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Review Article

Dentistry Section

Microcrack Formation after Root Canal Instrumentation: A Narrative Review

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ABSTRACT

The development of rotary files and other endodontic instrument techniques have revolutionised treatment by enhancing canal preparation and producing rounder, smoother canals that are constructed of Nickel-Titanium (NiTi) alloy. There are two types of movements in these instruments: rotary continuous and reciprocating. Rotary continuous movements involve torsion and flexion, and can cause instrument fractures. An alternative approach to avoid the issue is proposed, which involves reciprocating movement. The present literature review compares the incidence of dentinal crack formation in root canal walls when using stainless steel and NiTi rotary systems. It highlights the potential complications, such as tooth fracture and increased bacterial susceptibility due to contact between instruments and dentinal walls.

Keywords: Dentine, Root canal preparation, Rotation, Tooth fracture

INTRODUCTION

Endodontic therapy depends upon proper diagnosis, biomechanical preparation, and three-dimensional (3D) obturation of the root canal system. The long-term success of root canal treatment can be achieved by eliminating infections and preventing reinfections i.e., removal of microorganisms, debris, and tissues which depends on the ideal biomechanical preparation of the canal. This is achieved by enlarging the canal diameter and creating a shape that allows a proper seal [1]. Chemo-mechanical preparation of the root canal includes both mechanical instrumentation and antibacterial irrigation and is principally directed toward achieving biological objectives and facilitating the placement of a high-quality root canal filling [2]. This is likely to create space for irrigants and antibacterial medicaments, shaping the root canal with greater taper and larger apical foramen size is recommended, which should provide maximum contact with the root canal walls. The purpose of root canal preparation is to preserve the original course of the canal, along with bacteria removal from the entire root canal system. So, thorough debridement of the root canal space is essential for the outcome of the initial endodontic therapy [3]. Endodontic instruments used for root canal preparation can be classified into handheld instruments and NiTi rotary instruments.

Handheld stainless steel instruments exert less stress on root canal walls as they are more stable and stiff, having less chip space between the threads causing less amount of dentin being cut [4]. These instruments are used to clean the canal superficially and they can create canal aberrations such as ledges, zips, and elbows due to their straightening tendency [4]. The root canals prepared with these manual files are completely irregular when compared to rotary instruments [5]. As a part of progress in treatment modalities and to eliminate the shortcomings of stainless steel instruments, NiTi instruments have been developed with greatly improved properties such as shape memory and super-elasticity. The rotary NiTi instrument system over the last decade has metamorphosed the design as well as the techniques of root canal preparation and has become the mainstream approach over the last two decades [6].

In recent years, with the advent of rotary files, the size and taper of prepared canals have changed compared to manual file systems where the canals prepared with rotary file system are rounder and smoother [5]. Besides variations in the design of NiTi instruments, manufacturers have introduced several proprietary manufacturing procedures including thermal, mechanical, and surface treatment to improve the mechanical properties of NiTi alloys, and to produce instruments with enhanced resistance to fracture and increased flexibility [7]. The NiTi rotary systems boast two types of movements, rotary continuous and reciprocating movements. The rotary continuous movement is a 360° clockwise rotating motion that uses a rotary engine. This can lead to torsion, flexion, and instrument fracture [8,9]. To avoid this, reciprocating movements were proposed. The reciprocating movements are repetitive up-and-down or back-and-forth motions, also known as clockwise and counter-clockwise movements [10]. This method reduces stress on instruments, mimics manual movement, and increases instrument lifespan [11]. Various advantages of NiTi rotary systems are increased cutting efficiency, exclusive super-elasticity, and flexibility as well as minimised procedural errors [1]. Several other benefits associated with NiTi instrumentation are reduced instrumentation time, self-centering properties, and standardised smooth canal preparations. Despite these several benefits these files can exert different levels of stress onto root walls resulting in some degree of structural dentinal damage which depends on the alloy, taper, tip design, cross-section, and kinematic types of each system [1]. The design of endodontic files can impact the shaping forces exerted on the dentin and in the apical region, the excessive dentin removal during root canal preparation can contribute to the formation of dentinal cracks/craze lines [12-14]. Proper selection of file design, combined with appropriate technique and consideration of dentin removal, is crucial in minimising the risk of crack formation during root canal preparation.

A crack can be defined as a defect with complete crack lines extending from the inner root canal space up to the outer surface of the root and incomplete crack lines extending from the canal walls into the dentin without reaching the outer surface [15]. A fracture is a communicating crack; i.e., one that extends from the root canal space to the outer root surface. External crazing or cracks include cracks that extend from the root surface into the dentin without reaching the canal lumen. Some recent studies have shown that canal instrumentation also has the potential to cause dentinal cracks [1,3,4].

Microcracks can be classified as incomplete and complete microcracks. Incomplete microcrack is a line extending from the canal wall into the dentine without reaching the outer surface. A complete microcrack is a line extending from the canal wall to the outer surface of the root [16].

The association between root canal procedures and dentinal microcracks showed that the crack did not extend from the canal to the root surface. In 2009, Bier CA et al., found root canal instrumentation created dentinal defects, incomplete cracks, and fractures [1]. These microcrack formations could be considered serious side-effects of root canal preparation as they may influence the integrity of the remaining tooth structure and reduce its ability to withstand functional and parafunctional forces [17].

Studies by Yoldas O et al., Toure B et al., and Liu R et al., indicated that instrumentation with hand files did not cause dentinal cracks. Rotary and reciprocating NiTi instrumentation induced more root cracks than hand files, which were attributed to the NiTi instrument properties and motion [12,18,19]. Kim HC et al., have reported a possible link between the design of NiTi rotary instruments and the development of dentinal defects. Their findings indicate that the high-stress concentration in the walls of the root canal system, caused by the use of NiTi rotary instruments, can increase the risk of dentinal damage [20].

To observe dentinal microcracks, various techniques are currently used, such as stereoscopic microscopy, staining, Scanning Electron Microscopy (SEM), infrared imaging, and micro-Computed Tomography (micro-CT). However, stereoscopic microscopy, staining, and infrared imaging do not reveal cracks with a micro-scale resolution. Previously, microcrack studies were done using sectional methods that could damage specimens and compromise the credibility of results. SEM is commonly used to examine the cross-section of a root. However, during the preparation of the samples, microcracks may form. These tiny cracks can extend throughout the entire slice or remain on the surface, which can go unnoticed. This limits their usefulness in detecting or observing dentinal microcracks [21-23]. In recent years, micro-CT technology has opened up new possibilities by allowing non-destructive volumetric assessments before and after endodontic procedures. It is a multi-functional 3D scanning method that offers high resolution.

With the recent rise in the use of NiTi rotary instruments, the incidence of cracks and root fractures in endodontically treated teeth has increased. The literature provides inconsistent data regarding the formation of small fractures in the tooth's inner layer, known as dentinal microcracks, after root canal treatment. This implies that using various cleaning and shaping instruments with diverse designs for the mechanical preparation of root canals may lead to damage to the canal walls [24,25]. The purpose of this literature review is to compare dentinal crack formation in root canal walls following instrumentation with different file systems, such as stainless steel and NiTi rotary systems.

SEARCH STRATEGY

The review followed a process of searching articles and abstracts through an electronic search in the PubMed and Google Scholar databases. The search was conducted from January 2010 to September 2020. Specific terms were used to formulate a search strategy to identify relevant publications.

"{(dentinal cracks) OR (dentinal microcracks) OR (root cracks) OR (apical root cracks) AND (root canal preparation)}".

Inclusion criteria:

1. Studies investigating microcrack formation initiation due to different file systems
2. In vitro studies conducted on human permanent teeth
3. Only articles written in the English language

Exclusion criteria:

1. Studies that focused on evaluating obturation techniques for initiating microcrack formation
2. Studies conducted solely on animals
3. Studies that reported microcracks formed due to retrograde cavity preparation
4. Studies that lacked proper methodology data and reporting
5. Review articles, clinical trials, case series, or case reports
6. Studies not published in the English language

The articles were initially evaluated by scanning the title and abstract for duplicates. Information was selected from each article related to the initiation of microcracks due to different root canal file systems.

A total of 112 articles were identified from an electronic search. After careful screening, 43 full articles were selected, and 11 of them were excluded due to exclusion and inclusion criteria. Finally, a total of 32 studies were selected based on dentinal crack formation in root canal walls following instrumentation with different file systems [Table/Fig-1] [4,11,24-53].

DISCUSSION

Instrumentation allows the disinfectant solution to reach most of the infected root canal, but shaping is limited by dentine wall thickness, risking defects. Over the years, several generations of NiTi engine-

S. No.	Author	Year	Comparative groups	Teeth	Sample size	Groups (n=)	Detection method	Conclusion
1	Milani AS et al., [26]	2012	ProTaper Universal (PTU) System, K-Flexofile	Mandibular anterior	57	3 (n=19)	Dental Operating Microscope (DOM) under 40 × magnification	PTU produced microcracks
2	Pop I et al., [27]	2015	ProTaper, WaveOne (WO)	Mandibular molars	18	3 (n=6)	Synchrotron radiation-based µCT (SRCT) scans	A significant increase in the number and length of microcracks was detected post-shaping
3	Zhou X et al., [28]	2015	WO, PTU, Twisted File (TF), Twisted File Adaptive (TFA) at 1 mm shorter than canal length (CL–1 mm) or 1 mm beyond apical foreman (CL+1 mm).	Mandibular premolars and molars	240	12 (n=20)	Scanning Electron Microscopy (SEM) under 50 x and 100 x magnifications	During over-instrumentation (WL=CL+1 mm), the WO and PTU groups developed significantly more dentinal cracks at the 6 and 9 mm sections than the TF and TFA groups
4	Monga P et al., [29]	2015	PTU, K3XF rotary system, WO, K files	Mandibular premolars	150	5 (n=30)	Stereomicroscope under 12 x magnification	WO did not produce any significant dentinal cracks. ProTaper and K3XF rotary systems produced significant dentinal cracks as compared to control groups
5	Gergi RM et al., [30]	2015	Reciproc (REC) R25, Primary WO, TFA systems.	Mandibular molars	90	3 (n=30)	Digital stereomicroscope at 25 x magnification	Instrumentation with REC produced significantly more complete cracks than WO and TFA (p=0.032). The TFA system produced significantly less cracks then the REC and WO systems apically (p=0.004)

6	Li S et al., [31]	2015	PTU, WO, ProTaper Next (PTN)	Mandibular molars	60	3 (n=20)	60 x magnification using a stereomicroscope with 200 L 1% methylene blue	The PTN system induces less dentinal microcracks during root canal procedures in severely curved root canals compared with the PTU and WO systems
7	De-Deus G et al., [32]	2016	PTU	Mandibular molars	40	2 (n=20)	micro-Computed Tomography (micro-CT)	PTU system did not induce the formation of new dentinal defects. All dentinal defects identified in the postoperative images were already present in the corresponding preoperative image
8	Kesim B et al., [33]	2017	K3XF Rotary files, PTN, REC, Twisted File (TF) Adaptive, K-files	Mandibular premolars	150	5 (n=30)	Stereomicroscope at 25 x magnification	For the apical (3 mm) and coronal (9 mm) sections, the PTN and TF Adaptive produced significantly more cracks than the hand files, REC, and K3XF
9	Cassimiro M et al., [34]	2017	PTN, K3XF (K3XF), WO Gold (WOG)	Mandibular anterior	60	3 (n=20)	micro-CT images	PTN, K3XF and WOG groups represented 11,11% (5079 slices), 17,22% (7873 slices) and cross-sectional images respectively. All the dentinal defects presented in the postoperative images existed in the images prior to instrumentation
10	Harandi A et al., [35]	2017	ProTaper, Neolix, SafeSider systems	Mandibular molars	60	4 (n=15)	Stereomicroscope under 40 x magnification	Microcracks were seen in all experimental groups (13.3% in ProTaper, 26.7% in SafeSider and 40% in Neolix). No microcrack occurred in the control group
11	Saberi E et al., [36]	2017	ProTaper, RaCe, NiTi Tee systems	Mandibular molars	45	3 (n=15)	Digtal stereomicroscope at a 40 x magnification	More cracks were observed in NiTi Tee group
12	Li ML et al., [37]	2018	WO, OneShape (OS), REC	Mandibular molars	80	4 (n=20)	micro-CT images	Among the single-file NiTi systems, WO and REC were not observed to cause notable microcracks, while the OS system resulted in evident microcracks
13	Khoshbin E et al., [24]	2018	Neolix, REC, Mtwo, ProTaper systems, K-files	Mandibular anterior	100	4 (n=25)	Stereomicroscope under 12 x magnification	ProTaper caused significantly more cracks than Neolix and Mtwo
14	Cassimiro M et al., [38]	2018	REC, PTN WOG	Mandibular anterior	60	3 (n=20)	Stereomicroscope with 25 x magnification 1 mL of 0.5% methy lene blue solution (pH=7)	WOG, PTN and REC caused microcracks on 60%, 33.33% and 18.33% of the samples, respectively. No significant differences between the groups in the 3 mm sections were observed. There were significant differences in the 6 mm and 9 mm sections
15	Mandava J et al., [39]	2018	HyFlex EDM rotary file system, Vortex Blue rotary file system, NiTi flex files	Mandibular molars	60	3 (n=20)	micro-CT images	HyFlex EDM showed greater increase in post instrumentation dentinal defects
16	Amitha M et al., [4]	2018	ProTaper and PTN with Rotary Motion, WO and REC with Reciprocating Motion, K File	Mandibular anterior	90	6 (n=15)	Stereomicroscope at a magnification of 30 x	The number of dentinal microcracks formed by PTU was highest followed by WO, PTN, and REC as measured 3 mm from the root apex
17	De-Deus G et al., [40]	2014	REC, WO, BioRaCe	Mandibular molars	30	3 (n=10)	micro-CT images	No causal relationship between dentinal microcrack formation and canal preparation procedures with REC, WO, and BioRaCe systems was observed
18	Tsenova I et al., [41]	2018	REC, WOG	Mandibular anterior	36	3 (n=12)	Stereomicroscope by using a cold light source at 40 x magnification	WOG and REC systems performed equally and resulted in dentinal defect formation regardless of their alloy type, taper and cross-section
19	Cheema J et al., [42]	2018	PTN, Hyflex EDM, K3 XF, Twisted rotary files, K File	Mandibular premolars	60	6 (n=10)	Digital stereomicroscope	K3 XF caused more dentinal cracks when compared to other groups
20	Taç MC et al., [11]	2018	PTU, PTN, and REC, K File	Mandibular anterior	100	5 (n=20)	Digital stereomicroscope	The PTU file system caused more dentinal microcracks than PTN and REC file systems
21	Bhushan J et al., [43]	2018	PTN, HyFlex CM files, SmartTrack files	Mandibular premolars	60	4 (n=15)	30 x magnification using a stereomicroscope	The PTN and HyFlex instruments had a tendency to cause fewer dentinal cracks compared with the SmartTrack instruments
22	Tsenova I et al., [25]	2019	PTU, HyFlex CM	Mandibular anterior	36	3 (n=12)	Stereomicroscopically applying a cold light source at 40 x magnification	PTU and HyFlex CM systems performed equally and resulted in dentinal defect formation

23	Tomer AK et al., [44]	2019	ProTaper Gold, Mani Silk	Mandibular anterior	30	2 (n=15)	25 x magnification using a stereomicroscope	ProTaper Gold had more number of cracks followed by Mani Silk
24	Tomer AK et al., [45]	2019	ProTaper Gold, Hyflex EDM	Mandibular anterior	45	3 (n=15)	25 x magnificat ion using a stereomicroscope	ProTaper Gold had more number of cracks than Hyflex EDM
25	Karatas E, [46]	2019	ProTaper, RaCe, R40 REC, WO, K File	Mandibular premolars	120	6 (n=20)	Stereomicroscope at a magnification of 25 x	ProTaper instruments led to highest rate of crack formation
26	Zargar W et al., [47]	2019	REC, WO, WOG	Mandibular anterior	45	3 (n=15)	Stereomicroscope at a magnification of 24 x and 80 x	WOG caused less microcracks than the other instruments tested
27	Erkan E et al., [48]	2019	PTN with Continuous Rotation, PTN with Adaptive Motion, TF Adaptive with Continuous Rotation, TF Adaptive with Adaptive Motion	Mandibular premolars	75	5 (n=15)	Stereomicroscope at a magnification of 25 x and 80 x	Adaptive motion produced less dentinal defects all dentin levels but there was no significant difference
28	Jacob J et al., [49]	2019	PTN, Self-adjusting- file, K-flex File	Mandibular molars	92	4 (n=23)	Digtal stereomicroscope at a 40 x magnification	Self-adjusting-file-instrumented group showed significantly less incidence of crack formation when compared to the PTN group
29	Katanec T et al., [50]	2020	Self- Adjusting File (SAF), Reciproc Blue (RB), and PTN	Mandibular premolars	45	3 (n=15)	micro-CT images	No dentinal defect was found in any evaluated specimen, neither in pre-nor postoperative scans in wet and dry condition
30	Saberi EA et al., [51]	2020	Neoniti, REC ProTaper rotary systems	Mandibular molars	45	3 (n=15)	Digital stereomicroscope at 12 × magnification	The frequency of microcracks was observed in 46.7%, 40%, and 20% of root canals following the preparation with REC, Neoniti, and ProTaper files respectively. The cracks were in the middle thirds in teeth prepared by the REC and ProTaper files and in the coronal and middle thirds in those prepared by the Neoniti file
31	Frater M et al., [52]	2020	E3, E3 azure, NT2, Hyflex CM, Hyflex EDM, 2 Shape, OneCurve, PTN, ProTaper Gold, WOG, Mtwo, RB, TFA, K3XF	Mandibular anterior	180	15 (n=12)	DOM and the stereomicroscope	Crack formation occurred irrespective of the motion of the rotary system (rotational or reciprocation)
32	Wardoyo MP et al., [53]	2020	RB R25 in a reciprocating pattern, One Curve in a rotary continuous pattern	Mandibular molars	32	2 (n=16)	micro-CT images	Rotary continuous instrument group resulted in more microcrack formation when compared to reciprocating instruments

[Table/Fig-1]: Comparison of methodology and conclusion of different studies that had evaluated dentinal crack formation in root canal walls following instrumentation with different file systems [4,11,24-53].
DOM: Dental operating microscope; m-CT: micro-computed tomography; PTN: ProTaper next; PTU: ProTaper universal; REC: Reciproc; WO: WaveOne; WL: Working length

driven instruments have been introduced, each with different designs, alloy treatments, and kinematics. Newer designs featuring non-cutting tips, radial land, various cross-sectional designs, high torsional fracture strength, and various tapers have been developed to enhance the efficiency of NiTi rotary instruments [5].

Dentinal microcracks can occur due to several factors during root canal preparation. It is not possible to attribute the formation of cracks to a single factor. Instead, it is a result of a combination of various factors that may be additive or synergistic. Some of the factors that can cause microcrack formation include the kinematics of the instrument, the metallurgy of the file system, the number of files, the design and cross-section of the instrument, the taper of the instrument, glide path preparation, anatomy of the root canal, and the age of the patient [4].

Kinematics of Instrument

Rotary instruments require more rotations when used inside the canal, which makes them more vulnerable to fractures due to torsion or flexion. To enhance the fracture resistance of rotary NiTi files, manufacturers have introduced the use of reciprocating motion and new alloys such as M wire and R-phase NiTi files. These new alloys have a higher cyclic fatigue resistance as compared to the conventional files [54,55].

A study conducted by Wardoyo MP et al., compared the occurrence of microcracks in root canals using a single file system with either rotary continuous or reciprocating motions. The study found that both types of movements induced crack formation in root canals, however, there was no significant difference between the two. However, there was a difference in the percentage of cracks between the two groups, with a higher percentage recorded in rotary continuous motion (25%) than in reciprocating motion (12.5%). This may be because continuous rotating movements result in a high level of stress concentration in the root canal due to greater rotational forces and constant torques applied, whereas reciprocating motion avoids continuous rotational stress and constant torque that is generated from traditional rotary continuous motion on the inner surface of the root canal [53].

According to the studies that were reviewed, reciprocating instruments have a tendency to cause fewer dentinal defects compared to continuous rotary instruments. During canal preparation, momentary stress concentrations are created in dentin due to the contact between the instruments and canal wall. This can result in vertical root fracture, as reported in various studies [20,29,45,53]. However, reciprocating motion can help to reduce the torsional stress by periodically reversing the direction of rotation of the instrument. This can potentially reduce the magnitude of the forces generated on the root dentin and prevent root cracks and fractures [Table/Fig-2] [56].

Metallurgy of the File System

Stainless steel hand files produce fewer defects because the amount of force application is less, the number of rotations is less, and the screwing effect is not present [57]. According to a study conducted by Kim HC et al., conventional NiTi instruments tend to cause more dentinal cracks compared to instruments with thermal treatment of alloy. However, rotary systems with modified design and alloy composition, such as ProTaper Next (PTN) with M wire, WaveOne Gold (WOG) with Gold wire, and K3XF with R phase wire, are known to apply less stress to root dentine. This makes them a better option than older conventional NiTi systems such as ProTaper, as they are expected to cause fewer cracks [20].

ProTaper Next (Dentsply Maillefer) instruments have an off-centred rectangular design and a progressive and regressive percentage taper on a single file. They are made from M wire technology. The file's off-centred rectangular design decreases the screw effect, dangerous taper lock, and torque on any given file. This is achieved by minimising the contact between the file and the dentin. Several studies have shown that PTN has a lower likelihood of causing dentinal microcracks due to its specialised instrument design [31,34,38,42]. Additionally, instruments that have undergone different thermal treatments have been found to have greater flexibility and higher cyclic fatigue resistance than traditional NiTi instruments [12,20]. However, studies by De Deus G et al., and Karatas E have reported that there is no significant difference in the formation of dentinal defects between instruments subjected to different thermal treatments such as R-phase, M wire, and CM wire [Table/Fig-2] [40,46].

Number of Files

New NiTi files have been introduced with a unique cross-sectional design and a different working motion, which enables the completion of canal preparation with only one instrument. Single-file systems have also been developed to shape the canal with only a single file, thus reducing the time required for the preparation process. When compared to multiple-file rotary systems, single-file reciprocating systems have been found to generate significantly fewer cracks [14].

Liu R et al., compared the incidence of root cracks observed at the apical root surface and/or in the canal wall after canal instrumentation with 3 single-file systems: OneShape (MicroMega, Besancon, France), Reciproc (VDW, Munich, Germany), or the Self-Adjusting File (ReDent-Nova, Ra'anana, Israel) and the ProTaper system (Dentsply Maillefer, Ballaigues, Switzerland) and found that all three single-file systems used in this study (i.e., the Reciproc, OneShape, and SAF) caused less damage than the ProTaper system when five files were sequentially used [19]. A similar study was conducted to compare dentinal defects caused by different root canal preparation methods. The methods compared were hand K files, Hero Shaper (multiple files), and Oneshape (single file) rotary files. The results showed that root canals prepared with Hero Shaper had a higher number of defects than those prepared with OneShape, while the lowest percentage of dentinal defects were present in the canals prepared with hand files. This can be attributed to the variable pitch, positive rake angle, and non-working tip of hand files, which reduce the instrument screwing effect due to a variable cross-section along the blade of the instrument [Table/Fig-2] [57].

Design and Cross-section of the Instrument

Burklein S et al., and Gergi RM et al., found that instruments with an S-shaped cross-sectional design and sharp cutting edges cause more cracks than those with a triangular or modified triangular cross-section [15,30]. In contrast a study conducted by Wardoyo MP et al., the use of a NiTi rotary instrument with triangular cross-sections (OneCurve®) resulted in more cracks compared to the use of a NiTi rotary instrument with an S-shaped cross-section (Reciproc Blue®). Although both systems had the same D0, they had different cross-sections. While Reciproc Blue® had an S-shaped cross-section, OneCurve® had a triangular cross-section that resulted in a larger cross-sectional area. The larger cross-sectional area of OneCurve® instruments made contact with larger areas of the root canal wall, which removed more dentin and generated more pressure on the

S. No.	File system	Kinematics (motion)	Metallurgy	Single/multiple file system	Cross-section (design)
1	WaveOne (Dentsply Sirona Endodontics, Ballaigues, Switzer- land) [47]	Reciprocating	M wire	Single file	Modified triangular
2	ProTaper Universal (Dentsply Sirona Endodontics, Ballaigues, Switzerland) [35]	Continuous	M wire	Multiple file	Triangular
3	Twisted File (SybronEndo, Orange, California, USA) [29]	Continuous	R-phase	Multiple file	Triangular
4	Twisted File Adaptive (SybronEndo, Orange, California, USA) [33]	Reciprocating	R-phase	Multiple file	Triangular
5	ProTaper Next (Dentsply Sirona Endodontics, Ballaigues, Switzerland) [42]	Continuous	M wire	Multiple file	Rectangular
6	Reciproc (VDW, Munich, Germany) [47]	Reciprocating	M wire	Single file	S-shaped
7	SafeSider (Essential Dental Systems, South Hackensack, NJ, USA) [35]	Reciprocating	M wire	Multiple file	S-shaped- flat sides
8	Mtwo (Sweden and Martina, Padova, Italy) [52]	Continuous	M wire	Multiple file	S-shaped
9	Neoniti (NEOLIX, Châtres-la-Forêt, France) [35]	Continuous	R-phase	Single file	Rectangular
10	K3XF (Sybron Endo) [33]	Continuous	R-phase	Multiple file	Modified triple-U shaped
11	WaveOne Gold (Dentsply Sirona Endodontics, Ballaigues, Switzer- land) [47]	Reciprocating	Gold wire	Single file	Offset parallelogram
12	Hyflex EDM (Coltene-Whaledent, Allstetten, Switzerland) [42]	Reciprocating	CM wire	Multiple file	Rectangular-apically trapezoidal
13	ProTaper Gold (Dentsply Sirona Endodontics, Ballaigues, Switzerland) [44]	Continuous	CM wire	Multiple file	Triangular /modified triangular
14	Hyflex (Coltene-Whaledent, Allstetten, Switzerland) [43]	Continuous	CM wire	Multiple file	Triangular /rectangular
15	RaCe (FKG, LaChaux De Fonds, Switzerland) [36]	Continuous	M wire	Multiple file	Triangular
16	NiTi Tee (Sjöding Sendoline, Kista, Sweden) [36]	Continuous	M wire	Multiple file	S-shaped
17	OneShape (Micro-Mega, Besançon, France) [37]	Continuous	M wire	Single file	Asymmetrical with a S-shaped
18	Trunatomy (TRN; Dentsply Maillefer, Ballaigues, Switzerland) [60]	Continuous	CM wire	Single file	Off-centred parallelogram
19	XP Endo shaper (XPES; FKG Dentaire, Switzerland) [60]	Continuous	Max wire	Single file	Snake-shaped

[Table/Fig-2]: Comparative evaluation of different rotary file systems [29,33,35-37,42-44,47,52,60].

root canal wall. Triangular cross-section reduces cutting efficiency and space for dentine chips, increasing stress on root canal walls [53].

Monga P et al., conducted a study in 2015 comparing dentinal crack formation during root canal preparation using ProTaper, K3XF, and WaveOne methods. ProTaper resulted in the highest formation of microcracks (33.3%) due to its continuous rotating motion and triangular cross-sectional design [29]. The WaveOne file 25.08 has a continuously decreasing taper (0.8, 0.65, 0.6, 0.55) with different cross-sectional designs. It has radial lands in the tip region and changes to a triangular convex cross-section with a neutral rake angle near the shaft like the ProTaper F2 file.

Saberi E et al., study revealed microcracks in all preparation systems that used ProTaper, RaCe, and NiTi Tee systems. The study found dentinal defects in 20%, 13.3%, and 26.7% of specimens in ProTaper, RaCe, and NiTi Tee systems, respectively. Although the NiTi Tee system had more microcracks, there were no significant differences between groups [36].

According to most studies, rotary NiTi file systems, particularly those with triangular cross-sections like ProTaper, WaveOne, RaCe, Twisted files tend to cause more microcracks [4,11,33]. On the other hand, rotary file systems with an S-shaped, off-centred parallelogram or off-centred rectangular cross-sections allow minimal stress and less crack formation into the dentin due to restricted contact with the instrument and root surface [20,34]. A comparative evaluation of different rotary file systems is shown in [Table/Fig-2].

Taper of the Instrument

Based on the studies conducted by Kim HC et al., and Bier CA et al., it has been found that an increase in the taper of files can result in higher stress levels in root canal shaping procedures. This is because larger tapers remove more dentin, which increases the susceptibility of the root to fractures [1,20]. In 2019, Tomer AK et al., investigated microcrack formation during root canal preparation using two NiTi systems, ProTaper Gold and Silk. Their findings suggest that ProTaper Gold causes more cracks than Mani Silk. It is worth noting that the ProTaper F2 file has a large apical taper of 0.08, which could lead to a higher incidence of dentinal microcracks [44].

In 2019, Tsenova I et al., conducted a study that compared two different full-sequence rotary NiTi systems- ProTaper Universal and HyFlex CM- and evaluated their impact on dentinal defects following root canal shaping. The HyFlex CM system, made of heat-treated Controlled Memory (CM) alloy, has an asymmetrical cross-section design with three to four cutting edges and improved cyclic fatigue resistance and shaping ability. On the other hand, ProTaper Universal files are made of conventional NiTi alloy, and have a convex triangular cross-section design with several percentage tapers, allowing for a dynamic cutting motion and removing a greater amount of coronal dentin [25].

Anatomy of Root Canal

Lertchirakarn V et al., evaluated that oval roots that have a larger buccal-lingual diameter and thinner proximal dentin tend to accumulate more stress. Flat canals are more likely to develop dentinal defects when mesiodistal forces are applied from the inside out, compared to round canals. This might be because of the sharpened notch at the end of the oval extension [58]. Dentinal microcracks' shapes, such as complete and incomplete cracks, are linked to stress intensity, concentration zone, and the thickness of the root canal wall. The most significant root stresses are usually situated at the most curved mid-root canals during rotary instrumentation in curved roots with NiTi file designs [20].

A study conducted by Versluis A et al., found that oval root canals tend to have uneven stress distribution. This is due to their high construction buccal and lingual canal extensions and greater stresses in the coronal and middle third to apical third. Flat oval root canals are common in distal roots of lower molars, upper and lower bicuspid, lower incisors, and canines. In contrast, mandibular incisors are more likely to be affected by forces during instrumentation because of their smaller dimensions and thin dentinal walls [59]. A comparative evaluation of different rotary file systems is presented in [Table/Fig-2] [29,33,35-37,42-44,47,52,60].

Age

As per studies, once a person reaches their thirties, there is a change in the structure of dentin. The tiny tubes in the dentin start getting filled with inorganic material, making the tissue appear transparent and harder. This process increases the mineral content of dentin, unlike bones where mineral content decreases with age. However, this increase in mineral content may lead to weaker dentin and cause a change in its mechanical properties [61].

Crack Formation at Different Root Levels

A study conducted by Frater M et al., aimed to compare the incidence of cracks at various depths of mandibular incisors. The study found that there was no significant difference in the number of cracks between different file systems at 6 mm or 9 mm from the root tip. However, the incidence of cracks increased as the distance from the root tip decreased, with the highest number of cracks observed at 3 mm from the apex [52].

In 2018, Bhushan J et al., conducted a study that found that microcracks were more likely to form in the apical region (28%) of single-rooted mandibular premolars compared to the middle third (20%) or coronal third regions (20%). This is likely because the apical part is the narrowest part of the root canal, which increases the torque with penetration depth when the instrument contacts the greatest canal surface in this region [43].

On the contrary, to a study conducted by Üstün Y et al., dentinal defects were more prevalent in the coronal third of the root [62]. It is believed that the higher incidence of microcrack formation in the coronal region is due to increased exposure to stress compared to the apical region due to the less diameter of the finishing files used in this region [11].

Various Detection Methods

The common method used in studies to assess the occurrence of cracks in the dentin and apex of teeth is by taking photographs of root sections or apical surfaces using different techniques. Various methods such as Dental Operating Microscope (DOM), stereomicroscope, micro-CT (µCT), and Synchrotron light-based micro-CT (SRCT) can be used along with dye penetration.

a. **Dental Operating Microscope (DOM)/Stereomicroscope:**

One of the methods commonly used to assess the formation of microcracks after instrumentation is to section specimens at the apical, middle, and coronal levels, and then evaluate them under a DOM or stereomicroscope. However, this method of sectioning can generate additional cracks and does not allow for the assessment of pre-existing cracks. There is also a risk of getting false positive results with this methodology, as extraction and sectioning may create or propagate existing dentinal defects [38,41].

b. **Micro-Computed Tomography (micro-CT):**

The micro-CT is a detection method that provides high-resolution, three-dimensional scanning. This allows for accurate analysis of dentinal microcracks without the need for cutting the specimen. It also enables the comparison of the same samples before and after instrumentation. This non-destructive micro-CT method is considered the gold standard for dentinal microcrack studies, as it eliminates the possibility of false-positive results and enables the evaluation of hundreds of slices per sample. Micro-CT imaging is superior to the use of stereomicroscopes, and it also facilitates root canal visualisation before and after root canal preparation. This increases the internal validity of the study because each sample served as its own control [37,40].

c. **Synchrotron light-based micro-CT (SRCT):**

Synchrotron Radiation micro-CT (SR micro-CT) possesses significant advantages over standard micro-CT. A synchrotron source provides a high-flux, high-intensity and monochromatic X-ray beam, allowing acquisition of quantitative high-resolution 3D images with a high signal-to-noise ratio. SRCT scans use a parallel beam geometry to reconstruct different regions of a sample with high resolution and reduced artifacts. They also offer an increased signal-to-noise ratio compared to conventional sources. Phase-contrast micro-CT can visualise small density variations, and SRCT provides a monochromatic X-ray from a synchrotron operating at 2.0 GeV [62,63].

d. **Other methods:**

In addition to traditional diagnostic methods, other techniques could prove useful for detecting cracks in teeth. These include Cone Beam Computed Tomography (CBCT), which is a non-invasive method that can provide clear imaging of cracks, and ultrasound, which can image cracks in stimulated tooth structure. These techniques have the potential to become important diagnostic aids in the future [64].

The periodontal ligament (PDL) is a tissue that has viscoelastic properties which help to absorb and dissipate stress generated by the load application of teeth. This makes it essential in studies that investigate the impact of force on crack formation or fracture strength. Unfortunately, there is no artificial material that can absorb teeth forces as efficiently as natural PDL in clinical conditions. Therefore, there is no reasonable association between the results of in vitro studies and clinical conditions concerning microcrack formation [65].

CONCLUSION(S)

Based on the literature review, research studies have shown that the use of NiTi rotary files for root canal instrumentation can lead to higher microcracks. Most of the studies indicated that file systems with triangular cross-sections caused more microcrack formation. The instrument's kinematics also plays an important role in microcrack formation, where reciprocating motion leads to less microcrack formation compared to rotary continuous motion. However, some studies disagree with these results. Furthermore, single file systems that do not possess S-shaped, off-centred parallelogram, or off-centred rectangular cross-sections were seen to cause more microcracks compared to full sequence systems.

While the taper of the instrument is one of the factors leading to microcrack formation, a larger taper removes more dentine. The type of tooth is also a contributing factor, with oval-shaped canals leading to more dentinal crack formation in premolars and anteriors due to their thinner dentin thickness.

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