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Damages to Radicular Dentin during Root Canal Filling and Retreatment Procedures: Analysis, Evaluation Methods and Methodological Issues

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Abstract: ***This review article focuses on some of the factors leading to damages of radicular dentin in the course of different root canal filling techniques and retreatment procedures. Conflicting results in literature exist regarding the effect of single-cone obturation, cold lateral condensation and thermomechanical compaction of gutta-percha in terms of stress generation onto the root canal wall. Experimental data is inconsistent concerning the incidence of root cracks after retreatment procedures performed with specifically designed nickel-titanium rotary systems. These contradictory statements are likely due to the methodological issues and sample selection utilized in the laboratory experiments. An attempt is made to summarize and analyse the existing data concerning various observational methods used for microcrack detection, pointing out their advantages, disadvantages and limitations.***

Keywords: dentinal microcracks, nickel-titanium rotary files, observational methods, root canal filling, retreatment procedures

1. Introduction

The proper cleaning and shaping procedures during endodontic treatment of irreversibly damaged pulp tissue ensure adequate three-dimensional, tight-seal obturation of the root canal space, thus increase the function, integrity and long-term survival of pulpless teeth as a part of the dentition [1], [2]. Nevertheless, in cases of a failed endodontic treatment a retreatment is performed in an attempt to eliminate the existing microbiota and to improve tooth prognosis [3], [4], [5].

In the course of the primary endodontic treatment and retreatment cases damages on root canal dentinal wall may appear leading to formation of craze lines and microcracks. Some of them can propagate into vertical root fracture (VRF) which is believed to be one of the most frequent reasons for tooth extraction [6]–[9]. Due to the stress generated in the inner root canal wall and its distribution to the root outer surface, the binding dentinal forces can be overcome [9], [10]. In such cases, the ultimate tensile strength of dentin becomes lower than the tensile stress in the canal [11].

The current review article focuses on different root canal obturation and retreatment techniques as potential sources of damages to root canal dentin. The most common destructive and non-destructive methodologies involved in the study of radicular microcracks are discussed, as well.

2. Root Canal Filling Techniques

The final goal of the endodontic treatment is the complete, homogenous, three - dimensional sealing of the root canal system to a preliminary measured working length using biocompatible material [12]. The creation of a fluid-tight barrier between the root canal space and the periodontal tissues prevents passage of toxins and fluids that could compromise the treatment outcome [2], [13].

Various obturation methods and materials have been advocated. Gutta percha and sealers are mostly used for root canal filling with a single cone, cold lateral condensation (CLC), warm vertical compaction (WVC) and thermoplasticized gutta-percha techniques [2], [13]–[16]. Generation of stress on the root canal wall depends on the technique used [17]. The lateral, vertical or thermomechanical compaction itself always implies tension on the dentinal walls, depending on the force applied to the filling material [18], [19], [20]. These forces mechanically alter the matrix of dentin and can finally lead to a progression of minor cracks to complete cracks and vertical root fractures [21], [22].

Although the single-cone technique, cannot provide adequate seal of the root canal, it causes no strain accumulation onto the root canal wall and does not affect significantly the apical crack initiation and propagation. Thus, the so called monophase obturation does not induce the appearance of new, and the propagation of pre-existing microcracks [23].

Cold lateral condensation of gutta-percha is used and taught for many decades worldwide and is proven to be clinically effective [24]–[27]. The basic protocol comprises of: adjustment of a master cone; choice of a proper size of a conical steel or nickel-titanium (NiTi) spreaders 1 mm shorter than the full working length; application of a sealer; placement of the master cone at full working length and its lateral and apical compaction with a spreader; application of accessory cones. The procedure continues till the entire root canal is filled and gutta-percha is cut at the orifice level.

Many clinicians still use this technique because it does not require any special or expensive equipment and for the predictability of the filling at the apical level. However, this method is time-consuming and sometimes root canal fillings lack homogeneity [28] and poorly adapt to the canal walls [29]. Importantly, while attempting to create space for the insertion of additional gutta-cones, defects on the root canal wall might appear [21], [30]. Compared to the single-cone technique, the CLC method causes much more dentinal defects [9], [31], [32]. The excessive force during CLC is considered as the trigger for VRF because it causes ununiformly distributed surface strain [9], [21], [33]. To prevent this undesirable outcome some researchers, recommend the use of a light force (compared to that of holding a pan) when penetrating the spreader sideways the main gutta-percha cone [34].

According to the current knowledge, it is inconclusive whether the application of spreader low penetration forces (under 3kg) is prone to generate dentinal defects or VRF in endodontically treated teeth [22]. The spreader load causing VRF was first reported by Pitts et al. and ranged 7,2 kg [30]. Therefore, the authors recommend the use of a spreader load lower than 5,0 kg. Later investigations showed that even lower values such as 3,5kg and even 1,5 kg can cause fractures [35].

Another factor contributing to the strain accumulation in roots of extracted teeth might be the taper of the spreader [36], [37], [38]. The results of these studies were in accordance with Wilcox et al. who correlated the use of large-tapered spreaders with strain generation and root fracture [10].

The topic for spreader generated dentinal stresses and crack development is complex and there is a lack of agreement in the literature. The mechanism involves several different factors related to the tooth (anatomy, age, root contour and size, preparation size, dentin thickness, etc.), the technique (spreader type, maximum load at penetration, level of penetration, type of gutta-percha cone), and the operator's skills [22].

Warm vertical compaction was originally introduced to overcome the disadvantages of CLC and described by Schilder in his study "Filling of the root canal in three dimensions" [2], [13]. After a heated spreader is used to remove the coronal segment of the master cone, a cold hand plugger is used to apply vertical pressure to the softened master cone [2]. The obturation of the coronal portion of the canal is accomplished by adding gutta-percha segments that are softened by successive use of heat pluggers and gradual vertical compaction. A homogenous and dimensionally stable root canal filling is obtained through formation of waves of softened gutta-percha [22]. Thermoplasticized gutta-percha decreases the overall pressure of compaction, avoiding strong forces over the dentinal wall [22]. As no spreaders are used, it is hypothesized that when WVC is performed skillfully, root fractures are not likely to occur [39]. Nevertheless, hydraulic forces formed during the procedure could create pressure on the root canal wall and induce a wedging effect capable of damaging the root [17], [19], [20], [32], [40].

Stress generation on root canal wall during WVC depends on variety of factors: the taper of the prepared root canal, the size of the plugger, and the temperature of the material during the filling procedure. The radicular pressure decreases with the increase of the size and the taper of the root canal because of the development of areas with bigger contact surface. The greater the diameter of the canal is, the even the distribution of compaction forces [34], [35]. If the plugger fits precisely, the circumferential load on the root canal wall is less, though it can increase the pressure in its apical third [34].

Currently, some thermoplastic carrier-based obturation products are available on the market – Thermafil (Dentsply Sirona, Ballaigues, Switzerland), Thermafil Plus (Dentsply Sirona, Ballaigues, Switzerland), Gutta Core (Dentsply Sirona, Ballaigues, Switzerland), RealSeal 1 (SybronEndo, Glendora, CA), Soft – Core (Kerr, Orange, CA, USA), SimpliFill (Kerr, Orange, CA, USA). All these systems use proprietary ovens to heat the surrounding material to a specific temperature before placing the obturator into the root canal. Hand metal or plastic size verifiers aid proper choice of obturator size prior to its placement into the canal. Thermafil was manufactured with a metal carrier, whereas the new Thermafil Plus has a plastic one. The carrier of RealSeal 1 is a polysulfone-containing polymer with radiopaque filler that is coated by Resilon. GuttaCore has a rigid, cross-linked gutta-percha core as a carrier for the coating of alpha-phased gutta-percha. The manufacturer states that the inner part of this obturator is not affected by the heat and is more easily removed when retreatment is needed [41], [42]. This technique is easily performed and provides better three-dimensional and homogenous sealing of the root canal system compared to CLC [43]. Thermoplasticized gutta-percha acts thixotropically which means that it flows with less viscosity at faster insertion rates with greater force [44].

It is assumed that during root canal filling procedures the dentin is elastic enough to withstand the effect of the accumulated surface strain, without exhibiting root fracture. Nevertheless, when using different methods for hermetic obturation of the root canal system, certain deformations that initially remain latent, can occur [37]. In time, small, incomplete fracture lines may cause real vertical root fractures involving the periodontium [10].

In a recent study, De-Deus et al. compared the frequency of dentinal microcracks after root canal filling procedures with Gutta Core, cold lateral condensation and warm vertical compaction using micro-computed tomography (micro-CT) technology [45]. The results indicated that none of these techniques was associated with the development of new dentinal defects. Each microcrack observed in the cross-sectional slices after the root-filling procedures was also present in the corresponding post-preparation images [45]. The findings obtained by the use of this observational method differ from those in previous in vitro studies where a direct relationship between the obturation techniques and the microcrack formation was present [9], [23], [32]. The discrepancy might be explained by the differences in the methodological design, regarding the filling protocols, observational methods and sample selection [45].

3. Retreatment Procedures

Nonsurgical orthograde endodontic retreatment is usually the first choice whenever the initial endodontic therapy fails [3], [46], [47]. Retreatment procedures involve safe and efficient removal of the existing filling material from the root canal system to regain access to the apical foramen, and thus, promoting better cleaning, reshaping and placement of a homogenous three-dimensional root canal filling [4], [5], [46], [48], [49], [50].

Several techniques have been proposed to remove filling materials from the root canal system, including the use of endodontic stainless steel hand files, NiTi rotary instruments, heat, ultrasonic instruments, solvents, lasers and photon-induced photoacoustic streaming, and various combinations of these methods [51]–[57]. Most of them generate stress in the root canal wall during the retreatment and may initiate dentinal defects [9], [46]. Recently, NiTi rotary instruments with different designs have been developed for root canal retreatment [58], [59], [60] – ProTaper Universal Retreatment (Dentsply, Ballaigues, Switzerland), Mtwo R (VDW, Munich, Germany), R Endo (Micro-Mega, Besançon, France), D-Race (FKG, La Chaux de Fonds, Switzerland), etc. They are preferred to the use of hand files and solvents and are reported to be superior to manual instrumentation for removal of the bulk of the filling [61], [62], [63]. Retreatment with NiTi rotary systems causes increased apical crack initiation and propagation compared to hand files [60], [64]. In comparative studies between different engine-driven NiTi retreatment files, ProTaperUniversal Retreatment and Mtwo R files are reported to cause more dentinal defects than other NiTi rotary instruments [60], [64], [65]. The removal of gutta-percha by hand-files can be a time-consuming and tedious procedure, especially when the root canal filling is well-condensed [66]. Therefore, using rotary NiTi systems for retreatment cases might decrease patient and operator fatigue [46], [67].

None of the retreatment techniques completely removes the residual debris from the canal wall after retreatment procedures [62], [68], [69], [70]. The apical third of the root canal generally has greater percentage of root canal filling remnants because of the increased anatomical variability [71], [72]. Thus, further apical enlargement with ascending instrument sizes is recommended to facilitate better removal of the filling material after the use of retreatment instruments [59], [73]. In recently published articles SAF (ReDent Nova, Raanana, Israel), XP Endo Finisher (FKG, La Chaux de Fonds, Switzerland) and XP Endo Finisher – R (FKG, La Chaux de Fonds, Switzerland) have been investigated as a supplementary cleaning approach. They enhance the removal of the filling residue after the use of retreatment files even in oval-shaped canals [70], [74]–[80]. Manufactures of these files claim that due to their unique design they preserve the original anatomy of the root canal without unnecessarily enlarging it.

Shemesh et al. documented that the additional mechanical manipulations and further preparation of the root canal throughout the endodontic retreatment procedure weaken the structure of the root canal dentin and increase crack formation. Nevertheless, remaining dentin tissue itself is reported not to influence the appearance of defects significantly [46], [81]. They might be due to external contributing factors such as temperature change, and friction of the instruments with the root canal wall, additional tensions to the dental structure upon masticatory function [21], [46], [82]. However, Bello et al. observed no such defects in dentin when mechanical cycles, equivalent to 1-year clinical function, were applied after endodontic retreatment [83].

Up to date, only few studies have investigated the effect of root canal retreatment procedures on the extent of dentinal damage [65]. In these studies, direct observation by optical microscopy at magnifications varying from x12 to x40 is used to assess the occurrence of defects in horizontal root sections obtained at various levels from the apex by using low-speed saw [10], [46], [81], [83]–[87]. In other investigations [23], [60], [64] defect initiation and propagation is examined on the apical root surface only applying the sample preparation described by Adorno et al. [88]. Yilmaz et al. used micro-CT imaging to assess the effect of retreatment procedures on dentinal defect formation and longitudinal propagation of pre-existing defects [65].

An apparent discrepancy between the obtained experimental results for dentinal damage detection is present especially due to the observational methods used. Common finding in the studies using stereomicroscopy for detection crack initiation and propagation during root canal retreatment procedure is that retreatment with NiTi instruments causes defects with no significant difference between the examined groups [81], [86]. Some authors state that there is no difference between rotary NiTi retreatment instruments with different design properties (variable or constant taper, tip design and cross section) in terms of crack formation [64], [81], [85], [86]. Few investigations conclude that rotary NiTi files used for retreatment initiate more dentinal defects than hand files [60], [64], [87], [88], while others report no difference between the hand and the engine-driven files [46], [65], [81]. Results obtained by micro-CT analysis show that removal of gutta-percha seems not to increase the incidence of dentinal defect formation, but the registration of the longitudinal propagation of defects suggests possible cumulative damage to the dentin due to additional endodontic procedures [65].

Several investigations in the field of endodontic retreatment compare the effect of different files not specifically designed for retreatment on the incidence of dentinal crack initiation and propagation. Pro Taper Next (Dentsply, Ballaigues, Switzerland), TF Adaptive (Kerr, Orange, CA, USA), and Reciproc (VDW, Munich, Germany) have been examined regarding their type of motion – continuous rotation, adaptive motion and reciprocation [60], [85], [86]. The choice of the latter systems is done on the basis of previous studies that revealed their effectiveness in removal of root canal filling materials although they are fundamentally designed for initial root canal shaping [89], [90], [91]. The results obtained from these studies showed that dentinal defects during retreatment are formed regardless of the motion kinematics of the used NiTi rotary systems [60], [85], [86].

A comparative study between ProTaper Universal (Dentsply, Ballaigues, Switzerland) and Reciproc found out no significant difference among the retreatment groups in the apical third of the root canal, whereas Reciproc initiated formation of more cracks in the middle and coronal parts of the root [85].

4. Methods for Microcrack Detection

In an attempt to find the safest way an endodontic treatment should be conducted, various evaluation methods are used nowadays for detection and investigation of dentinal defects appearing in the course of initial root canal shaping and filling procedures, and retreatment techniques.

Methods used for observation and tracing of microcracks into root canal dentin can be divided into destructive and non-destructive ones. The first group includes: sectioning [9], [32], [88], [92]–[95] and observation of the samples by stereomicroscopy [96], [97] or scanning electron microscopy (SEM) [52], [81], [98]. The non-destructive methods comprise of: endoscopy [99]; infrared thermography [100]; microcomputed tomography with and without contrast agents [45], [79], [101]–[103]; optical coherence tomography [104]; transillumination [105]–[107].

It is beyond the scope of this review article to explain in details how these methods are applied. Nevertheless, it is important to point out some of their advantages and certain disadvantages.

The most prevailing method enabling direct visualization of the exposed dentin surface is sectioning in combination with a stereomicroscope under different magnifications or a scanning electron microscopy. Consequences of root canal shaping [9, [32], [88], [92]–[95], filling [5], [9], [10], [32] [35], [37], [46], [74], [84] and retreatment protocols [10], [23], [46], [60], [64], [81], [83]–[87] are examined and evaluated at different levels of the sectioned tooth. Intracanal cracks are usually verified by three to four sections made, either at 1, 3, 7 or 9 mm or at 2, 4, 6 or 8 mm from the apex of the root. Magnification used in most of the investigations ranges from x8 up to x100 under high level of illumination. Light reflection and irregularities on the sectioned root surface make the assessment of dentinal defects complicated. The reflected light may cause false-positive appearance of cracks as well as obscure the presence of real ones [22].

By using sectioning approach, part of the sample is inevitably lost and the risk of appearance of new or propagation of pre-existing cracks might increase as well [106]. In order to avoid false interpretation of the received results this methodology usually relies on a negative control group with unisntrumented root canals. By comparison of its root canal surface with the experimental groups that have gone through different endodontic procedures potential influence of the observational method used is excluded [108].

The major deficiencies of this destructive method are the unknown initial condition of the dentin and the relatively small number of slices done at specific levels in each tooth. As a result of this, root surface defects existing before sectioning and microcracks along the longitudinal axis of the root can be omitted. Another limitation of the method is the inability to assess the severity of the cracks (i.e. depth), particularly of subsurface dentinal defects [22].

Most observational studies on dentinal defects apply sectioning and direct monitoring by stereomicroscope with [30], [88], [99], [105] or without the use of dyes [9], [10], [32], [35], [37], [46], [81], [84], [92]–[96].

A lot of investigations rely on the combination of the sectioning method with the scanning electron microscopy. Some of its advantages are: a higher quality of the images revealing details less than 1 mm; a three-dimensional appearance, useful for better understanding of sample surface structure; a wide range of magnifications. Although it provides better results, some disadvantages are present, as well. SEM is a time-consuming, labor-intensive and expensive procedure that requires elaborated specimen preparation - chemical fixation that requires dehydration of the sample, and metal ultra-thin coating. The vacuum desiccation can result in the appearance of additional cracks and artifacts causing misinterpretation of the results [22].

Recently, only few experimental studies in the endodontic field used endosocopy for identifying dentinal cracks after root-end resection [99], [109]. Analysis of the data concerning identification of certain type of cracks showed that the sensitivity of the endoscope was higher for complete root canal cracks than for the incomplete ones. Endoscopy at x 64 magnification showed more false-positive results for incomplete canal cracks (13,7%) and intracanal dentinal cracks (40%) compared to the results obtained by dental operative microscopy at lower magnifications [22].

Infrared thermography was used in one study to identify dentinal microcracks after cleaning and shaping procedures [100]. The cracks were detected at 0,89 W and a detection angle within 45° of the ultrasonic vibration scaler when the temperature of the surrounding dentin increased. According to the authors this method detects microcracks that are difficult to be defined by commonly used detection methods and are as wide as 4 to 3,5 µm. On the other hand, cracks exceeding 42 µm have less contact area and are difficult to be found because no frictional heat will be generated. Therefore, the inability of wide crack detection can be considered as a limitation of the aforementioned method [110]. It is necessary to point out that the magnitude and the direction of the frictional heat generated by the ultrasonic vibration, used in this method, would affect the formation and the increase of microcracks. Harmful effects such as crack elongation in dentin may occur if more than 1,86W and 60 seconds application time are used [22].

Light-emitting diode transillumination (LED) is another tool for crack assessment used in in vitro studies [105]–[107]. In recent clinical studies Tawil et al. used 0,8 mm LED transilluminator to detect dentinal defects in teeth that have undergone periapical microsurgery [111], [112]. It is an appropriate non-destructive method characterized with lower requirements for sophisticated sample preparation, lower cost, less manipulation time and lack of necessity of special software [22]. This methodology enhances dentinal defect detection by showing the areas where the light stream is interrupted and reflected [113]. Yet, staining agents may be needed for better visualization of the root-end dentinal defects [105]. In these cases, some of the dyes cannot penetrate into the cracks unless there is a break in the surface or until enamel and dentin of the specimens are decalcified. Additionally, dyes may cause misinterpretation due to the coloring of some anatomical grooves [22], [114].

Although impossible to implement micro-CT for in vivo human imaging, it has evolved into a highly accurate research tool for the examination of root canal anatomy and evaluation of the outcome of different endodontic procedures [22], [45], [79], [115]–[117]. Recently, it has gained an increasing significance in endodontic research due to its non-destructive and reproducible nature. It can be applied quantitatively and qualitatively for two and three-dimensional accurate assessment of the root canal system [115]. Micro-CT provides higher spatial resolution and allows visualization of the interior of opaque solid objects. Thus, precise information is obtained on the two- and three-dimensional properties and geometries of the root canal system. The most important advantage of this method is that microcracks evaluation can be done at each step throughout the endodontic treatment without damaging the initial specimen. The use of this experimental model allows further overlapping on the same specimens by subsequently tracking for dentinal defects after endodontic retreatment, post-preparation and post-removal procedures. As a result of this, one and the same sample can serve as its own control [22], [108], [118].

The micro-CT assessment of the frequency of appearance of dentinal microcracks can be performed with or without a contrasting agent. Mostly $BaSO_4$ is used as a contrast media and the staining is done under vacuum [84], [119]. It is noteworthy to mention that $BaSO_4$ is nonspecific for cracks and includes all void spaces – vasculature and free surfaces [120].

The micro-CT method is time-consuming and an expensive one. Along with these limitations, the complexity of the technical procedures requires an in-depth knowledge of a dedicated software. However, profound quantitative measurements of crack dimensions, volume, density, orientation etc. can be obtained by applying image analysis to the acquired micro-CT data [120]. It has been questioned whether the scanning resolution of a conventional micro-CT scan offers sufficient sensitivity in microcrack and fracture detection [121]. According to Nyquist-Shannon sample theorem a definite physical separation has to be present in order to be detected through digital signal processing technology. Therefore, such fine defects might be impossible to be detected by micro-CT [108]. In 2015 SHEMESH emphasized the importance of the wettability of the sample throughout the scanning procedure. Since the entire process can last for an hour or more, the tooth placed in the scanner dries [122]. It has been previously investigated that spontaneous cracks in dentin may occur under dry conditions [106], [123], [124]. Fortunately, micro-CT imaging could be carried out in wet conditions which supposedly might overcome the aforementioned bias [122].

5. Experimental Teeth

There are no unified criteria in terms of sample selection in in vitro investigations on dentinal microcrack initiation and propagation. Teeth from one and the same group are preferred and selected on the basis of preliminary two-dimensional radiographs ensuring common anatomical characteristics [22]. Parameters such as curvature radius of the external proximal root surface, size and shape of the root canal, and dentin thickness are believed to influence the fracture susceptibility [125]. A finite element analysis showed that stress concentrations were highest in oval roots, presenting greater buccal-lingual diameter [126]. It is assumed that the higher strain accumulation observed in buccal-lingual direction is due to the reduced proximal dentin thickness. Oval root canals present sharpened notch at the edge of the oval extension, which compared to round canals, is a site more susceptible to crack initiation when mesio-distal forces are applied from the inside out [127]. Roots exhibiting such canal configuration are relatively common and are more prone to fracture [128], [129]. In an attempt to overcome the bias in the sample selection and to provide reproducible conditions for the conduction of the in vitro experiments, numerous studies utilize mandibular incisors and single-rooted lower premolars [9], [32], [46], [81], [84], [93]–[97], [119].

6. Conclusion

Dentinal defects might be a trigger point for root-originating vertical fracture that can jeopardize the treatment outcome and the prognosis of endodontically treated teeth. In vitro studies are inconsistent concerning the incidence of dentinal microcrack formation after various root canal filling procedures. Single-cone obturation, cold lateral condensation and warm vertical compaction are claimed to generate different stress levels onto the dentinal wall depending on the load applied throughout the procedure. The experimental data on the effect of retreatment with NiTi rotary instruments is inconclusive regarding their ability to induce formation of new cracks and propagation of pre-existing ones. The contradictory findings might be due to the methodological differences and sample selection utilized in the laboratory experiments. Recent technological advances in dentin imaging might lead to the transition from destructive to non-destructive methods for microcrack diagnosis. Further investigations are necessary to find safe endodontic filling and minimally-invasive retreatment protocols for dental practitioners.

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