Characterization of Deformed or Separated XP instruments after Clinical Retreatment of Molar Teeth – A Multicenter Experience

by

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the degree of ___Master of Science____

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ABSTRACT

Objectives: The present study examined the defect characteristics of clinically used, discarded nickel titanium rotary retreatment instruments, and analyzed the impact of clinical use on their metallurgical properties.

Materials and methods:

92 XP Endo Shaper (XPS; FKG Dentaire) and 20 XP Endo Finisher-R (XPFR; FKG Dentaire) instruments with structural deformation or separation were collected from four specialty endodontic offices over a 20-month period. The types of defects and their relative locations were recorded. The lateral and fractured surfaces of the separated instruments were examined with scanning electron microscopy. Differential scanning calorimetry was used to investigate the thermal behavior of new, as well as deformed and/or fractured instruments.

Results:

77 (84%) XP Endo Shapers and 4 (20%) XP Endo Finisher-Rs had an area with structural deformation while 15 (16%) XP Endo Shapers and 16 (80%) XP Endo Finisher-Rs were fractured. All unfractured, deformed XP Endo Finisher-Rs showed unwinding close to the coronal end of the flute. Fractures in the XP Endo Shapers and XP Endo Finisher-Rs were often close to the coronal end of the flutes or the expanding segments of the instruments. Most of the XP Endo Shaper fractures were because of torsional failure (67%), while XP Endo Finisher-Rs failed predominantly by cyclic fatigue (81%). The austenite finishing temperature of XP Endo Finisher-R (40°C) was

higher than that of XP Endo Shaper (35°C). Both XP Endo Shaper and XP Endo Finisher-R exhibited 2-stage phase transformation.

Conclusion:

Torsional failure was more prevalent in XP Endo Shaper instruments and fatigue failure was more prevalent in XP Endo Finisher-R instruments. Among the investigated instruments, XP Endo Finisher-Rs were more likely to separate without warning whereas XP Endo Shapers frequently exhibited plastic deformation. The latter may be used as a pre-separation forewarning sign during clinical retreatment.

Clinical significance:

The failure mode of XP Endo Shaper and XP Endo Finisher-R used clinically for retreatment, appeared to be different. Plastic deformation, the forewarning sign of instrument separation, occurs when XP Endo instruments are used for retreatment.

LAY SUMMARY

The XP 3D system is a new file system that does not rely on traditional file shapes. Instead, it rotates in an off center, snake like fashion that enables it to touch areas that were previously not possible. Additionally, it rotates at a higher rate of speed (RPM), which can potentially increase the risk of its fracture and/or deformity. When used for endodontic retreatments, the previous filling materials inside the canals, will put additional stress on the files used and the file has to work extra hard to detach and remove the said materials. In this publication, we studied a number of fractured and/or deformed files that were already used in a clinical setting by an endodontist and determined whether there could be forewarnings before one of these files fractured. Additionally, we studied the effect of temperature changes on these files, which mimics the function of the file in body temperature.

PREFACE

Some of the material included in this thesis has been previously published in the following paper:

Shabehpour, K., Liu, H, Wang, Z., Sobotkiewicz, T., Kwak, S. W., Haapasalo, M., Ruse, N. D., Coil, J. M., Tay, F. R., & Shen, Y. (2022). Characterisation of deformed or separated nickel-titanium retreatment instruments after clinical use - A multicentre experience: Defect profiles of clinically used retreatment instruments. Journal of Dentistry, 117, 103939-103939.

This publication as well as this thesis is the principal work of the candidate, Dr. Kiarash Shabehpour. The research questions and study design were prepared under direct guidance and supervision of the research supervisor, Dr. Ya Shen. Specimen collection was carried out by Dr. He Liu. Data collection, including microscopic photography and scanning electron microscopy was done by Dr. Kiarash Shabehpour with help from Dr. Zhejun Wang under guidance from Dr. Ya Shen. Differential scanning calorimetry was done by Dr. He Liu and Dr. Kiarash Shabehpour. Data processing and statistical analysis were done by Dr. Kiarash Shabehpour and Dr. He Liu. Writing of the thesis was done by Dr. Kiarash Shabehpour while editing was done by Dr. Ya Shen. Support and consultation were provided by Dr. Markus Haapasalo.

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LIST OF SYMBOLS AND ABBREVIATIONS

=	Equals
°	Degree
°C	Degrees Celsius
>	Greater than
<	Lesser than
#	Number
/	Per
%	Percentage
α	Type I error rate
β	Power
NiTi	Nickel Titanium
RPM	Revolutions Per Minute
XPFR	XP Endo Finisher-R
XPS	XP Endo Shaper

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DEDICATION

I would like to dedicate this publication to my parents. You have taught me the value of hard work and perseverance. You have always encouraged me to dream big and to shoot for the stars. You have always been my biggest cheerleaders. This is for you.

And most importantly, to my beautiful wife, my best friend, Nassim. Thank you for staying by my side through the hardest times imaginable and still supporting me in pursuing my dreams. Thank you for listening to me when I was stressed and tired, and for always having my back. I love you!

Chapter 1. Review of Literature

1.1 Definitions

1.1.1 Pulpal Involvement

The dental pulp can get inflamed due to a local irritant like a recent restoration or be colonized by microorganisms either through carious exposure, coronal fracture, or infection of the pulp through dentinal tubules that have been compromised (Kakehashi et al. 1965). This inflammation is called pulpitis which is a clinical and histologic term. Clinically, it can be reversible or irreversible. Histologically, it can be described as acute, chronic or hyperplastic. If the cause is not treated, this can lead to pulp necrosis, which is a clinical diagnosis, indicating the death of the dental pulp (AAE glossary of endodontic terms 2020).

1.1.2 Periapical Involvement

Apical periodontitis has been designated to be an infectious disease (Nair et al. 1997). If the cause has been due to endodontic origin, the goal of endodontic treatment at this point would be to eradicate the infection, create the necessary conditions for periapical healing while preventing the reinfection of the root canal system and the periapical tissues (Siqueira et al. 2005).

1.1.3 Root Canal Treatment

Root canal treatment is the procedure that is performed in order to save the natural dentition when there is an inflammation of root canal space and/or infection of the periapical area in combination with pulpal involvement.

1.1.4 Procedure of Root Canal Treatment

During root canal treatment, the pulp chamber is accessed by mechanical removal of its roof. Canal space(s) will then be chemo mechanically debrided, cleaned and obturated with a solid, inert material as well as sealer to prevent reinfection of the system. Historically, the root canal system has been obturated with gold cones, silver points, different types of pastes or cements. These days, canal spaces are most commonly obturated using gutta percha and root canal sealers.

1.1.5 Failure of Initial Root Canal Treatment

Initial root canal treatment can fail due to a number of different reasons. These reasons can range from persistent microbial infection (due to different reasons) to reinfection of root canal space due to leakage. In these occasions, one of the treatment options can be nonsurgical endodontic retreatment. (Torabinejad et al. 2009)

1.1.6 Nonsurgical Root Canal Retreatment (Orthograde Retreatment)

During endodontic retreatment, after accessing the pulp chamber, the previous root filling material is removed, chemo mechanical cleaning and disinfection of root canal space will be performed, and the space will be sealed with and obturation material, typically gutta percha and sealer or other bioceramic materials (e.g., MTA). (Ersev et al. 2012)

1.1.7 Instruments and Materials used for Root Canal Retreatment

Depending on what was used to obturate the canal during the previous root canal treatment, different instruments and/or materials can be used to retrieve or clean out the previous fillings. In case of obturations with silver points, the preferred technique is the mechanical removal after getting a hold of the point. In other cases that the obturation is a solid or semi solid material like Gutta Percha or some sort of paste, the preferred technique is usually a combination of solvent (most commonly Chloroform, but traditionally Eucalyptol, Halothane, Rectified turpentine or Xylenes have also been suggested and used), heat and mechanical removal with Hedstrom file, retreatment files or other rotary systems (Ladley et al. 1991, McDonald et al. 1992, Kaplowitz et al. 1996, Hansen et al. 1998). In this project, one of these rotary systems that is capable of efficiently removing previous filling materials from the root canal system, has been studied after each of the files were used during retreatment of a molar tooth in a specialized clinical setting.

1.1.8 File Fracture/Separation

Endodontic file fracture or separation can occur either due to cyclic fatigue or torsional failure. An instrument can also separate due to a combination of these two methods.

1.1.9 Cyclic Fatigue

In endodontics, work hardening, and metal fatigue can happen when a repetitive stress is placed on a certain part of an endodontic file. In this stance, cyclic fatigue can start with a microcrack formation. If the stress of work hardening continues, the crack will propagate until final fracture of the instrument. (AAE glossary of endodontic terms 2020)

1.1.10 Torsional Failure

Torsional failure is a fracture of an endodontic file due to binding of a part of the file, most commonly the tip, within the canal while the handpiece is still turning the file. In this instance, the elastic limit of the file is exceeded, and fracture will happen. (AAE glossary of endodontic terms 2020)

1.2 Introduction

Utilizing a nickel titanium alloy for rotary instruments was first suggested in 1988 by Walia (Walia et al. 1988), but the first actual rotary system – Profile- came to the market in 1993. Since then, these instruments, that are currently in their 5^{th} generation, have been marketed for creating a continuously tapered funnel shape within the root canal system. (Haapasalo, Shen 2013)

Many studies have shown that these NiTi rotary systems are able to prepare root canals with excellent taper, less canal transportation, greater conservation of tooth structure and at a much faster rate than hand files. Another possible use for these NiTi instruments would be removing previous root filling materials from already treated root canals.

After completion of initial endodontic treatment, if satisfactory results are not obtained or patients' symptoms are not relieved, one of the possible options for continuing management of the root filled teeth with persistent or secondary apical periodontitis, would be nonsurgical root canal retreatment. This procedure involves re-accessing the pulp chamber and removing the existing root filling to enable further disinfection of the root canal system (Torabinejad et al. 2009). Ideally, an instrument used for root canal retreatment should be able to completely remove the root filling material in an efficient and timely manner but should not extrude debris out of the apical foramen, alter the root anatomy or create untoward events such as instrument separation. However, previous studies have shown that contemporary retreatment techniques and instruments are not successful in completely removing root canal fillings from previously treated canals (Ersev et al. 2012, Ma et al. 2012, Li et al. 2020).

One of the newly suggested techniques for removing root canal fillings from previously treated canals, is the use of off-centre rotating instruments. Concept of off-centre rotation was introduced in the 5th generation of rotary files. One of these novel systems is XP 3D (FKG Dentaire, La Chaux-de-Fonds, Switzerland) which now consists of a Shaper, a Finisher, and a Finisher-R.

At the time of introduction, the XP 3D system (FKG Dentaire, La Chaux-de-Fonds, Switzerland), consisted of two files, a Shaper, with a 30-size tip and a Finisher, with a 25-size tip. Within just a few years of using the system, endodontists quickly learned of its ability to remove gutta percha and its remnants from previously treated canals. In order to utilize this use, the manufacturer (FKG Dentaire, La Chaux-de-Fonds, Switzerland) introduced a third file in the system; the XP Finisher-R. It has a tip size of 30, it is slightly more rigid than the original Finisher and is better suited for gutta percha removal.

These instruments are manufactured from Max Wire (Martensite-Austenite Electropolish Flex, FKG Dentaire) which keeps them soft/relaxed and relatively straight at room temperature (Martensitic phase). At body temperature however, they will become robust and go into their memorized shape. (Austenitic phase). According to the manufacturer, this enables the XP Endo system to adapt better to the 3D anatomy of the root canal system when undergoing eccentric rotational movement. The XP Endo Finisher-R instruments can supplement chemo mechanical disinfection because they are designed to better reach the more complex areas of the root canal, such as isthmuses and fins. Previous studies have already reported the efficacy of these two instruments for retreatment (Silva et al. 2018, De-Deus et al. 2019, Machado et al. 2019, Volpani et al. 2020, Liu et al. 2021). Recently, the manufacturer recommended the combined use of both XP Endo instruments to remove root filling materials.

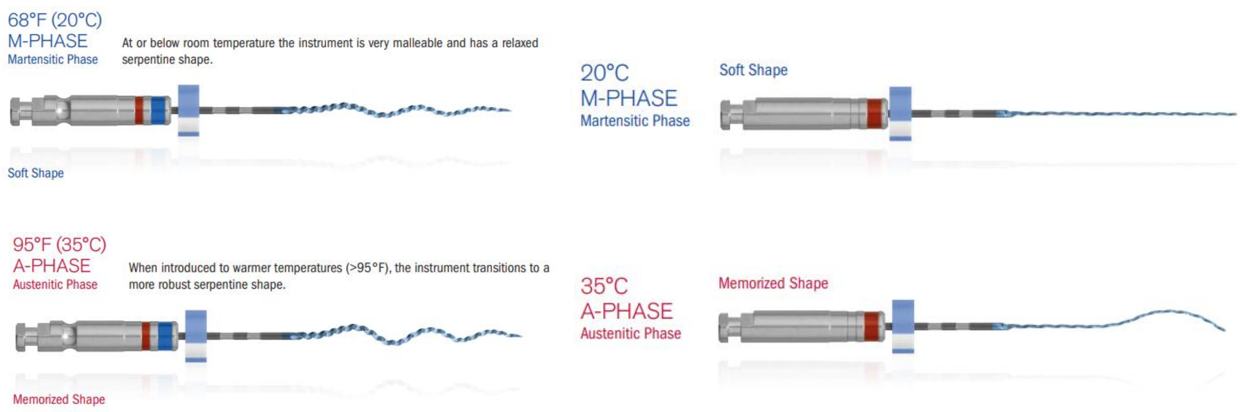

Figure 1. XP Endo 3D files at room and body temperatures

The XP 3D system does not rely on file taper like traditional rotary files and as previously stated, the manufacturer claims that it can clean fins and isthmuses that were not previously reachable, unless excessive amounts of dentin was removed first.

Despite the increasing popularity of NiTi instruments, unexpected fracture of these files, remains an issue during clinical use, which has been the subject of numerous studies in the past. *In vitro* studies have shown that NiTi instruments can become damaged, less efficient, and more susceptible to fracture when they are used in nonsurgical retreatment situations, removing the previous root filling materials (Imura et al. 2000, McGuigan et al. 2013). Instrument separation during retreatment, results in a complex treatment situation and may generate considerable anxiety for both clinician and the patient. Previous studies have examined NiTi instruments that had failed during initial root canal treatment procedures (Shen et al. 2006, Shen et al. 2009 – Part 1, Shen et al. 2009 – Part 2, Shen et al. 2009 – Part 5). However, the stresses acting on NiTi files used for retreatment may differ from those used for initial root canal treatment. To the best of my knowledge, defects in any NiTi instruments that were used for clinical retreatment procedures have yet to be systematically studied.

According to the American Association of Endodontists' glossary of endodontic terms, instrument separation can be caused by either cyclic fatigue, torsional failure, or a combination of these two at the same time.

In order to reduce cyclic and torsional fatigue, other file systems use multiple files in their toolkit, which can add cost, complexity, and chair time. This XP 3D system however, started with 2 files for the whole procedure and modified it to include 3 files that are currently in the market. As previously mentioned, these 3 files are the XP Endo Shaper, XP Endo Finisher, and the newly introduced XP Endo Finisher-R. This can be considered another advantage of using this file system.

Chapter 2. Aims and Hypotheses

2.1 Aim

Aim of the present study was to characterise the defects that developed in XP Endo instruments after they were used for clinical retreatment of molar teeth.

2.2 Null hypotheses

The null hypotheses to be tested were:

1. There is no difference in the type of defects between the XP Endo Shaper and XP Endo Finisher-R instruments collected from 4 specialty clinics after clinical retreatment of molars.
2. There is no difference in the metallurgical properties between new XP Endo Shaper and XP Endo Finisher R instruments, and those deformed/separated instruments that had been used once for retreatment.

Chapter 3. Materials and Methods

3.1 Specimen Collection

Nine endodontic specialists participated in the study. The collected XP Endo Shaper and XP Endo Finisher-R instruments had been used by endodontic specialists in four different specialty endodontic clinics between May 2019 and December 2020. Maxillary and mandibular molar were referred to the clinics for non-surgical root canal retreatment. Each instrument was used for one clinical case only. The rotary NiTi instruments were used in electric motors with a 1:8 reduction handpiece at the recommended rpm/torque values (XP Endo Shaper: 2,000 rpm, XP Endo Finisher-R: 1,000 rpm).

Non-surgical root canal retreatment procedures were performed according to the manufacturer's recommendations. After access cavity preparation, D-Race DR1 (size 30/0.10 taper, FKG Dentaire) was used to remove the coronal portion (2-3 mm) of the root filling materials to facilitate initial penetration of the XP-endo Shaper. A drop of chloroform was placed in the canal orifice and left for 1 min before proceeding. The XP-endo Shaper was used to remove the bulk of root filling material. Approximately 1 mL of 3% sodium hypochlorite was used after each instrument to flush out gutta-percha, sealer tags and debris from the root canals. The XP Endo Finisher-R instrument was subsequently used for removing root filling materials that remained after use of the XP Endo Shaper. Instruments were discarded after each case, or when they were worn, fractured, or showed visibly discernible deformation before a case was completed.

3.2 Specimen Analysis

The total number of XP Endo Shaper and XP Endo Finisher-R instruments used by the 4 specialty clinics during the study period was not determined. Ninety-two discarded XP Endo Shaper and 20 XP Endo Finisher-R were collected after clinical use. All discarded instruments were ultrasonically cleaned, autoclaved and examined by one investigator using a stereomicroscope at 2.5 – 12.5X magnification. All defects were noted and classified into one of the following categories:

1. Intact instruments with defects that comprise unwinding and straightening of the files.
2. Separated instruments with or without other defects.

The location of the defect was determined at 12.5x magnification, using a surgical operating microscope (Zumax), by measuring the length from the instrument tip to the distal end of the unwound region. The length of each separated fragment was determined by subtracting the length of the fragment from the total length of the file. The separated instrument was cleansed with absolute ethanol in an ultrasonic bath for 90 seconds. The rest of the instrument was examined in the lateral view with scanning electron microscopy (SEM; Helios Nano Lab 650; FEI, Eindhoven, Netherlands) operated at 3 kV. For fractographic examination, the same instrument was mounted on a microscope stage with the fractured surface facing upward. The mode of fracture was classified as "fatigue" or "torsional" (Shen et al. 2009).

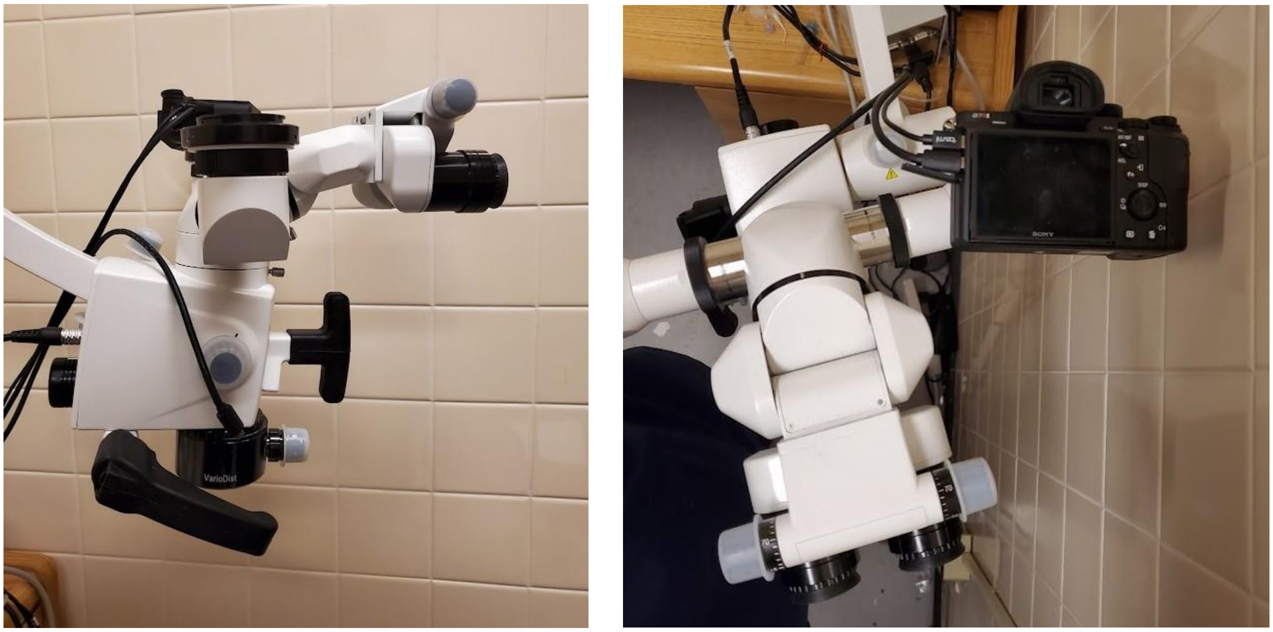

Fig. 2. The Zoomax Dental Operating Microscope with a mounted 4K Sony Digital Camera that was used for the initial defect determination

3.3 Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) was used to analyse the thermal behaviour of new and clinically used XP Endo Shaper and XP Endo Finisher-R instruments. Each specimen was sectioned with a slow-speed water-cooled diamond saw to produce segments that were 4-5 mm in length. The specimens were subjected to full DSC cycles between -80 ˚C and 80 ˚C inside a differential scanning calorimeter (PYRIS, Perkin Elmer Diamond Series DSC; PerkinElmer, Shelton, CT). The DSC process used liquid nitrogen as a cooling accessory to achieve sub ambient temperatures. Three partial DSC cycles of the specimens were also performed to sequence the multi-stage transformations. The first, second and third partial cycles were performed over a temperature range from -20 ˚C to 80 ˚C, from -40 ˚C to 60 ˚C and from -60 ˚C to 60 ˚C, respectively. Phase transformation temperatures, including the austenite-finishing (A_f) temperature, were determined from the DSC plots by finding the point of intersection between the extrapolated baseline and maximum gradient line of the lambda-type curve. (Alghamdi et al. 2020)

3.4 Statistical Analysis

The chi-square test was used to compare the failure modes and types of defects between XP Endo Shaper and XP Endo Finisher-R. Statistical significance was pre-set at $\alpha = 0.05$. Analysis was performed using SPSS for Windows (SPSS 20.0, Chicago, IL, USA).

Chapter 4. Results

The number of defective XP Endo Shaper and XP Endo Finisher-R instruments from the four clinics is shown in Table 1. Of the 92 defective XP Endo Shaper instruments collected, 77 (84%) were deformed but intact, while 15 (16%) were separated (Table 2). Of the deformed but intact XP Endo Shaper instruments, 21 (27%) were bent, 24 (31%) showed evidence of unwinding and 32 (32%) showed evidence of both features. File separation most commonly occurred close to the tip of the flutes (47%), followed by the coronal end of the flutes (33%). Separation was the least common at the middle of the flutes (20%).

Fractographic analysis of the 15 separated XP Endo Shaper instruments revealed that two-thirds were due to torsional failure while one fifth was due to fatigue failure. The failure mode of the remaining 2 separated instruments could not be identified due to contamination of the fractured surface. In the torsional group, most separations (5/10) occurred at the coronal end of the flutes, whereas all separations for fatigue failure occurred at the middle of the flutes or close to the tip of the flutes (Figure 3). Every instrument that separated by torsional failure showed more than one type of defect. Photographs and SEM images of one of the separated XP Endo Shaper instruments with an unwinding defect are illustrated in Figure 4.

Of the 20 defective XP Endo Finisher-R instruments, only four were distorted while 16 were separated. Photographs and SEM images of one of the separated XP Endo Finisher-R instruments are illustrated in Figure 5. All XP Endo Finisher-R instruments that were deformed but intact showed unwinding at the coronal end of the flutes. The majority of XP Endo Finisher-R files separated close to the instrument's tip (62%). The rest of the separations occurred at the coronal end of the flutes (38%). Of the 16 separated XP Endo Finisher-R instruments, two instruments were lost during processing, leaving 14 available for SEM characterization. Microscopic fatigue striations were found in 81 % (13/16) of the separated XP Endo Finisher-R instruments. There was no evidence of torsional failure in those 13 separated instruments. Most of the fatigue cracks were initiated at the cutting edge of the fracture cross-section (Figures 4 and 5). The location of the fatigue failures was seen either close to the tip of the flutes (69%) or at the coronal end of the flutes (31%).

Figure 6 shows DSC curves for both the cooling and heating cycles of the tested instruments. There were two peaks in the heating cycle for both the XP Endo Shaper and XP Endo Finisher-R instruments. The DSC plots showed similar trends among the new, deformed and separated instruments for both the XP Endo Shaper and XP Endo Finisher-R instruments. The austenite finishing temperature of XP Endo Finisher-R (40 °C) was higher than that of XP Endo Shaper instruments (35°C).

Table 1. Summary of defects for the XP Shaper (XPS) and XP Finisher-R (XPFR) instruments from the four participating clinics.

	N	XPS			XPFR		
		Separated	Deformed	Subtotal	Separated	Deformed	Subtotal
Clinic A	21	3	16	19	2	0	2
Clinic B	34	5	22	27	6	1	7
Clinic C	26	1	20	21	3	2	5
Clinic D	31	6	19	25	5	1	6

Table 2. Type of defects and fractured failures modes of discarded XP Shaper (XPS) and XP Finisher-R (XPFR) instruments.

File system	N	File separation failure modes				Intact instruments with plastic deformation			
		Torsional failure	Fatigue failure	Unable to determine	Subtotal	Unwind	Straighten	Unwind and straighten	Subtotal
XPS	92	10	3	2	15	16	30	32	77
XPFR	20	0	13	1	16*	4	0	0	4

*Two files were lost during processing.

Significant difference between XPS and XPFR on failure modes: chi square test, *P = 0.0001*

Significant differences between XPS and XPFR on types of defects: chi square test, *P = 0.001*

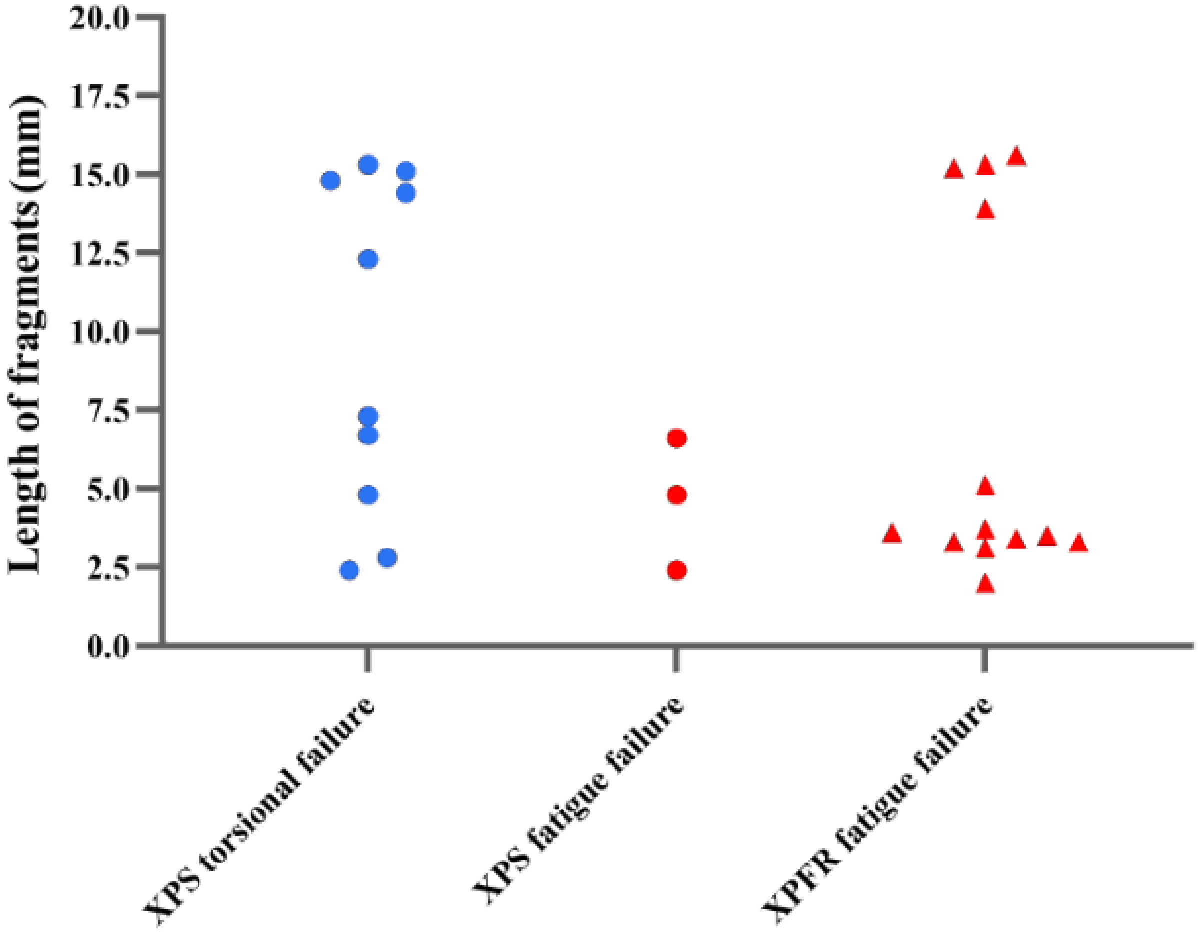

Figure 3. Length of the separated XP Shaper (XPS) and XP Finisher-R (XPFR) instruments relative to their type of failure.

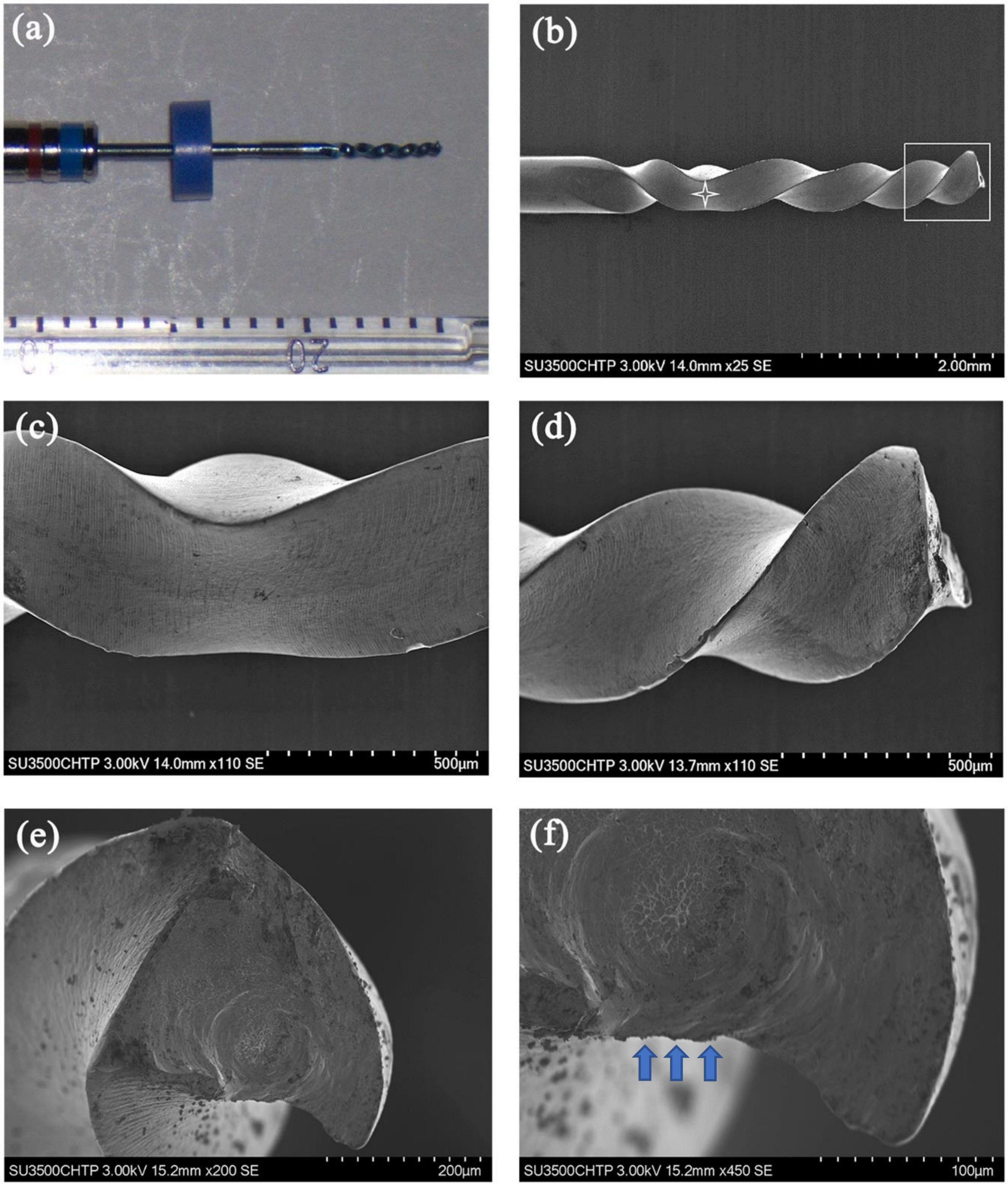

Figure 4. (a) Photograph of a separated XP Shaper instrument with an unwinding defect (b) Lateral view SEM of the same instrument at 25x magnification. Note the deformation around the spiral section of the separated instrument. (c) The unwinding area at 110x magnification under SEM [starred area in (b)]. (d) A higher magnification of (b) showing the lateral view of the fractured surface. (e) SEM of the fractured surface which shows signs of torsional failure. (f) A higher magnification of (e) arrows showing abrasion.

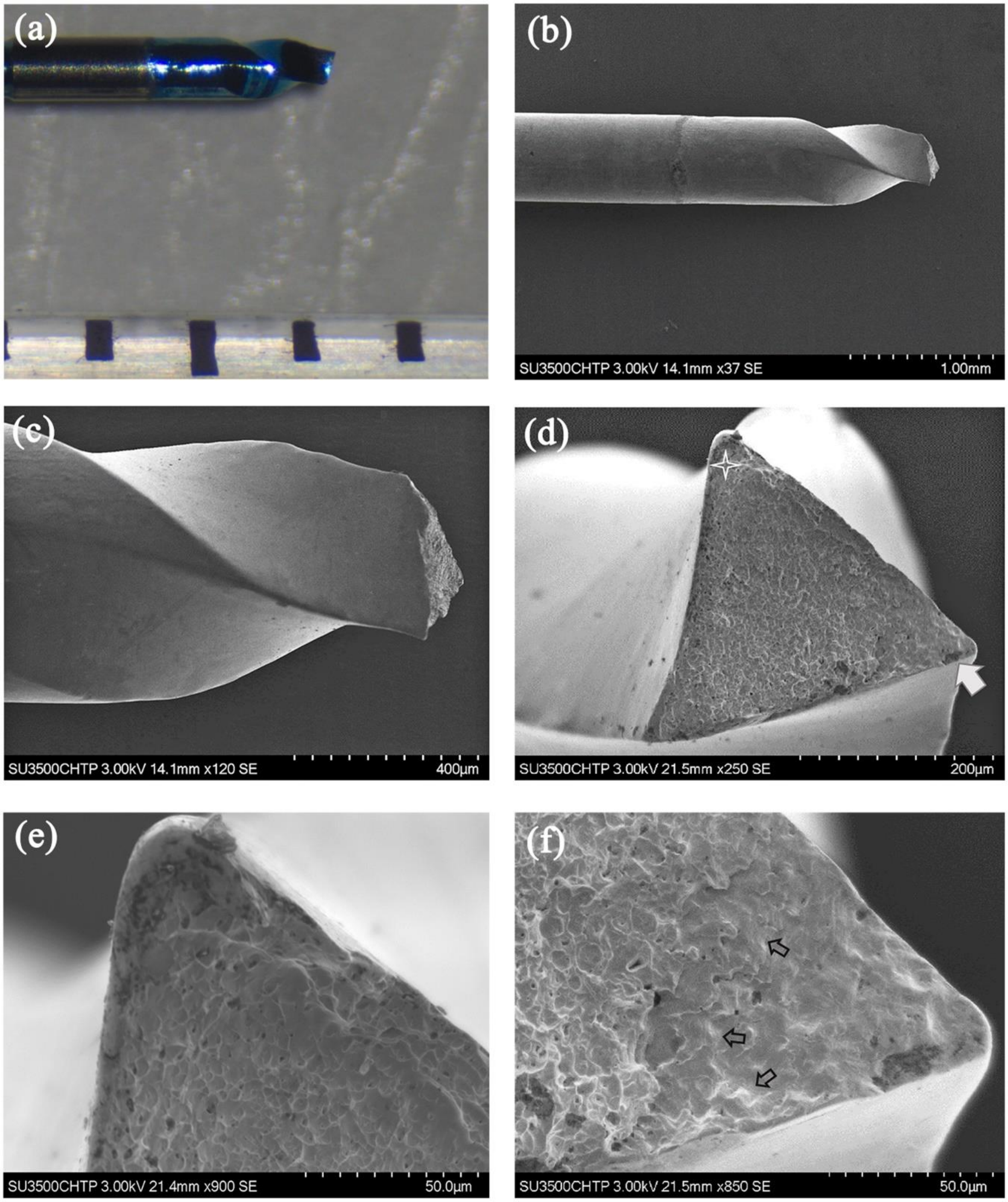

Figure 5. (a) Photograph and (b) SEM image of a separated XP Finisher-R. The site of separation was at the coronal end of the flutes. (c) A higher magnification of (b). (d) SEM image of the fractured surface showing signs of fatigue failure. (e) A higher magnification of a dimple area of the cutting edge [starred in (d)]. (f) A higher magnification of (d) (solid arrow) showing fatigue striations (arrows) and the crack initiation point on the cutting edge.

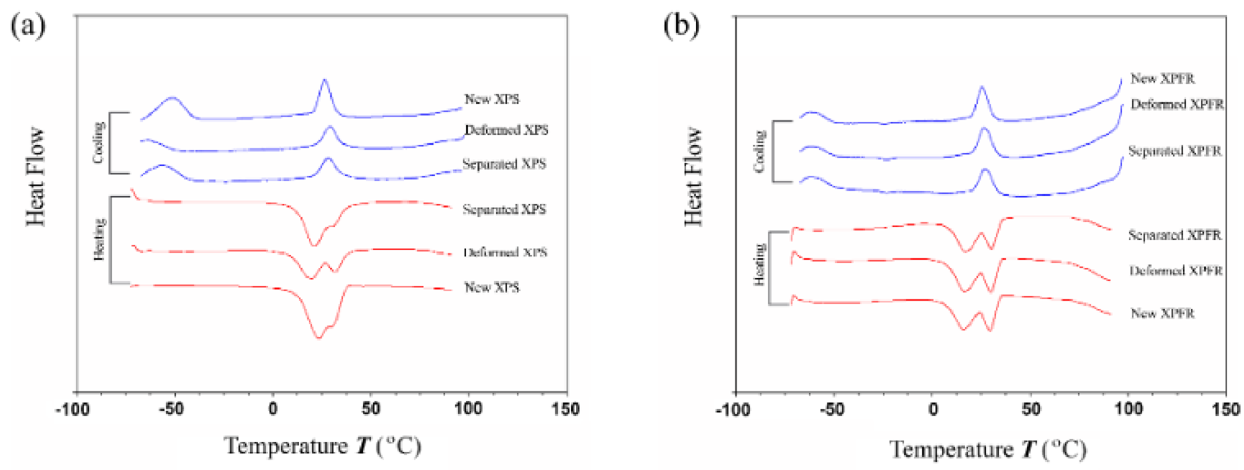

Figure 6. Differential scanning calorimetry (DSC) of unused (new) and separated (a) XP Shaper (XPS) and (b) XP Finisher-R (XPFR).

Chapter 5. Discussion

The mechanical kinetics of instruments designed for root canal retreatment are more complex than those of instruments used for primary root canal preparation. This is because retreatment cases involve not only cutting and abrading the canal wall, but also engaging the filling material and dislodging gutta percha. The instruments are subjected to multi-directional torsional and bending stresses simultaneously, which is more challenging than the stresses experienced by files rotating in a curved root canal. To the best of my knowledge, this was the first study to analyse the type and location of defects in retreatment instruments that were collected from multiple specialty clinics. The used and discarded specimens were collected from four clinics involving nine experienced endodontic practitioners in one country, who utilised these instruments for retreatment of molar teeth. This provides reliable information on the fracture profiles of instruments that were used clinically for root canal retreatment.

Results from laboratory usage tests could only indicate the relative risk of deformation or separation under a particular set of conditions for the brands of instrument being examined. Many variables, such as accessibility of the canal, apically directed force and the use of a hybrid technique, could not be faithfully reproduced in the laboratory setting. Operator-related variables may be more important factors that are associated with instrument separation than the design of the instrument (Shen et al. 2009). It should be appreciated that these variables could only be identified, and the desired result achieved through the evaluation of large clinical samples. Utilizing single use instruments may be a positive move to prevent separation of a rotary instrument.

It was not possible to obtain accurate data on the total number of instruments that were used at the multicentre clinics. Hence, statistical analysis could not be performed and the percentage of instruments that resulted in defects after use could not be determined. Both the instrumentation technique and instrument design can influence the magnitude of stress concentration and the risk of instrument fracture (Shen et al. 2009, Berutti et al. 2003, Xu et al. 2006, Kim et al. 2008). The results of the present study indicate that torsional failure predominated in the XP Endo Shaper instruments, whereas the majority of XP Endo Finisher-R instruments failed due to fatigue. Accordingly, the first null hypothesis that "there is no difference in the type of defects between the XP Endo Shaper and XP Endo Finisher-R instruments collected from 4 specialty clinics after clinical retreatment of molars" has to be rejected. In addition, the DSC data indicated that one-time use of XP Endo Shaper and XP Endo Finisher-R instruments in retreatment cases did not cause a significant change in their metallurgical properties. Consequently, the second null hypothesis that "there is no difference in the metallurgical properties between new XP Endo Shaper and XP Endo Finisher-R instruments, and those deformed and/or separated instruments that had been used once for retreatment" cannot be rejected.

The excessive torsional forces on the XP Endo Shaper tip, caused by friction and binding of the instrument's tip in the filling material, are the most likely factors that contributed to the high number of plastic deformations. The XP Endo Shaper has been available for a couple of years for primary root canal treatment (Lacerda et al. 2017). Recently, it was recommended for the purpose of root canal retreatment along with the XP Endo Finisher-R. The XP Endo Finisher-R instruments were used as a supplementary approach to enhance the removal of filling material that remained after the use of the XP Endo Shaper or other retreatment NiTi instruments. The majority of the separated or distorted files were XP Endo Shaper files. This is not surprising because the XP Endo Shaper instruments were used to remove old root fillings and were exposed to considerable amounts of pressure. In contrast, the XP Endo Finisher-R instruments are designed to run in an almost empty canal to detach remnant root filling material from the canal wall. The present study demonstrated that plastic deformations were the most common type of defect observed on the XP Endo Shaper instruments. One explanation is that the instrument is subjected to high torsional forces when it is used in the small canal lumen during the first stage of clinical retreatment. The instruments were discarded upon identification of any distortion, or when reduction in cutting efficiency was noted during the retreatment process.

The ability to visualise plastic deformations on instruments used for root canal treatment/retreatment can alert the operator to abandon the instrument prior to file separation. Operators should also use tactile sensation to gauge the amount of torsional stresses an instrument experiences during retreatment. Once a flaw is developed on an instrument surface, the torsional stresses cause further propagation of the initial crack that ultimately results in catastrophic failure. When the tip of the instrument binds in the root filling material or when high resistance is felt, the operator should remove the instrument from the canal, clean the flutes and inspect the instrument for deformations prior to continued use. If there are any deformations, the operator should discard the instrument.

During retreatment, contact exists between the expanding segments (bulge portions) of the XP instruments and the filling material/dentine. This generates a lot of stress at the contact area of the instrument. Hence, most fracture locations occurred along the bulge portions. Interestingly, 67 %

of the XP Endo Shaper instruments separated because of torsional failure, in which one-third of those failure were found close to the spiral sector. Unlike primary root canal treatment in which a glide path may be established prior to the use of rotary instruments, this is not possible for secondary root canal treatment and the retreatment instruments have to drill through the existing root filling material. This places substantial torsional stress on the instrument and increases the risk of instrument separation. It is possible that the XP Endo Shapers separated close to the shank because of inadequate access or instrument design. Instruments with a narrow cross-sectional diameter have decreased torsional resistance compared to those with a wider cross-sectional diameter. The XP Endo Shaper instruments (size 30, 0.01 taper) are designed in such a way that they have relatively small core diameters. This, theoretically, makes them more prone to torsional overload. Fortunately, instruments separation close to the shaft are amenable to retrieval relatively easily.

Instruments with smaller diameters are generally more resistant to cyclic fatigue than those with larger diameters (Pruett et al. 1997, Hieawy et al. 2015). The XP Endo Finisher-R has a size 30 tip and zero percent taper design, which produces greater flexibility than traditional NiTi instruments with large tapers. The XP Endo Finisher-R instruments underwent a 2-stage transformation behaviour and had a high austenite finishing temperature (40 °C). These findings indicate that the XP Endo Finisher-R instruments contain a mixture of martensite and austenite phases at body temperature. It was expected that the XP Endo Finisher-R would have a high fatigue resistance because of its small cross-sectional diameter. However, the results of the present study indicate that fatigue failure appears to be an important factor for the separation of the XP Endo Finisher-R instruments. This may be explained by the fact that a glide path was already established to the working length with an XP Endo Shaper or other retreatment instrument before the XP Endo Finisher-R was introduced into the canal. The established glide path may have reduced the instrument “taper locking” or “jamming” in the canal, which is the main cause of torsional failure (Blum et al. 1999, Kwak et al. 2018). When considering separation of the XP Endo Finisher-R that occurred due to fatigue failure, the location of fractures was commonly seen around the “bulb area” (69 %) and close to the coronal end of the flutes (31 %). During rotation, the XP Endo Finisher-R instruments expand to a bulb/sickle shape inside the root canal at body temperature. It appears that high magnitudes of stress are generated at the bulb area when the XP Endo Finisher-R abrades and touches the canal walls. The XP Endo Finisher-R is recommended to be pressed against the canal walls during retreatment in order to remove residual obturation material during retreatment. This may result in a complicated condition of multi-axial loading. The diameter between the shank and the fluted section of the XP Endo Finisher-R dramatically reduces from 1mm to 0.3mm. This abrupt change in cross-sectional diameter could have increased the stress concentration in the area and consequently increased the likelihood of crack initiation. This may explain why the fracture locations for some of the XP Endo Finisher-R instruments were close to the shaft. Further laboratory experiments and finite-element analysis are required to examine whether the connection area between the shaft and the spiral sector plays a role in the separation of XP Endo Finisher-R instruments.

Chapter 6. Conclusions

Within the limitations of this study, the failure mode of the XP Endo Shaper and the XP Endo Finisher-R appears to be different. The majority of defects found in the XP Endo Shaper instruments for retreatment cases were plastic deformations or torsional failure, whereas 81% of XP Endo Finisher-R instruments that experienced structural changes during use were separated by fatigue failure. The fracture locations for both types of instruments were often close to the coronal end of the flutes or the expanding segments of the instruments. A forewarning sign such as plastic deformation or alteration in tactile sensation may be noticed that is indicative of an impending risk of instrument separation when XP Endo instruments are used for retreatment of previously root canal treated molar teeth.

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