).

In the present study, even though apex locators were used to establish working length, overfills occurred in a proportion of patients. It has been reported that apex locators can locate the apical constriction and apical foramen within a range of 0.5 mm (Connert et al., 2018). Reduction of the previously established working length can occur in curved root canals during instrumentation with rotary files (Kumar et al., 2013). Further, errors in maintaining the working length could be attributed to various factors such as measurement error due to inaccuracies in the adjustment of the rubber stop, operator variability in reading the length, and reproducibility of the coronal reference point (ElAyouti & Löst, 2006). Repeating apex locator measurements during root canal instrumentation is essential to help in overcoming such errors.

One of the limitations of the current study includes the lack of knowledge of preexisting radicular dentinal microcracks (PradeepKumar et al., 2017) in teeth prior to the root canal treatment, although the role of preexisting cracks in VRF (PradeepKumar et al., 2017; De-Deus et al., 2019) may be minimal. Other risk factors such as degree of dentine removed during endodontic/restorative procedures (Wilcox et al., 1997; Kishen, 2006; Tang et al., 2010), effects of irrigant/intracanal medicaments on dentine (Kishen, 2006), canal curvature and microdefects caused by rotary instruments in root dentine (Zandbiglari et al., 2006; Bier et al., 2009; Kim et al., 2010), which may predispose root filled teeth to VRF, were not considered for matching in the current study. In addition to the above causes, factors such as root/root canal anatomy (Tamse et al., 1999; Chai & Tamse 2012) could also play a role in the formation of VRF.

Conclusion

Within the limitations of the case-control study design, after matching for age, gender, tooth type, instrumentation system, MAF size and taper, technique of canal filling and time period from completion of root canal treatment, the findings suggest that root canals filled to or beyond the radiographic apex with lateral compaction were more often associated with VRFs than the controls. Maintaining the length of instrumentation/root canal filling short of the radiographic apex is one of the controllable factors that can be incorporated into root canal treatment procedures to reduce the risk of VRF.

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The authors deny any conflicts of interest related to this study.

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CHAPTER 5

In vivo root canal preparation and dentin microcracks

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Abstract

Introduction: This *in vivo* study aimed to evaluate the development of dentinal microcracks after root canal preparation of contralateral premolars with rotary or hand instruments using micro-computed tomographic technology.

Methods: Sixty contralateral intact maxillary and mandibular premolars in which extraction was indicated for orthodontic purposes were selected and distributed into positive (n=6, teeth with induced root microcracks) and negative (n=6, intact teeth) control groups as well as 2 experimental groups (n=24) according to the instrumentation protocol: ProTaper rotary (PTR) or ProTaper hand (PTH) systems (Dentsply Maillefer, Ballaigues, Switzerland). After root canal preparation, teeth were extracted using an atraumatic technique and scanned at a resolution of 17.18 µm. A total of 43,361 cross-sectional images of the roots were screened for the presence of dentinal microcracks. The results were expressed as the percentage and number of root section images with microcracks for each group.

Results: All roots in the positive control group showed microcracks at the apical third, whereas no cracks were observed in the specimens of the negative control group. In the PTR group, 17,114 cross-sectional images were analyzed, and no microcrack was observed. In the PTH group, dentinal microcracks were observed in 116 of 17,408 cross-sectional slices (0.66%) of only 1 specimen. These incomplete microcracks extended from the external root surface into the inner root dentin at the area of reduced dentin thickness.

Conclusions: Root canal instrumentation with PTR and PTH instruments of contralateral maxillary and mandibular premolars did not result in the formation of dentinal microcracks *in vivo*.

Significance: This study highlighted that *in vivo* root canal instrumentation of maxillary and mandibular premolars did not result in the formation of dentinal microcracks.

Key words: Dentinal defect, instrumentation, micro-computed tomography, microcrack, root canal preparation, root fracture.

Introduction

Vertical root fracture (VRF) is one of the complications after root canal treatment that results in a poor prognosis of the root filled teeth (Tamse, 2006; Versiani et al., 2015). Although several iatrogenic and noniatrogenic factors have been suggested to contribute to the occurrence of VRF (Tamse, 2006) , there has been a growing interest in the effect of the root canal treatment procedure as a risk factor that may increase the predisposition of endodontically treated teeth to fracture (Versiani et al., 2015). Iatrogenic steps that contribute to dentin removal and/or increased wedging forces that exceeded the binding strength of dentin may result in root dentinal microcracks (Rivera & Walton, 2015). Thus, root canal instrumentation may be a risk factor that leads to the formation of incomplete root dentinal cracks (Onnink et al., 1994; Bier et al., 2009; Shemesh et al., 2009; Ceyhanli et al., 2016), which may progress under the influence of chewing forces to result in VRF (Onnink et al., 1994; Wilcox et al., 1997).

Root canal shaping is an integral step in root canal treatment, which facilitates mechanical debridement and creates an optimal shape for adequate root canal irrigation, medicament delivery, and root filling (Peters, 2004). Many studies have implicated that crack or defect formation in root dentin can be caused by root canal instrumentation and obturation procedures per se (Onnink et al., 1994; Wilcox et al., 1997; Bier et al., 2009; Shemesh et al., 2009; Ceyhanli et al., 2016). Others have highlighted that apical root dentinal microcracks (Adorno et al., 2009; 2011) may arise after root canal instrumentation at the apical foramen or beyond.

Conversely, non-destructive evaluations by micro–computed tomographic (micro-CT) imaging have concluded that root canal preparation may not result in the formation of new dentinal microcracks and that dentin defects/microcracks observed after preparation were preexisting cracks (De-Deus et al., 2014; 2015; 2017). A recent publication using cadaveric bone–block models concluded that microcracks observed in stored extracted teeth could be a result of extraction forces or storage conditions rather than a preexisting condition (De-Deus et al., 2019).

Most research on root canal instrumentation-derived dentinal microcracks have been performed under *in vitro* conditions with extracted teeth without standardization of age and pre-extraction conditions (Versiani et al., 2015). More recently, *in situ* studies have also been conducted using a human cadaver model (Arias et al., 2014; De-Deus et al., 2017; Bahrami et al., 2017) and a pig jaw model (Rose & Svec., 2015). However, *in vivo* evaluation is imperative in order to investigate the results of orthograde root canal instrumentation on dentinal microcrack formation in human teeth, while teeth remained in the oral environment supported by the periodontium. The presence of vital periodontal tissues is critical because it links teeth to the surrounding alveolar bone and aids in distributing forces to supporting bone (Beertsen et al., 1997). The purpose of this *in vivo* study was to evaluate the development of dentinal microcracks after root canal preparation of contralateral premolars using rotary and hand ProTaper Universal instruments (Dentsply Maillefer, Ballaigues, Switzerland) by means of micro-CT technology. The null hypothesis tested was that root canal instrumentation does not result in the formation of root dentinal microcracks *in vivo*.

Table 1 –The distributions of samples in the study.

Group	**Maxillary premolars**		**Mandibular premolars**	**Total**	
	Single rooted	Double rooted	Single rooted	Teeth	Roots
ProTaper rotary	6	6	12	24	30
ProTaper hand	6	6	12	24	30
Positive control	2	2	2	6	8
Negative control	2	2	2	6	8
Total	16	16	28	60	76

This study would provide clinically pertinent information on the probability of the occurrence of instrumentation derived microcracks in root dentin.

Material and Methods

The study protocol was approved by the University Ethical Review Board and registered in the national clinical trials registry (CTRI/2018/03/012519). Patients who required extraction of contralateral maxillary and mandibular first premolars for orthodontic treatment purposes were assessed. Written informed consent was obtained from each patient who agreed to participate (15-30 years old, healthy, nonmedicated human donors) after the methodology and purpose of the study were explained. The inclusion criteria were as follows: only intact vital premolar teeth presenting with relatively straight root canals (<20° curvature) and a fully formed apex without caries, restoration, previous root canal treatment, traumatic occlusion, or periodontal/ periapical disease. Based on these criteria, 30 contralateral premolar pairs (n=60, 76 roots), including 16 double-rooted maxillary premolars, 16 single-rooted maxillary premolars, and 28 single-rooted mandibular premolars, were selected. All maxillary premolars (32 teeth) had 2 root canals (64 canals), whereas mandibular premolars (28 teeth and 28 canals) had 1 root canal each (Table 1).

Sample Size Calculation

The ideal sample size for this *in vivo* study on microcrack formation was calculated from the results of a previous study (Ceyhanli et al., 2016). The sample size was calculated using G power v.3.1.9.2 for Windows (University of Düsseldorf, Düsseldorf, Germany) based on the proportional difference formula with an alpha-type error of 0.05 and a beta of 0.95. The estimated sample size was 21 teeth per group.

Root Canal Preparation and Groups

After local anesthesia and rubber dam isolation, access cavities were prepared using a round bur (Mani Inc, Tokyo, Japan) in a high-speed handpiece. The working length (WL) was established with an electronic apex locator (Dentaport ZX; J Morita, Tokyo, Japan) and radiographically verified with a stainless steel (SS) size 10 K-file

(Mani Inc, Tokyo, Japan). A glide path was prepared with a SS size 15 K-file (Mani Inc). Contralateral premolars were randomly assigned to 2 experimental (n=24) and 2 control (n=6) groups in a split-mouth design using a coin toss method (Graunaite et al., 2018). This resulted in an equal and random distribution of tooth types. Canal preparation was performed according to the manufacturer's directions as follows:

1. The ProTaper rotary group (PTR, n=24): in maxillary premolars (n=12), rotary preparation was performed in both canals using S1 and S2 followed by F1, F2, and F3 instruments up to the WL. A similar protocol was followed in mandibular premolars (n=12), and further apical enlargement was performed with F4 and F5 instruments. An X-Smart endodontic motor (Dentsply Maillefer, Ballaigues, Switzerland) was used with a specific torque and velocity for each instrument in accordance with the manufacturer's instructions, and the instrumentation was performed with in and out strokes in an apical direction.
2. The ProTaper hand group (PTH, n=24): in maxillary premolars (n=12), hand preparation was performed in both canals using a crown-down modified balanced force technique with S1 and S2 followed by F1, F2, and F3 manual instruments up to the WL without apical pressure (Shen et al., 2007). A similar protocol was followed with the mandibular premolars (n=12), and further apical enlargement was performed with F4 and F5 manual instruments.
3. The positive control group (n=6): after extraction and access cavity preparation, instrumentation was performed intentionally beyond the apex with a SS size 80 K-file (Mani Inc.) to induce microcracks (Rose & Svec, 2015).
4. The negative control group (n=6): intact teeth (no access preparation or instrumentation)

A single experienced operator, who was trained in the instrumentation protocols, performed all root canal preparations. Instruments were used for 2 canals only and discarded. Apical patency was verified in between instruments in both groups with a SS size 10 K-file. Each canal was irrigated with 30 mL 3% sodium hypochlorite during preparation with a 30-G side-vented needle (Dentsply Maillefer). Final irrigation was performed with 5 mL 17% EDTA followed by 5 mL bidistilled water (De-Deus et al., 2017). Teeth were extracted by an experienced oral surgeon using an atraumatic technique, as previously reported (PradeepKumar et al., 2017). In brief, an intrasulcular incision was used to separate the mucoperiosteum from the root and bone. Periotomes were used to sever the periodontal ligament from the root surface. Extraction was completed with luxators and forceps (PradeepKumar et al., 2017). The extracted teeth were stored in 0.1% thymol at 5°C for further evaluation.

Micro-CT Evaluation

All specimens were scanned using a micro-CT system (SkyScan 1176; Bruker-micro-CT Kontich, Belgium) at 90 kV and 276 mA with an isotropic resolution of 17.18 μm with 180° rotation around the vertical axis, a rotation step of 0.7°, a camera exposure time of 650 milliseconds, and frame averaging of 2. X-ray was filtered with a 0.1 mm copper filter. Images were reconstructed with NRecon v.1.6.10.4 (Bruker-micro-CT) using 20% of beam hardening correction, ring artifact correction of 5, and smoothing of 5, resulting in the acquisition of approximately 1226 transverse cross sections per sample (De-Deus et al., 2014). A total of 43,361 cross-sectional images of roots from the cementoenamel junction to the apex were screened for the presence of dentinal microcracks using Dataviewer software version 1.5.1.2 (Bruker-micro-CT) by 2 previously calibrated examiners who were blinded to the experimental groups. Image analysis was repeated twice at 2-week intervals. In case of discrepancies, images were examined together, and an agreement was reached (PradeepKumar et al., 2017). A crack was identified as a break or disruption in the tooth structure without the separation of parts (Ratcliff et al., 2001).

Statistical Analysis

The results were expressed as the percentage and number of cracked root section images for each group. The Fisher exact test was used to compare differences between the 2 experimental groups. All the analyses were performed using SPSS 16.0 software (IBM Corp, Chicago, IL). The level of significance was set at $\alpha < 0.05$ Kappa statistics was used to evaluate interexaminer variability.

Results

In the positive and negative control groups 4210 and 4629 cross-sectional images of the roots were analyzed, respectively. All roots in the positive control group showed microcracks at the apical third in 792 (18.8%) sections, whereas no cracks were observed in the specimens of the negative control group (Fig. 1A and B). In the screened cross-sectional images from the PTR (n=17,114) and PTH (n=17,408) groups (Fig. 2A and B), microcracks were observed in 116 (0.66%) sections of the PTH group only, corresponding to 1 tooth sample. Dentin microcracks were observed in 1 tooth (1/24) in the PTH group and were not observed in the PTR group (0/24), which was not significant ($P < 0.05$). These cracks extended from the external root surface into the inner root dentin at the area of reduced root dentin thickness (Fig. 3A–E). A Kappa value of 0.9 was attained, indicating good interobserver reliability.

Discussion

The current study aimed to evaluate the formation of dentinal microcracks after *in vivo* root canal preparation of contralateral maxillary and mandibular premolars with ProTaper Universal rotary and hand instruments. Since 2014, experimental protocol has been suggested to play a major role in the results obtained while reporting post instrumentation root microcracks (De-Deus et al., 2014; Arias et al., 2014). This research aimed to reduce the influence of confounding factors such as age, sex, and tooth type on sample selection by using contralateral premolars of the same patient presenting similar canal/root morphology according to a previously validated split-mouth study design (Johnsen et al., 2018). Additionally, root canal instrumentation systems used in the rotary (PTR) and hand (PTH) groups had a similar tip size and taper. The preparation protocols using the ProTaper system were chosen because of contradictory results from previous studies (Bier et al., 2009; Liu et al., 2013; Capar et al., 2014; Rose & Svec, 2015). Although laboratory investigations using conventional sectioning and microscopic approaches have reported a variable incidence of microcracks (i.e., 56% (Capar et al., 2014), 50% (Liu et al., 2013), and 16% (Bier et al., 2009) after canal instrumentation with the ProTaper system, an *in situ* investigation using a pig jaw model (Rose & Svec, 2015) reported no microcrack formation after canal instrumentation with this system. Additionally, *in vitro* and *in situ* human cadaver based experiments that used non-invasive micro-CT technology concluded that the mechanical instrumentation of root canals did not induce dentinal defects, whereas the microcracks observed were categorized as preexisting cracks (De-Deus et al., 2014; 2015; 2017).

The use of a human cadaver model allowed the assessment of preexisting microcracks in the experimental teeth (De-Deus et al., 2017). However, the approach does not allow the evaluation of teeth in their natural condition (i.e., supported by vital periodontium), which would most accurately reflect clinical conditions. In the current study, clinical steps for *in vivo* instrumentation were followed, and the teeth were subsequently evaluated using non-destructive micro-CT technology (Versiani et al., 2015) after atraumatic and careful extraction in order to avoid damage to the roots (Fernandes et al., 2011; PradeepKumar et al., 2017). Preoperative micro-CT scans were not performed because of the clinical nature of the study.Therefore, no information regarding the condition of the roots before canal preparation was available. However, the current results supported the present practice because no dentinal microcrack was observed in the negative group and only one sample in the experimental groups had microcracks. This observation is in accordance with the previous micro-CT based studies (De-Deus et al., 2014; 2015; 2017). In this study, all positive control specimens showed apical cracks in the buccolingual direction, involving the canal and the root surface, which can be attributed to the aggressive/intentional instrumentation beyond the root apex. In the experimental group, the only exception was a double-rooted maxillary first premolar of the PTH group, which showed a buccolingually oriented crack at the furcation region, similar to VRF (Tamse, 2006; Rivera & Walton, 2015). The crack was incomplete and originated from the root surface rather than from the root canal wall (Fig. 3E) (Tamse, 2006; Rivera & Walton, 2015; Kishen et al., 2004). Therefore, it could not be associated with canal preparation. Although the possibility of a preexisting crack cannot be fully excluded (PradeepKumar et al., 2017), in this specimen, it is likely that the presence of a deep groove in this root surface associated with the reduction of dentin thickness (Chai et al., 2018) after instrumentation (Fig. 3D) favoured microcrack formation when this root had been submitted to extraction forces. Therefore, the null hypothesis that root canal instrumentation does not result in the formation of root dentinal microcracks *in vivo* was accepted. This finding is supported by a recent *in situ* cadaveric model study (De-Deus et al., 2019) that suggests that microcracks observed in extracted teeth subjected to root canal procedures are the result of the extraction process and/or the post extraction storage conditions.

The current *in vivo* study was performed on patients requiring extraction of contralateral maxillary and mandibular first premolars as part of their orthodontic treatment. Maxillary premolars (PradeepKumar et al., 2016) and mandibular premolars (Tamse, 1988) have been reported to be susceptible to VRF.

Double-rooted maxillary premolars, single-rooted maxillary premolars, and single-rooted mandibular premolars were randomly and equally distributed in both experimental groups (Table 1). To the best of our knowledge, this is the first report that assessed the potential correlation between *in vivo* root canal preparation and the formation of dentinal microcracks using highly accurate and non-invasive micro-CT technology. There was no significant difference between the experimental groups, suggesting that both hand and rotary instrumentation may not result in the formation of dentinal microcracks. However, one of the limitations of this study was that all patients were between 15 and 30 years of age. Root dentin in older individuals may exhibit a significant decrease in strength and resistance to fatigue because of changes in the microstructure and chemical composition (Yan et al., 2017). Also, post endodontic VRF has been reported to be more common in patients >40 years of age (PradeepKumar et al., 2016). Therefore, further research may be necessary to evaluate the results of root canal preparation in older patients. A micro-CT system resolution of 17.18 µm was used in this study, whereas future investigations with higher-resolution imaging may be beneficial.

Figure 1: Control groups. Representative 3-dimensional models and cross sections of the root and root canals of (A) a maxillary first premolar (negative control) and (B) a mandibular first premolar (positive control) depicting the absence of cracks in the negative control and the presence of a complete dentinal crack (white arrows in cross sections 1 and 2) at the apical third of the positive control specimen.

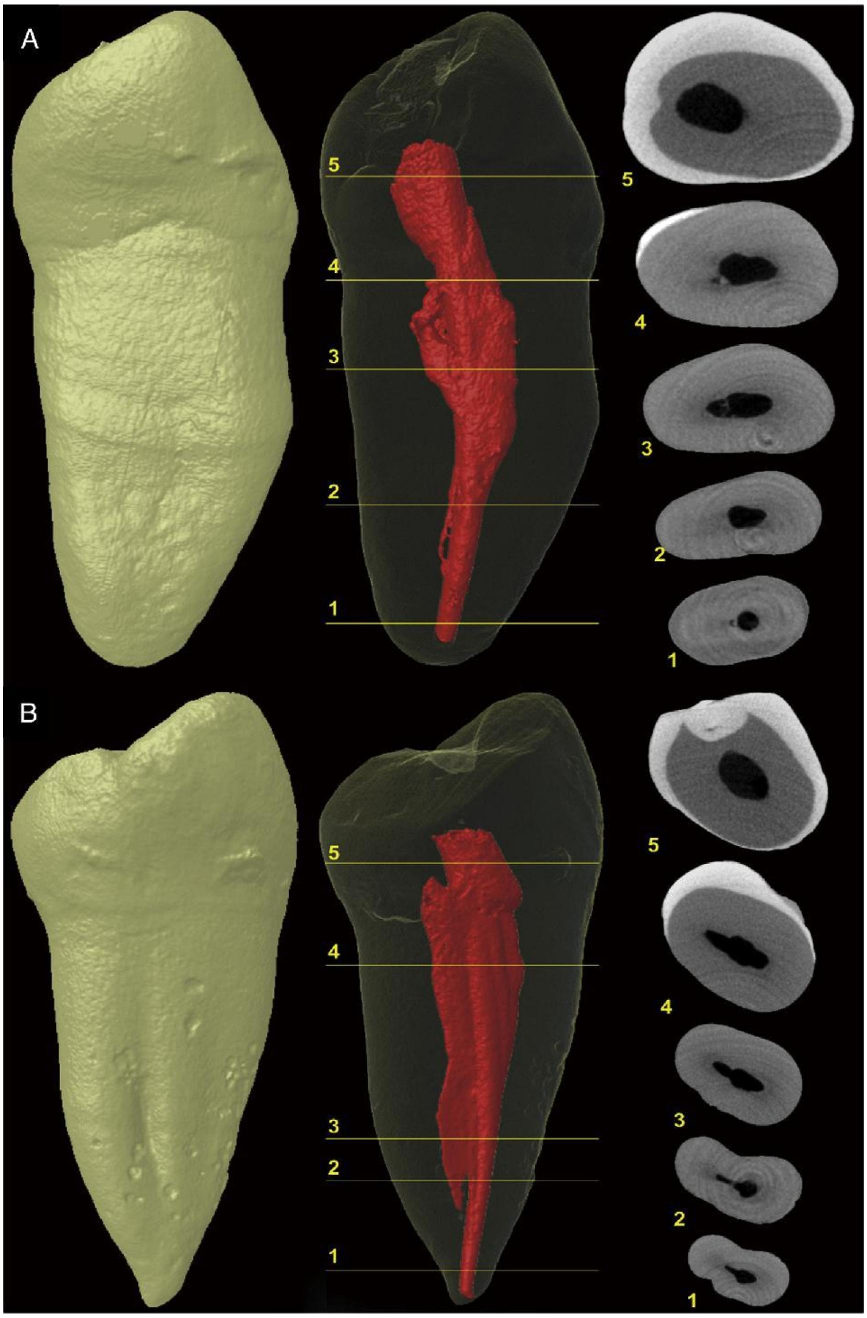

Figure 2: Experimental groups. Representative 3-dimensional models and cross sections of the root and root canals of (A) a mandibular first premolar prepared with PTH instruments (PTH group) and (B) a mandibular first premolar prepared with PTR instruments (PTR group) showing the absence of cracks in different levels of the root.

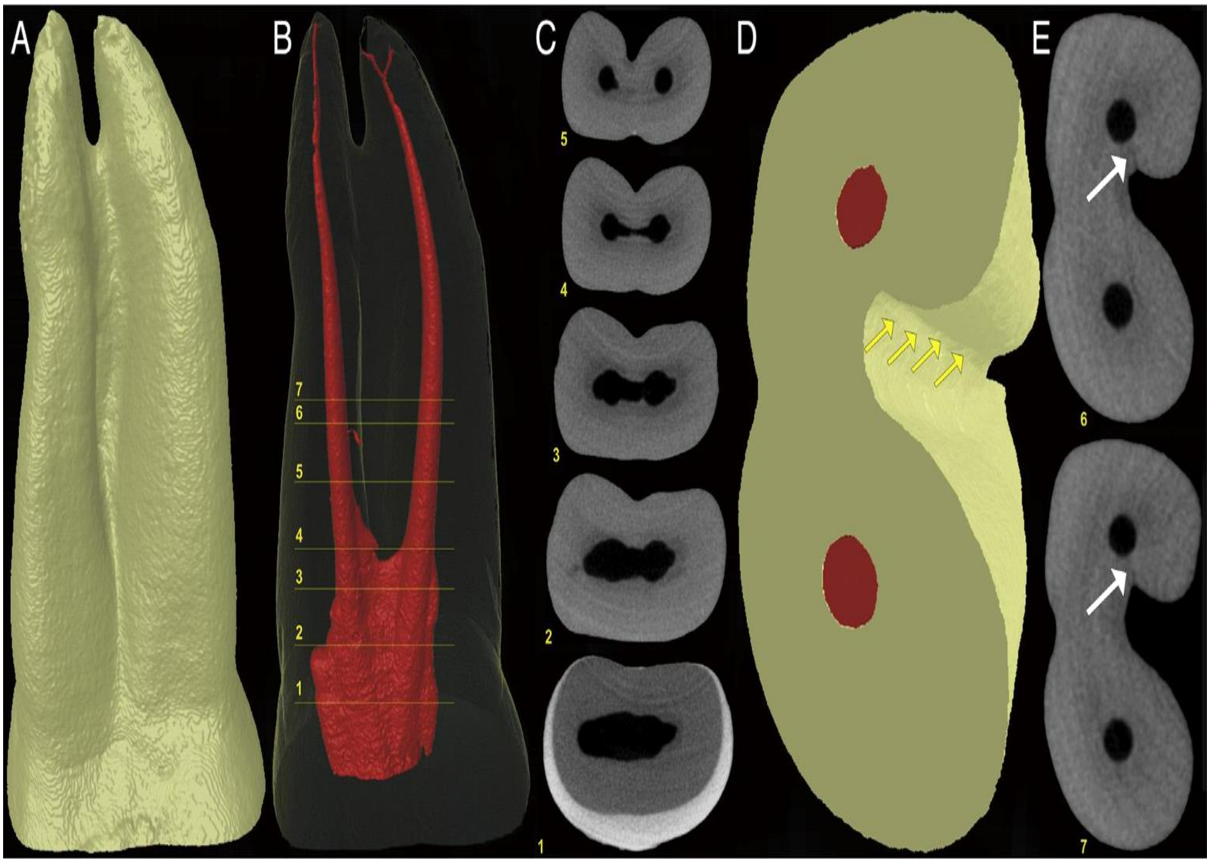

Figure 3 – A representative (A and B) 3D models and (C) cross sections of the root and root canals of a maxillary first premolar prepared with PTH instruments (PTH group) showing the absence of cracks at the coronal level. (D) A view of the root sectioned at the middle level depicting the presence of a radicular groove (yellow arrows). (E) Cross sections of the root at the middle third showing the presence of an incomplete dentinal crack (white arrows in cross sections 6 and 7) at the thinnest dentin thickness area.

Conclusion

Within the constraints of this *in vivo* study, it was concluded that the preparation of root canals with PTR or PTH instruments did not result in root dentinal microcracks. These findings also indicate that previous data from *ex vivo* experiments on root dentinal microcracks should be considered with caution.

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CHAPTER 6

General Discussion

A tooth with VRF has a poor prognosis and is usually treated by extraction of the affected root or tooth (Rivera & Walton, 2015). Therefore, it may be prudent to take preventive measures to reduce the possibility of VRF. In this regard, it would be better to avoid excessive dentin removal (Wilcox et al., 1997) during root canal procedures and to minimize intracanal wedging forces (Rivera & Walton, 2015). Once a VRF has occurred, diagnosis can be complicated (Tamse, 2006) due to variable signs, symptoms and radiographic findings. Also, clinical signs and symptoms of VRF can manifest years after endodontic treatment (Fuss et al., 2001). Therefore, the first part of this thesis (Chapter 2) dealt with the related clinical and radiographic diagnostic features of VRFs in crowned endodontically treated teeth. In this study, root canal treated teeth with post and without a crown were excluded to avoid confounding factors. It was found that mandibular molars and maxillary premolars were most commonly affected by VRF. Overfilled root canals, posterior teeth and patients aged above 40 years were associated with VRF. This study also indicated that females might be more at risk for VRF than males. Also, signs and symptoms associated with VRF were found to be: pain on percussion, pain on palpation, presence of a sinus tract and an isolated narrow periodontal pocket. It was concluded that the mean postoperative time period before the presentation of VRFs in endodontically treated teeth with crowns and without posts was 4.35 (±1.96) years. In this study, presence of VRF was confirmed by surgical flap elevation and detection of a fracture line in the root. Thus, it was recommended to confirm VRF by surgical flap elevation (PradeepKumar et al., 2016). Therefore, it would be prudent to recall patients with root canal treated teeth for a period of five years to evaluate for VRF.

VRF has been reported in teeth without a history of root canal treatment, mainly in a Chinese population (Chan et al., 1999). The etiology has been suggested to be habitual mastication of hard foods or repetitive and excessive masticatory forces (Chan et al., 1998). Therefore, it could be speculated that root dentin may exhibit microcracks due to occlusal/masticatory forces. The second part of this thesis evaluated teeth without endodontic treatment which were extracted for reasons not related to this study. These teeth were scanned with micro-computed tomography and the images were examined for the presence of root dentinal microcracks.

633 nonendodontically treated teeth were evaluated and fortyfive exhibited preexisting microcracks in roots resulting in a prevalence of 7.1%. It was found that the prevalence of preexisting microcracks was higher (8.3%) in patients aged 40–70 years compared with patients (3.7%) aged 20–39 years. It has been reported that the flexural strength, fatigue strength and fracture toughness of dentin can reduce with increase in age (Arola & Reprogel, 2005; Nazari et al., 2009). Therefore, an increased tendency to formation of root cracks and fractures may be anticipated in older patients. Also, a significant association was present between tooth location and the presence of root dentinal microcracks. Preexisting microcracks were mainly present in mandibular teeth (10.3%) when compared with maxillary teeth (2.9%). All preexisting microcracks in this study were located mesiodistally; more than 60% occurred in the middle and cervical thirds of roots. 33% of the preexisting microcracks were complete cracks with canal involvement (PradeepKumar et al., 2017). All microcracks extended from the root surface and proceeded towards the root canal. However, the origin of VRF in endodontically treated teeth has been reported to be from the canal surface (Arias et al., 2014). This difference in crack origin may be due to different biomechanical principles underlying crack initiation in nonendodontically treated and endodontically treated teeth. Preexisting root dentinal microcracks can lead to pulpal necrosis (Berman & Kuttler, 2010). This study has demonstrated the presence of root dentinal microcracks in teeth without root canal treatment.

Root canal treatment is done in various stages as follows: access preparation, shaping and cleaning the root canals and root filling. It was indicated in the first part of this thesis that overfilled root canals can be associated with VRF. The third part of this thesis evaluated the impact of apical extent of root canal filling on VRF by a case control study design. In this study, roots with VRF (cases) were compared to roots without VRF (controls) and the apical extent of root canal filling (overfilled: filled up to or beyond the radiographic apex or not overfilled: filled short of the radiographic apex) was registered as the dependent variable. Cases and controls were matched for gender, age, tooth type, MAF size, MAF taper, canal filling technique (lateral compaction) and the time period after completion of root filling. It was found that root canals filled up to or beyond the radiographic apex (overfilled) had a greater association with VRF than root canals that were filled short of the radiographic apex (not overfilled). Matching of VRF cases with controls without VRF was done to reduce the effect of confounding factors. It has been reported that the apical extent of root canal instrumentation can correlate with the apical extent of root filling (Ng et al., 2011). Therefore, overfilled root canals may represent over-instrumented root canals.It was concluded that overfilled canals can be a risk factor for VRF. Repeating apex locator measurements before and in-between root canal instrumentation steps may help in the prevention of overinstrumentation and subsequent overfilling.

In this study, the root canal treated teeth with VRF were extracted. Then, the teeth were sectioned and the bucco-lingual extent of VRF was evaluated. It was found that fracture lines propagated horizontally through the isthmus in the majority of cases of VRF occurring in a root with isthmus. Therefore, an isthmus may act as a weak plane and help in horizontal propagation of VRF (Chai & Tamse, 2018).

It has been reported that root canal instrumentation can be a risk factor which can lead to the formation of dentinal microcracks which may develop into a VRF (Wilcox et al., 1997; Shemesh et al., 2009). However, most research on root dentinal microcracks formed as a result of root canal instrumentation have been done under *in vitro* conditions using extracted teeth (Versiani et al., 2015). Recently, *in situ* human cadaver studies have also been done (Arias et al., 2014; De-Deus et al., 2017). However, there were no published *in vivo* studies which may result in clinically relevant information. Therefore, the fourth part of this thesis was done to evaluate the effect of *in vivo* root canal instrumentation on the formation of root dentinal microcracks. Patients who required tooth extraction as part of their orthodontic treatment plan were invited to participate in this study. Root canal instrumentation was done with either hand or rotary ProTaper instruments. The teeth were subsequently extracted and evaluated by micro-computed tomographic imaging analysis for the presence of root dentinal microcracks. It was found that only one tooth in the experimental groups had root dentinal microcracks. This tooth also demonstrated the presence of a deep radicular groove. Also, the microcrack appeared to originate from the external surface of the root and might have been caused due to reduced dentin thickness in that region coupled with extraction forces. Therefore, this study concluded that root canal instrumentation under *in vivo* conditions with ProTaper rotary or ProTaper hand instruments may not lead to the formation of root dentinal microcracks (PradeepKumar et al., 2019).

To sum up, this thesis presents information on the clinical and radiographic diagnostic features of VRF, the presence of preexisting root dentinal microcracks, the impact of overfilled root canals on VRF and the effect of *in vivo* root canal instrumentation on the formation of root dentinal microcracks.

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CHAPTER 7

Summary and Conclusions

Prevalence and clinical aspects of cracks and fractures in teeth

This thesis has investigated prevalence and clinical aspects of cracks and fractures, specifically root dentinal microcracks and vertical root fracture (VRF). This thesis has also investigated the effect of root filling length on VRF and the effect of *in vivo* root canal instrumentation on the formation of radicular microcracks. The summary and conclusions offered by this thesis are as follows:

1. The purpose of the first experiment was to examine different patient and treatment related factors associated with the time of presentation of VRFs in endodontically treated teeth restored with crowns. One hundred ninetyseven root filled, crowned teeth with no post and suspected of VRFs were included in the study. Patient endodontic treatment details and clinical signs/symptoms were documented, and radiographs were taken. A diagnosis of a VRF was confirmed after surgical flap elevation. Most frequent clinical findings were pain on percussion (60%), pain on palpation (62%), presence of a deep narrow pocket (81%), and sinus tract/swelling (67%). ''Halo''-type radiolucency (48.7%) was the most common radiographic feature related to VRFs. The first experiment concluded that the mean time period from root filling to the clinical presentation of VRFs in root canal treated teeth restored with crowns and without posts was 4.35 (± 1.96) years. Posterior teeth, older patients (>40 years), female patients, and overfilled canals were all found to be potential risk factors for the presentation of VRF within 5 years of root canal treatment.
2. The second experiment analyzed 633 nonendodontically treated teeth with advanced, non-invasive micro-computed tomographic imaging technology. This study evaluated the prevalence, location, and pattern of preexisting dentinal microcracks in roots of extracted teeth without endodontic treatment in patients from two age groups. Teeth were scanned with micro-computed tomographic imaging (resolution of 26.7 μm) to examine the presence of preexisting dentinal microcracks in roots. The characteristic features of preexisting dentinal microcracks determined were location, extent, length, and coronoapical distribution. Fortyfive of 633 non-endodontically treated teeth exhibited preexisting microcracks in roots with a prevalence of 7.1%. The prevalence

of preexisting microcracks was found to be 8.3% in older patients (40–70 years) compared with 3.7% in younger patients (20–39 years) ($P < 0.05$). Significantly more preexisting microcracks were found in mandibular teeth (10.3%) when compared with maxillary teeth (2.9%) ($P < 0.001$). All preexisting microcracks were located mesiodistally; 66% occurred in the cervical and middle thirds of roots. Only 33% of the preexisting microcracks were complete in nature, showing canal involvement. Complete dentinal microcracks exhibited a mean length of 6.9 mm, whereas incomplete cracks had a mean length of 3.75 mm ($P < 0.001$). This analysis revealed a 7.1% prevalence of preexisting radicular dentinal microcracks in teeth without root canal treatment. These preexisting radicular dentinal microcracks were found more commonly in mandibular teeth and in older patients (>40 years).

3. The third experiment was a case–control study. Eightysix patients (119 roots) diagnosed with VRF in crowned root filled anterior and posterior teeth were selected. In this clinical study, root canal treated teeth with VRF (cases) were matched with root canal treated teeth without VRF (controls) for age (± 5 years), gender, tooth type, root canal instrumentation system, master apical file size and taper, technique of canal filling (lateral compaction) and time period from root canal treatment to a diagnosis of VRF (same or more for controls). All root canals had been prepared using nickel–titanium (NiTi) rotary instruments and filled using the lateral compaction technique. The apical extent of root filling (overfilled: to or beyond the radiographic apex or not overfilled: short of the radiographic apex) was recorded as the dependent variable by two individual examiners. Inter-examiner agreement was obtained using Kappa statistics. Recorded numbers of overfilled and not overfilled canals in cases and controls were analyzed using chi-square tests and conditional logistic regression, and an odds ratio was calculated. In addition, the frequency distribution of vertical and cross-sectional VRF extensions and the course of VRFs were evaluated. When compared to roots not overfilled, overfilled roots had 11.5 times higher odds for occurrence of VRF (OR=11.5; CI: 4.99-26.48). Most VRFs had a complete corono-apical longitudinal extension and were present bucco-lingually/palatally. The results suggested that when root canals were filled to or beyond the radiographic apex with lateral compaction technique, they were more likely to be associated with VRFs than in the controls. The

results also indicated that the length of instrumentation/root canal filling should be maintained short of the radiographic apex to reduce the risk of VRF.

4. The fourth experiment was an *in vivo* study. Sixty contralateral intact maxillary and mandibular premolars in which extraction was indicated for orthodontic purposes were selected and distributed into positive (n=6, teeth with induced root microcracks) and negative (n=6, intact teeth) control groups as well as 2 experimental groups (n=24) according to the instrumentation protocol: ProTaper rotary (PTR) or ProTaper hand (PTH) systems (Dentsply Maillefer, Ballaigues, Switzerland). After root canal preparation, teeth were extracted using an atraumatic technique and scanned with micro-CT at a resolution of 17.18 µm. A total of 43,361 cross-sectional images of the roots were screened for the presence of dentinal microcracks. All roots in the positive control group showed microcracks at the apical third, whereas no cracks were observed in the specimens of the negative control group. In the PTR group, 17,114 cross-sectional images were analyzed, and no microcrack was observed. In the PTH group, dentinal microcracks were observed in 116 of 17,408 cross-sectional slices (0.66%) of only 1 specimen. These incomplete microcracks extended from the external root surface into the inner root dentin at the area of reduced dentin thickness. This microcrack was associated with a radicular groove and reduced dentin thickness and may have formed due to extraction forces. Within the limitations of this *in vivo* study, it was concluded that the preparation of root canals with ProTaper hand or ProTaper rotary instruments did not result in root dentinal microcracks.

The conclusions of this thesis throw light on the clinical and radiographic features of VRF. Posterior teeth, overfilled canals, female patients, and older patients (>40 years) are potential risk factors for the presentation of VRF within 5 years postoperatively. Therefore, it would be prudent to recall patients with root canal treated teeth for a period of five years to evaluate for VRF. Also, the presence of preexisting microcracks in teeth without root canal treatment was demonstrated.

It was also concluded that overfilled canals can be a risk factor for VRF. Repeating apex locator measurements before and in-between root canal instrumentation steps may help in the prevention of overinstrumentation and subsequent overfilling. Finally, root canal instrumentation under *in vivo* conditions was investigated and it was found that root canal instrumentation with ProTaper rotary or ProTaper hand instruments may not lead to the formation of root dentinal microcracks.

CHAPTER 8

Samenvatting

Prevalentie en klinische aspecten van barsten en fracturen in gebitselementen

In dit proefschrift zijn de prevalentie en klinische aspecten onderzocht van barsten en fracturen, in het bijzonder van microbarsten in het radiculaire dentine en verticale wortelfracturen (hier verder afgekort als VWF). In dit proefschrift is ook het effect onderzocht van de lengte van een kanaalvulling op VWF en het effect van instrumentatie van wortelkanalen *in vivo* op de vorming van radiculaire microbarsten. De uitkomsten van het proefschrift zijn hieronder samengevat:

1. Het doel van het eerste experiment was het onderzoeken van verschillende patiënt- en behandelingsgerelateerde factoren die verband houden met het moment van diagnose van VWF in endodontisch behandelde gebitselementen die voorzien zijn van een kroonrestauratie. Het onderzoek omvatte 197 gebitselementen, voorzien van een wortelkanaalvulling en kroonrestauratie, zonder gebruik van wortelstiften, waarbij het vermoeden van VWF bestond. De details van de endodontische behandelingen die de patiënten hadden ondergaan en de klinische symptomen werden gedocumenteerd en er werden röntgenopnamen gemaakt. De diagnose VWF werd vastgesteld na een kijkoperatie in de vorm van een diagnostische flap. Voor de bepaling van de frequentieverdelingen en de statische analyses werd gebruik gemaakt van de chi-kwadraattoets van Pearson, Fishers exacte toets, kruistabulatie, de correlatiecoëfficiënt van Pearson en multipele logistische regressie. De meest voorkomende klinische verschijnselen waren pijn bij percussie (60%), pijn bij palpatie (62%), aanwezigheid van een diepe, nauwe parodontale pocket (81%) en sinusvorming/zwelling (67%). Een ‘halo’-achtige radiolucentie (48,7%) was de meest voorkomende röntgenologische eigenschap die met VWF in verband kon worden gebracht. Uit het eerste experiment bleek dat de gemiddelde tijdsperiode tussen het vullen van het wortelkanaal en de klinische presentatie van VWF in wortelkanalen van gebitselementen die zonder gebruik van wortelstiften zijn behandeld met kronen, bij 4,35 (± 1,96) jaar lag. Posterieure gebitselementen, oudere patiënten (>40 jaar), vrouwelijke patiënten en overvulde wortelkanalen bleken allen potentiële risicofactoren te zijn voor de vorming van VWF binnen 5 jaar na uitvoering van de wortelkanaalbehandeling.

2. Bij het tweede experiment werden 633 niet-endodontisch behandelde gebitselementen geanalyseerd met behulp van geavanceerde, niet-invasieve beeldvorming door middel van micro-CT-technologie. Bij dit onderzoek is gekeken naar de prevalentie, de locatie en het patroon van reeds bestaande microbarsten in het radiculaire dentine van niet-endodontisch behandelde, geëxtraheerde gebitselementen van patiënten uit twee leeftijdsgroepen. De gebitselementen werden gescand met behulp van micro-CT-scans (resolutie van 26,7 µm) om deze te onderzoeken op de aanwezigheid van reeds bestaande microbarsten in het radiculaire dentine. De karakteristieke kenmerken van de vastgestelde, reeds bestaande microbarsten in het radiculaire dentine, waren de plaats, omvang, lengte en coronoapicale spreiding. Voor het bepalen van het verband tussen de verschillende parameters werd gebruik gemaakt van bivariate chi-kwadraatanalyse. Bij 45 van de 633 niet-endodontisch behandelde gebitselementen was sprake van reeds bestaande radiculaire microbarsten, met een prevalentie van 7,1%. De prevalentie van reeds bestaande microbarsten bleek bij oudere patiënten (40–70 jaar) bij 8,3% te liggen, vergeleken met 3,7% bij jongere patiënten (20–39 jaar) (P< 0,05). Er was sprake van een significant verband tussen het bestaan van microbarstjes in gebitselementen van de onderkaak (10,3%) vergeleken met die van de bovenkaak (2,9%) (P< 0,001). Alle reeds bestaande microbarsten bevonden zich mesiodistaal; 66% ervan deed zich voor in het halsgedeelte en middelste gedeelte van de wortel. Slechts 33% van de reeds bestaande microbarsten was volledig en was daarmee ook het kanaal betrokken. De complete microbarsten van het radiculaire dentine hadden een gemiddelde lengte van 6,9 mm, terwijl dit bij incomplete microbarsten een gemiddelde lengte was van 3,75 mm (P< 0,001). Bij deze analyse was sprake van een prevalentie van 7,1% ten aanzien van reeds bestaande microbarsten in het radiculaire dentine, zonder voorafgaande wortelkanaalbehandeling. Deze reeds bestaande microbarsten in het radiculaire dentine kwamen vaker voor bij gebitselementen in de onderkaak en bij oudere patiënten (>40 jaar).
3. Het derde experiment was een casusonderzoek met controlegroep. Er werden 86 patiënten (119 wortels) geselecteerd waarbij VWF kon worden vastgesteld in anterieure en posterieure gebitselementen, voorzien van een kroon en een wortelkanaalvulling. Bij dit klinische onderzoek werden gebitselementen met VWF waarin een

wortelkanaalbehandeling was uitgevoerd (casussen) vergeleken met gebitselementen met wortelkanaalbehandeling waarin zich geen VWF had voorgedaan (controlegroep), op basis van leeftijd ± 5 jaar, geslacht, type gebitselement, instrumentatiesysteem voor het wortelkanaal, formaat en coniciteit van de laatste apicale vijl, vultechniek voor het wortelkanaal en de tijdsperiode tussen de wortelkanaalbehandeling en de diagnose VWF (vergelijkbaar of groter voor de controlegroep). Alle wortelkanalen waren geprepareerd met behulp van roterende instrumenten van nikkel–titanium (NiTi) en werden gevuld met behulp van de laterale compactietechniek. De apicale lengte van de wortelvulling (overvulling tot aan of verder dan de röntgenologische apex of niet overvuld en tot kort voor de röntgenologische apex lopend) werd als afhankelijke variabele vastgelegd door twee afzonderlijke onderzoekers. Onderlinge overeenstemming tussen de onderzoekers werd verkregen door middel van Kappastatistiek. Het vastgelegde aantal overvulde en goed (op lenge) gevulde kanalen bij casussen en in de controlegroep werd geanalyseerd met behulp van chi-kwadraattoetsen en conditionele logistische regressie en er werd een odds-ratio berekend. Daarnaast werd de frequentieverdeling beoordeeld van de uitbreiding in verticale richting en aan de hand van doorsneden en tevens van het verloop van verticale wortelfracturen. Vergeleken met goed gevulde wortelkanalen, was er bij overvulde wortelkanalen sprake van een odds-ratio die 11,5 keer hoger lag ten aanzien van het optreden van VWF (OR=11,5; CI: 4,99-26,48). De meeste VWF strekten zich over de volledige coronoapicale lengte uit en bevonden zich buccolinguaal/palataal. Uit de resultaten blijkt dat bij vullen van de wortelkanalen tot aan of verder dan de röntgenologische apex door middel van de laterale compactietechniek, zich vaker VWF voordeed dan bij de controlegroep. Uit de resultaten kwam ook naar voren dat de lengte van de instrumentatie/wortelkanaalvulling tot net voor de röntgenologische apex zou moeten reiken, om zo het risico van VWF te verminderen.

4. Het vierde experiment was een *in vivo* onderzoek. Er werden 60 contralaterale, intacte premolaren van de boven- en onderkaak geselecteerd, waarbij extractie geïndiceerd was om orthodontische redenen. Deze werden verdeeld in een positieve controlegroep (n=6, gebitselementen met bewust veroorzaakte radiculaire microbarsten) en een negatieve controlegroep (n=6, intacte gebitselementen) en in 2 onderzoeksgroepen (n=24), aan de

hand van het instrumentatieprotocol: Roterend ProTaper-systeem (PTR) of handmatig ProTaper systeem (PTH) (Dentsply Maillefer, Ballaigues, Zwitserland). Na de wortelkanaalpreparatie werden de gebitselementen geëxtraheerd door middel van een atraumatische techniek en vervolgens gescand door micro CT bij een resolutie van 17,18 µm. In totaal werden er 43.361 doorsneden van de wortels gescreend op de aanwezigheid van radiculaire microbarsten. Bij alle wortels in de positieve controlegroep was er sprake van microbarsten in het apicale derde deel, terwijl er geen barsten werden vastgesteld in de exemplaren uit de negatieve controlegroep. In de PTR groep werden er 17.114 doorsneden geanalyseerd en was er geen sprake van microbarsten. In de PTH groep was er sprake van radiculaire microbarsten in 116 van de 17.408 doorsneden (0,66%) van slechts 1 exemplaar. Deze incomplete microbarsten liepen vanaf het externe worteloppervlak naar het interne radiculaire dentine, naar de plaats waar het dentine dunner was. Deze microbarst kon in verband worden gebracht met een wortelgroeve en verminderde dikte van het dentine en kan zijn ontstaan door de kracht die bij de extractie werd uitgeoefend. Binnen de beperkingen die dit *in vivo* onderzoek eigen waren, kon worden vastgesteld dat preparatie van wortelkanalen met behulp van ProTaper-handinstrumenten of roterende ProTaper-instrumenten niet tot microbarsten leidde.

De conclusies uit dit proefschrift werpen licht op de klinische en röntgenologische eigenschappen van VWF. Posterieure gebitselementen, overvulde kanalen en oudere patiënten (>40 jaar) zijn mogelijke risicofactoren waardoor zich 5 jaar na een wortelkanaalbehandeling VWF kunnen voordoen. Het zou daarom verstandig zijn om patiënten die een wortelkanaalbehandeling hebben ondergaan, gedurende een periode van 5 jaar op controle te laten komen ter beoordeling van mogelijke VWF. Ook de aanwezigheid van bestaande microbarsten in gebitselementen zonder wortelkanaalbehandeling werd aangetoond.

Bovendien werd vastgesteld dat overvulde kanalen een risicofactor kunnen vormen voor het optreden van VWF. Het doen van apex lengte metingen voor en tijdens de instrumentatie van het wortelkanaal kan mogelijk helpen om overinstrumentatie en later overvullen te voorkomen. Tenslotte werd er onderzoek gedaan naar de wortelkanaalinstrumentatie onder *in vivo* omstandigheden en kon worden vastgesteld dat wortelkanaalinstrumentatie met roterende ProTaper-instrumenten of ProTaper-handinstrumenten vermoedelijk niet tot de vorming van radiculaire microbarsten leidt.

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List of publications

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AR contributed to conception, design, data acquisition, data analysis and interpretation, drafted, and critically revised the manuscript.

HS, **AK and SJL** contributed to conception, design, data analysis and interpretation, drafted, and critically revised the manuscript.

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